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A Technical and Economic Study of a Photovoltaic–phase Change Material (PV-PCM) System in Jordan

Salem Nijmeh[a], Bashar Hammad[b], Mohammad Al-Abed[c,d,*], Riad Bani-Khalid[a,e]

[a]Department of Mechanical Engineering, The Hashemite University, Zarqa, Jordan
[b]Department of Mechanical and Maintenance Engineering, German Jordanian University, Amman, Jordan
[c]Department of Biomedical Engineering, The Hashemite University, Zarqa, Jordan
[d]Center of Renewable Energy, Water, and Environment, The Hashemite University, Zarqa, Jordan
[e]Ministry of Education, Amman, Jordan

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Abstract

This work presents a technical and economic evaluation of the application of phase change material (PCM) in the cooling and thermal regulation of photovoltaic (PV) panels. The technical study is performed based on experimental tests carried out on two identical 3.99 kWp PV systems for one full year at the Hashemite University, Jordan. The backside of the first system was integrated with BioPCM. It is a safe, environmentally friendly, and economically sustainable product that is typically employed in the building industry to save energy in HVAC. This PCM has the potential to answer the many concerns associated with the traditional PCMs. The second PV system is used as a reference for performance comparison purposes. The actual performance results show there is an increase of 3.4% in the annual power production due to the application of BioPCM. The annual conversion efficiency is 12.50% for the PV/BioPCM system, while it is 12.08% for the reference PV system. The economic study investigates the viability of the inclusion of PCM in terms of the payback period, net present value, and internal rate of return. These parameters indicate that the PCM investment is economically unattractive at present.

Keywords: photovoltaic systems; phase change material; experimental study; technical evaluation; economic feasibility;

1. Introduction

1.1. Energy situation in Jordan

Jordan is a Middle Eastern country with limited resources and an estimated population of about 10.554 million inhabitants in 2019 [1]. Jordan imports most of its primary energy requirements (92% in 2018), which leads to severe financial strain on the national economy. The cost of consumed energy reaches 10% of the GDP [2]. Jordan's energy strategy has focused primarily on reducing dependence on oil products, increasing natural gas, and alternative energy inputs, including renewable energy, especially in the electricity generation sector. It is blessed with high annual daily average solar irradiance, which ranges between 4-8 kWh/m^2, and adds up to a total of 1400-2300 kWh/m^2 annually [3].

The updated national energy strategy set a 10% target of renewable energy by 2020 [4]. To meet this target, the Renewable Energy and Energy Efficiency Law (REEEL) No.13 was approved in 2012 [5]. The law gives incentives and tax exemptions to promote the installation of renewable energy systems. The law allows the development of distributed electricity generation under the Net Metering and Wheeling mechanisms, allowing small RE installations for different sectors to sell the exceeding electricity to the grid.

The most promising application of RE in Jordan is solar PV power generation. National Electric Power Company (NEPCO) estimates in 2018 that the electricity generated from solar energy amounted to nearly 7% [6]. Recent projects accomplished on the ground with the collaboration of the private sector include Almafraq and Al-Quweira solar PV plants with capacities of 100 MW and 103 MW, respectively. The largest project currently under construction is the Baynouna (east of Amman) with a 200 MWp solar power plant. The connectivity to the grid is expected in 2020 [7]. The total installed renewable capacity is expected to reach 2400 MWp by 2021, and that will constitute 20% of the total electricity generation [8].

1.2. Effect of rising temperature on PV modules

Rising temperature of PV module causes reduction in power output which is determined by temperature coefficient [9]. This coefficient depends on the type of cell and was determined as -0.446%/°C, -0.387%/°C, and -0.172%/°C for mono-crystalline, multi-crystalline and CdTe cells, respectively [10]. Another work [11] investigated the power-temperature coefficient for different types of modules. It shows that all thin-film technologies have lower values (-0.13%/°C to -0.36 %/°C) in comparison

* Corresponding author e-mail: drnijmeh@hu.edu.jo.

with to the c-Si wafer-based modules (-0.45%/°C). The percentage loss at 80 °C compared to power at Standard Test Condition ranges from 7.2% to 24.8%. Alrwashdeh [12] simulated the output of five PV panels at different operating temperatures in Amman, Jordan. The power output was reduced between 0.25% and 0.30% for each °C of temperature rise.

