A review on the selection of phase change materials for photovoltaic thermal management

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Abstract. Integrating the phase change materials with photovoltaic cells improve the electrical conversion efficiency by storing the heat in the form of latent heat. The crystalline silicon cells has been widely lead the photovoltaic industry but it has a high temperature coefficient from 0.4 to 0.5%/°C, so rising the temperature during peak solar irradiation can be regulated passively by integrating the phase change material (PCM). Selection of PCM based on the thermophysical properties is an important criterion to enhance the performance of photovoltaic cells. This paper mainly focuses on three criterion (i) phase transition temperature (<45°C) (ii) latent heat (iii) thermal conductivity. The main objective of this work is to make comparative analysis to select the suitable PCM for an effective thermal management of photovoltaic.

Keywords: Photovoltaic thermal management, phase change materials, Melting point, Thermal conductivity, Latent heat

1. Introduction
Power generation through renewable energy technology developed in recent years due to global warming and depletion of conventional energy sources. Among various renewable energy sources, solar energy is abundant and eco-friendly. Photovoltaic (PV) technology is a promising one to meet the energy demand by utilizing the solar energy. Photovoltaic device is a semiconductor-based device, which converts maximum 20% of energy from the sun remaining 80% converts as heat and thus increasing the surface temperature. The electrical efficiency and power output is highly influenced by surface temperature of PV. In Libya, maximum solar cell surface temperature observed was 125°C, which causes 69% of power reduction from standard test condition [1]. Increasing the surface temperature of PV highly influence the performance and its electrical conversion efficiency from the various researchers [2-6] are shown in figure (1) and Table (1).
Figure 1. Performance characteristics of polycrystalline silicon solar module for various cell surface temperature [4]

Table 1. Effect of PV surface temperature rise on electrical efficiency

| References | Temperature rise | Drop in electrical efficiency |
|------------|------------------|------------------------------|
| [2]        | 35 °C            | 22.55%                       |
| [3]        | 45 °C            | 19.70%                       |
| [4]        | 45 °C            | 19.51%                       |
| [5]        | 28 °C            | 12.6%                        |
| [6]        | 56 °C            | 41%                          |

2. Phase change materials in photovoltaic cooling

2.1 Selection criteria based on melting point of PCM

Using phase change materials in photovoltaic cooling provides many benefits, for example high energy storage, higher heat transfer rate compared to forced air and water circulation, isothermal (constant temperature) heat removal, passive techniques as well as supply heat on demand [7]. The selection of PCM - based on the melting point is a main criterion for isothermal heat removal. Waqas et al. [8] reviewed the PCM based photovoltaic cooling, the melting point of PCM has been selected based on the climatic conditions of the region where experiment has been conducted. Hasan et al. [9] used the equation 1 and found the temperature for solid and liquid PCM should be 34 °C and 46°C respectively. Around 65% of research study selected melting point in the range 25°C to 35°C, the melting point has selected above 40°C for the hot and dry climatic conditions. The melting temperature of phase change materials selected by depending on the surface temperature of the solar cell. Sivashankar et al.[10] selected the OM35 for thermal regulation of concentrated photovoltaic for the climatic condition of India, an average