Another adverse effect of rising temperatures is accelerated degradation. The operating solar PV module at lower temperatures increases its lifespan [13]. The high temperatures cause stresses which accelerate degradation rates, with cell encapculation and soldering being the most susceptable [14]. A study in the high-temperature desert region of Algeria predicted that the life of a PV module, under conditions of the open-circuit could be shortened by four years [15]. Another mathematical study by the same research group predicted that the annual rate of degradation is in the order of 1.5%/year [16]. This has led to a strong requirement for PV thermal control to increase panel power yield and lifespan [17].

1.3. Cooling techniques of PV panels

Many researchers have proposed and tested several new materials and techniques to manage the temperature of the PV systems thermally using passive and active means. The simplest and least expensive is by using natural- or forced-air cooling. A theoretical and experimental study conducted in Iraq shows that using fin cooling technique results in an increase in the module generated power by about 15.3% [18]. Natural ventilated systems can reach PV temperatures between 50-70 °C [19]. The main drawback of natural ventilation is the very high panel temperature during peak insolation [20].

As for the active or forced-air cooling, Amelia et al. [21] have developed an active air-cooling system using fans fitted at the backside of PV panels. It was found that the optimum number of DC fans used was two units. The power output increased by about 37.17% for this case. There is no mention of the electrical power consumed or the capital investment required.

There is a large number of technical studies on active water-cooling systems. Odeh and Behnia [22] did a long-term simulation of a solar PV water pumping system. The cooling of the PV module is obtained by water trickling on the upper surface. Results show an increase of 5% in energy output during dry and warm seasons. Irwan et al. [23] conducted an indoor test performance of a PV panel sprayed with water over the front surface. Results indicate that the power output increased by 9-22%. Bahaidarah et al. [24] introduced a water-cooled mono-crystalline PV module from the backside in the hot climate of Dhahran, Saudi Arabia. This has led to an improvement of 9% in efficiency.

Other works employed nanofluids in PV and PV/T (photovoltaic thermal) systems because of their higher thermal conductivity and heat capacity [25]. Hashim et al. [26] evaluated employing Al2 O3-water for cooling by applying forced convection. The authors concluded that at 0.3% concentration, the electrical efficiency rose from 8% to 12.1%. Ebaid et al. [27] carried out an experimental investigation of cooling PV cells using water and two different types of nanofluids under the real outdoor conditions of Jerash-Jordan. The generated power increases for TiO2 nanofluid and water as compared to no cooling by 6.05% and 3.75%, respectively. In general, active systems raise the cost greatly due to the pumping costs of air and water.

Other cooling techniques include heat thermosyphon cooling. Habeeb et al [28] studied the use of this method in cooling different PV modules. Results show that the efficiency is enhanced by 4 -14 % as compared with the reference module. One of the most critical techniques studied in the past few years is the photovoltaic cooling utilizing phase change materials (PCMs). Most of the work in literature are either theoretical or in laboratory. The few studies conducted under field conditions are for a short duration, which puts a significant limitation on the reliability, repeatability, and generalization of the results obtained [20].

1.4. Cooling techniques using PCM

1.4.1. Technical and economic feasibility studies

In general, PCMs are classified into three groups, organic which includes paraffin-based materials, inorganic, which includes salt hydrates, and eutectics of organic and inorganic compounds [29]. Organic PCMs have low thermal conductivity, high flammability, and can release toxic vapors [30]. This can be a problem in high insolation areas where the back-surface temperature of PV panels can exceed 80 °C during peak hours. Also, for none of the systems studied in the literature, the economic advantage out-performed the invested cost. On the other hand, salt hydrates have high thermal conductivity and latent heat of fusion [29]. The main disadvantages may include solidification problems at night, corrosion, long term degradation, and chemical instability.

Literature works of cooling techniques using PCM are focused on the groups mentioned above. In a recent work carried out in Jordan [31], the effect of using PCM (paraffin graphite PCM47) on both the efficiency and power output using two identical PV panels was investigated. The theoretical results were compared with short-term outdoor experimental results in October. It is found that the PCM would give positive results only when the panel temperature surpasses the PCM melting temperature.

Another simulation and experimental study [32] was carried out in the city of Ljubljana using organic PCM (Rubitherm RT28 HC) with a melting temperature of 28°C. An average increase in efficiency of 1.1–2.8% was obtained based on temperature measurements. Simulation results reveal that the generated power rose by 7.3% in one year. On the other hand, a recent study [33] conducted under Mediterranean climate in Portugal on another organic product (Rubitherm RT 22 HC) concluded that the use of this PCM have a negative effect on the performance. The daily energy produced decreased between 3.3-6.5%, and it is concluded that a PCM with a higher melting temperature is required for this climate.

Nada and Nagar [34] investigated the performance of free stand and building-integrated PV modules using PCM (paraffin wax RT 55) and PCM with added 2% Al2O3 in Giza, Egypt. It was found that adding PCM to a building-integrated PV module improves its daily efficiency by 7% to 14.2%.

There are many technical studies on PV-PCM systems, but few studies investigated their cost and financial viability. A very recent work [35] investigated numerically paraffin-based PV-PCM and PV-FPCM (finned phase change material) systems for PV cooling under the climatic conditions of Southeast of England. The extracted heat is used for space heating. It was observed that the daily power increased by 7% for the PCM cooled system and 8% for the FPCM cooled system as compared with the reference PV. A short cost analysis study shows that PV-FCPM is not economical. The cost of electricity generation is 0.094 £/kWh for the PV system as compared with 0.119 £/kWh for the system using FPCM. This is due to the low irradiance level and low ambient temperatures. A short experimental study conducted in Lebanon [36] concluded that the installation of Petroleum jelly PCM would have a payback period of 12.3 years. Arici et al. [37] performed a simulation study on a 10 kW PV system with different PCMs in two Turkish cities (Ankara and Mersin). The calculated Levelized Cost of Energy (LCOE) varied between 0.13 €/kWh and 0.146 €/kWh, as compared with 0.096 €/kWh to 0.108 €/kWh for the reference PV system.

1.4.2. Criteria for selecting appropriate PCM for our tests

It can be seen that there are many concerns associated with traditional PCMs relating to safety, environment, and performance. This led the authoring team to consider a more environmentally friendly and safer product derived from sustainable, renewable sources. The PCM used in this work is the Phase Change Energy Solution BioPCM^{TM} M51 Q25. It is made from a renewable and sustainable plant extract, which is picked and then manufactured into blankets [38,39]. The M-value gives the heat storage capacity of the material in Btu per square foot (51). The second code Q refers to the melting temperature of the BioPCM^{TM} (25 °C in our case).

BioPCM^{TM} is used in the building industry, where it is claimed that HVAC energy savings in the 25–35% range can be achieved. It is both a LEED and a BEES (Building for Environmentally and Economic Sustainability) friendly product. The product is tested to ASTM E84 Standards and meets or exceeds the safety guidelines of the building products industry [39].

This particular product was chosen based on availability and previous works on BioPCM^{TM} in other applications recommending low melting temperatures. For example, a simulation study on BioPCM^{TM} [40] investigated the thermal improvement through retrofitting existing residential buildings in the Mediterranean area. Results for Bari, Athens, and Tunis show that PCM M91/Q25 with a melting point temperature of 25 °C is the most effective. For example, energy savings of 66% was obtained for Bari for the whole summer. Similar results were obtained for Athens and Tunis with cooling savings of 43% in both cities. Another simulation work [41] investigated the use of 3 types of PCMs in envelopes of buildings. Results show that BioPCM^{TM} with a low melting point temperature produced superior energy savings for the HVAC system over other types of PCMs. For example, electricity savings present in present in Tokyo were shown to be 9.69%. Hence, for the concerns and merits mentioned above, BioPCM^{TM} M51 Q25 is selected for our tests. A technical and economic evaluation of PV cooling employing this particular PCM is conducted in this work.

2. Materials and Methods

2.1. Systems Setup

Two on-grid identical PV systems (PV/PCM and reference PV) are installed at the Hashemite University, Jordan (lat. 32.1° N, long. 36.2° E). They are fixed systems sloped at 26° towards the south. Both systems are positioned on rooftop of the Presidency Building, as shown in Figure 1. A rooftop view of the Presidency Building and PV systems from Google Map is shown in Figure 2.

Figure 1. PV systems on the rooftop of the Presidency Building.

Figure 2. Google Map of Presidency Building and PV systems.

Each system consists of 14 Poly-Crystalline cell-type panels of 285 W rated capacity (SunTech, China). The total capacity of both systems is 7.98 kWp (DC) wired to a three-phase 8 kW inverter. The AC power is supplied to the university grid. The two systems are fitted with data acquisition systems to obtain system and weather data outputs, synchronously collected at a one-minute interval. The data is acquired using pyranometers to measure the total incident radiation on tilted planes, and type-k thermocouples to measure the ambient and cell temperatures. Also, voltage and current transducers are used to obtain the output DC voltage and current, respectively. The data is monitored directly over the internet by authorized persons and can be studied and analyzed offline.

The experimental data were collected over one full year from the 1st of August, 2015 up to the 31st of July, 2016. The collected data is analyzed, and the following parameters are determined for both systems on a daily, monthly, and yearly bases as discussed later:

1. Total incident solar radiation on a 26° tilted plane (kWh/m^2)

2. PV modules DC electrical power output (kWh)
3. PV modules actual conversion efficiency (%)

2.2. Integration of PCM into PV panels

An Allen key was used to disassemble the 14 modules of the first system (PV/PCM) from their frames. The back surface of the panels and the outer surfaces of the PCM plastic envelopes were bonded together using Bison epoxy double syringes workable for 5 minutes (6305448), as shown in Figure 3. The surfaces to be bonded must be clean, dry, free of dust, and grease. Equal amounts of both components (resin and hardener) from the Bison epoxy were pressed out and mixed thoroughly in a mixing tray until an even color is obtained. A thin layer of about 1 mm thickness was then applied to the outer surface of the plastic envelopes, which contain the PCM. The parts to be bonded together were pressed using a square thin wooden block and kept in place for 20 minutes. Curing time is one hour approximately. A total of 57 double syringes was used in the bonding process. Finally, the PV panels were mounted back and tightened onto the frames. The 28 m^2 BioPCM^{TM} mats used has the specifications tabulated in Table 1 [39].

Figure 3. Pasting PCM on the PV panels backside.

Table 1. Thermo-physical properties of BioPCM^{TM}.

Parameter	Value
Model	M51/Q25
Melting point temperature	25 °C
Latent heat storage capacity	0.161 kWh/ m^2
Unit thickness	15 mm
Product weight per m^2	3.76 kg

2.3. Methodology

2.3.1. Technical evaluation

The technical performance of the two PV systems are assessed using the following parameters:

1. Instantaneous DC power output (P_{DCout}) in Watts:

It is determined as by multiplying the measured DC voltage (*V*) by the measured DC current (*I*) and expressed as

$$P_{DCout} = V \times I \quad (1)$$

The instantaneous power values are utilized to determine the daily, monthly, and annual values in kWh, as discussed later in this work.

2. Conversion efficiency (η):

The operating efficiency obtained under real outdoor conditions is different from the one achieved in the laboratory under Standard Test Conditions (STC). The values of STC are solar irradiance of 1000 W/m^2, cell temperature of 25 °C, and air mass of 1.5 [42]. However, these conditions are rarely achieved in reality. The real operating efficiency of the PV modules is expressed as:

$$\eta = \frac{P_{DCout}}{n_p\, A_c\, I_d} \times 100 \quad (2)$$

where P_{DCout} is the DC power output in kWh of the PV modules, A_c is the area for each panel (=1.752 m^2), and I_d is the measured total incident radiation on the tilted plane in kWh/m^2. In this work, n_p is the number of panels in each system (14). Monthly and annual values are determined to compare between the two PV systems.

2.3.2. Economic analysis

The economic analysis parameters utilized in this work are as follows [43]:

1. Payback Period (*PBP*):

Defined as the time taken to recover the cost of an initial investment from the annual savings it makes. The *PBP* is expressed as:

$$PBP = \frac{Investment}{Savings} \quad (3)$$

However, depending on a simple PBP calculation is not preferential, since it does not include other economic factors such as inflation, system depreciation, and maintenance overheads.

2. Net Present Value (NPV):

It is a measure of the difference between the present value of cash inflows and outflows over some time by discounting the flows at a specified rate. In our case, the discount rate is assumed to be 10%, as discussed later. A positive *NPV* indicates that the investment will be profitable while a negative *NPV* presents a business case with a net loss. The *NPV* metric is used to evaluate commercial and large-scale PV systems, and possibly some residential systems. The *NPV* is expressed as [43]:

$$NPV = -C_0 + \sum_{i=1}^{T} \frac{C_i}{(1+r)^i} \quad (4)$$

where C_0 is the initial investment, C_i is the annual balance net cash flow, *r* is the discount rate, and T is the lifespan of the project, which is taken as 20 years. This is dependent on the power purchase agreements (PPAs) signed between investors or independent power producers (IPPs) and Jordan's electricity company NEPCO [44].

3. Internal Rate of Return (IRR) [45]:

It represents the discount rate at which the project *NPV* is zero. This is a useful parameter for comparing the returns of different investments and choosing precisely between them.

If the *IRR* exceeds the discount rate r, then the investment is viable. It is expressed as:

$$NPV = 0 = -C_0 + \sum_{i=1}^{T} \frac{C_i}{(1+IRR)^i} \quad (5)$$

where C_0 is the initial investment, C_i is the annual balance net cash flow for the i^{th} year, and *T* is time (20 years) similar to the *NPV* calculations.

It should be noted that the *IRR* is an inferior metric for characterizing the value of solar systems in some cases. This is due to the incentives and nature of financed costs, which could lead to an inflated misleading value [46].

3. Results and Discussion

3.1. Technical analysis

1. Solar irradiance

Solar irradiance measurements on the 26° tilted plane were recorded over a one-year testing period. They were analyzed to determine the daily solar irradiation, as shown in Figure 4. The peak value of 7.84 kWh/m^2 is reached on the 1st of July, while the minimum value of 0.87 kWh/m^2 is captured on the 25th of January. There are significant drops in winter due to cloudy and wintry weather conditions. The annual average daily irradiation is about 6.15 kWh/m^2.

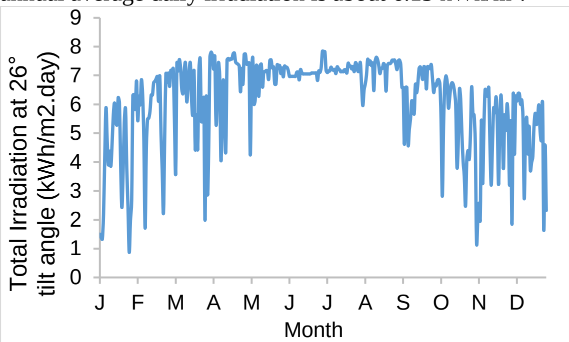

Figure 4. Daily irradiation on 26° tilted plane over a one-year testing period.

The daily values are added up to obtain the monthly irradiation illustrated in Figure 5. The maximum and minimum values received are 223.8 kWh/m^2 in July and 130.8 kWh/m^2 in January, respectively. The total annual irradiation is the sum of the monthly values, which is 2246.2 kWh/m^2. The monthly and annual irradiations are used to determine the conversion efficiencies.

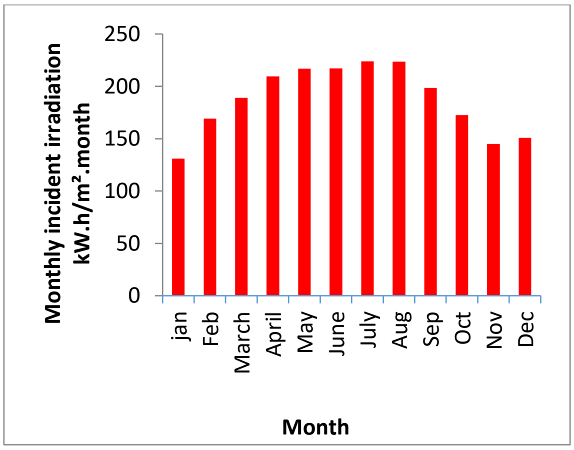

Figure 5. Monthly incident irradiation on a 26° tilted plane.

2. Actual power output

The instantaneous DC power output under actual operating conditions is determined from Equation (1) and presented in Figure 6 for a sample day (the 4th of September). The power curves are nearly symmetrical and typical for a clear day. The peak values obtained at 12:30 pm are 3089 W for the PV/PCM system, and 2806 W for the reference PV system.

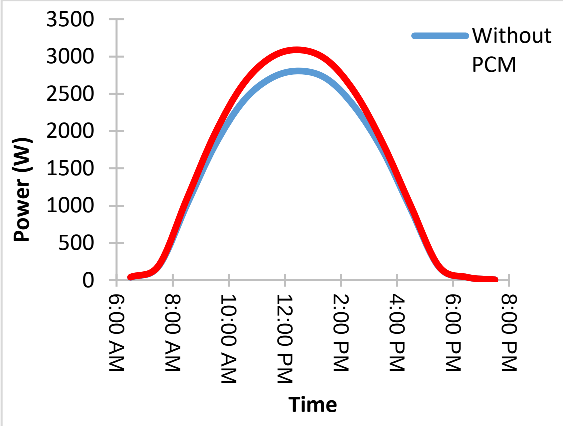

Figure 6. Instantaneous DC output power on the 4th of September.

This output is used to calculate the total daily yield power in kWh/day, as presented in Figure 7. There is a good match between the daily irradiation and power curves, as expected, with significant falls on cloudy days and little variations over the summer period.

The summation of the daily values produces the monthly yield power, as shown in Figure 8. It can be seen that there is no substantial difference in power output between the two systems from October till March due to the mild ambient and cell temperatures recorded. The PV systems operated below the STC temperature (25 °C) for the period from November to February, ranging from 16.4 °C to 23.8 °C. The results show that the benefit of PCM in cooling the modules at low temperatures is negligible. This is in agreement with literature in which it is reported that the PCM in general works better in warm and stable climatic conditions than the colder and variable conditions [47]. Smith et al. [48] found that the most considerable enhancement in performance was achieved in areas with high values of solar insolation and ambient temperatures all year-round, such as Africa, South Asia, Australia, and South America.

The yearly power output is obtained by adding up the monthly values. Under actual operating conditions, the yearly output of the PV/PCM system is 6879.2 kWh by comparison with 6654.7 kWh for the one without PCM. Hence, the increase in power production is about 3.4% due to the application of PCM.

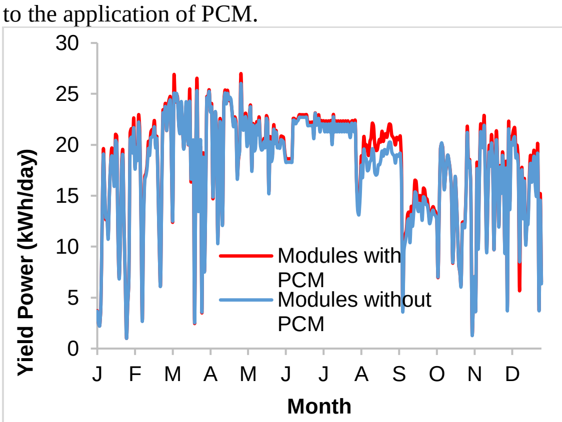

Figure 7. Daily yield power of the two PV systems.

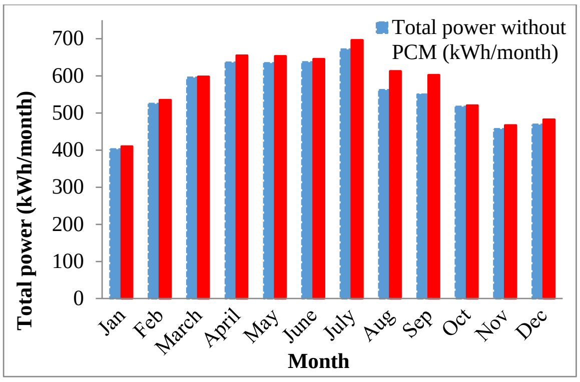

Figure 8. Monthly yield power of the systems with and without PCM.

3. Conversion efficiency (η)

The monthly average conversion efficiencies of the two PV systems are determined using Equation (2) and shown in Figure 9. The maximum monthly efficiencies obtained are 13.2% in November for the PV-PCM system and 12.9% in March for the reference system. It can be seen that the maximum efficiencies occur from November to March due to the low ambient temperatures experienced in these months. Another contributing factor can be attributed to the minimal dust build-up because of the repeated rainfall in this period. A recent study in Jordan [49] found that the efficiency decreases because of dust are 0.768%/day and 0.607%/day based on two different models. The minimum efficiencies occur in August for both systems, with 11.2% for the PV-PCM system and 10.2%, for the reference system. This is expected mainly due to the high ambient temperatures and considerable dust accumulation

The annual conversion efficiency is an essential parameter in the technical comparison between the two systems. It is determined as 12.50% for the PV-PCM system, while it is 12.08% for the reference PV system. There is an improvement of about 3.48% due to the employment of PCM.

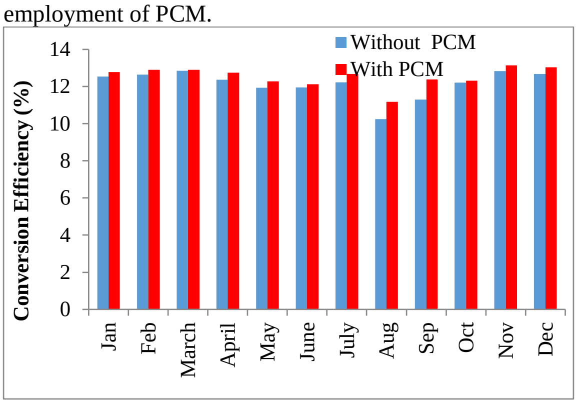

Figure 9. Monthly average conversion efficiencies of the two PV systems.

3.2. Economic analysis

1. Basic assumptions

The economic study is carried out in the local currency (Jordanian Dinar JD). Every 1 US$ is equal to 0.708 JD. The economic metrics used and cost assumptions made to perform this economic study are as follows:

1. The electricity tariff for the Hashemite University in 2016 is 0.256 JD/kWh, including additional charges [44].
2. Based on electricity costs in Jordan between 2005-2013 [50], the annual tariff increment is assumed to be 5%.
3. The operating and maintenance costs (*OMCs*) are assumed to be approximately 14 JD/kWp/year for each PV system [51]. The total *OMCs* add up to around 56 JD with an annual inflation rate of 3%.
4. The average value for the interest rate on bank credit to the private sector in Jordan is around 9±0.2% for the period 2008-2012 [52]. Hence, an upper limit for the discount rate *r* is assumed to be 10% in this study.
5. The PV modules' annual output power is reduced linearly from the nominal power output based on the 25-year transferrable power output warranty [53].

Also, the actual cost and quantity of PCM mats and epoxy purchased to conduct the tests are presented in Table 2.

Table 2. Cost and quantity of purchased PCM and epoxy.

Item	Description	Origin	Quantity	Total Price (JD)
1	BioPCM™ M51 Q25	USA	28 m^2	735
2	Bison Epoxy 6305446	Holland	57 syringes	178
				913

2. Yearly balance cash flows

Based on the assumptions presented above, the *OMCs* for the next 20 years is determined by:

$$OMCs = 56\ \times (1.03)^{Y-1} \quad (6)$$

Similarly, the annual electricity tariff rate *TR* is calculated as follows:

$$TR = 0.266\ \times (1.05)^{Y-1} \quad (7)$$

where *Y* is the year number.

Throughout our study, the PV/PCM system generated 6879.2 kWh/yr, whereas the system without PCM generated actual power of 6654.7 kWh/yr. The annual power production (*APP*) of each system is projected for the next 20 years using the reduction percentage values derived from the manufacturer's brochure.

The cash flow resulting from Annual Sold Energy (*ASE*) is determined by multiplying the annual power production (*APP*) by the tariff rate (*TR*) as follows:

$$ASE = APP\ \times TR \quad (8)$$

By combining the cash flows for the capital cost C_0, *OMCs*, and *ASE*, the annual balance cash flow for the PV system using PCM is presented in Figure 10. Similarly, the annual balance cash flow for the PV system without PCM is shown in Figure 11. This is obtained by adding the cash flows for *OMCs* and *ASE* with no initial investment. The annual balance net cash flow C_i is the difference between the cash flows presented in Figures 10 and 11. This net balance is shown in Figure 12.

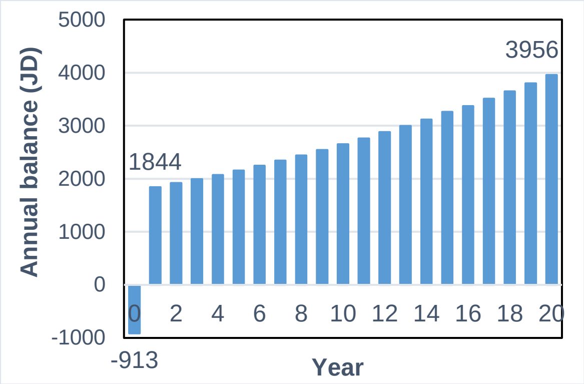

Figure 10. The annual balance cash flow for the PV system using PCM.

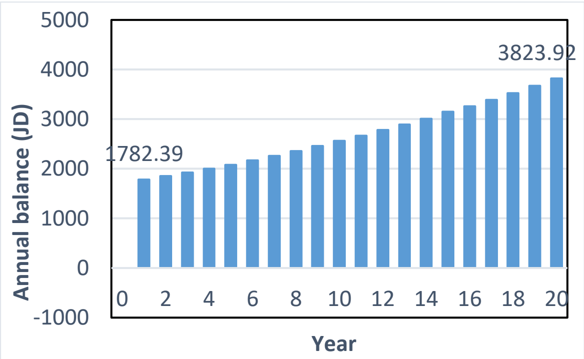

Figure 11. Annual balance cash flow for the PV system without PCM.

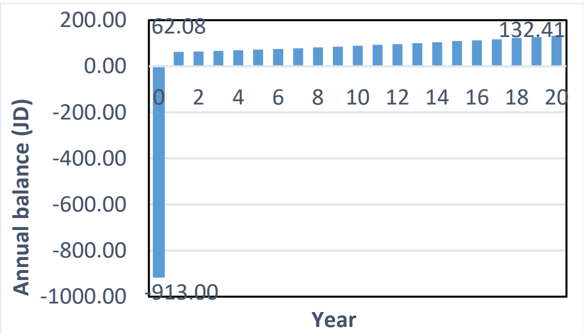

Figure 12. Annual balance cash flow for the net difference between the two systems.

3. Payback Period (PBP)

The initial PCM investment is calculated as 913 JD, as shown in Table 2. From the net cash flows in Figure 12, the savings achieved by using the PV system with PCM is 838.70 JD for the first eleven years. Hence,

$$PBP = 11 + \frac{913 - 838.70}{100.41} = 11.74 \text{ years} = 11 \text{ years } \mathit{and} \text{ } 9 \text{ months}$$

where 100.41 JD is the savings achieved in the 12th year.

4. Net Present Value (NPV)

The *NPV* is determined by using spreadsheets based on Equation (4), and net cash flows C_i in Figure 12. It is found that:

$$NPV = -913 + \sum_{i=1}^{20} \frac{C_i}{(1+0.10)^i} = -212.41 \text{ JD}$$

Net present value is negative, which implies that the PCM investment is not profitable and will result in a net loss.

5. Internal Rate of Return (IRR)

Similarly, the *IRR* is determined by using an Excel spreadsheet based on Equation (5) and net cash flows. It is found that *IRR* = 6.87%, which is less than the discount rate of 10%. This indicates that the PCM investment is not economically attractive based on the *IRR* metric.

4. Conclusions

This study presented a technical-economic investigation of the enhancement of PV power production utilizing the PCM passive cooling means. Two identical 3.99 kWp PV/PCM and reference PV systems were installed and tested year-round at the Hashemite University, Jordan.

Technical analysis shows that the annual output of the PV/PCM system is 6879.2 kWh by comparison with 6654.7 kWh for the reference PV system. Hence, the modest increase in power generated is about 3.4% due to the application of BioPCM. Also, the monthly yield power indicates that there is no considerable difference in power output between the two systems from October till March due to the mild ambient and cell temperatures recorded. The PV systems operated below the STC temperature (25 ºC) for this fraction of the year. It can be concluded that the benefit of PCM in cooling the modules at low temperatures is negligible.

The brief economic study carried out in this work does not currently support the application of PCM in Jordan and countries of similar climates. The analysis reveals that the payback period for the PCM investment is 11.74 years. The net present value *NPV* is negative, and the internal rate of return *IRR* is 6.87%, which is less than the discount rate. The feasibility of the PV/BioPCM system will vary if PCM is purchased in much larger quantities or if it was manufactured locally. Other economic metrics that might positively affect the financial viability of this investment include falling discount rate, rising electricity tariff, and longer operating lifespan (dependent on the agreement between investors and National Electricity power Company NEPCO). The current trends of these metrics are in favor of the PCM investment in the future.

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Conflicts of Interest

The authors declare no conflict of interest.

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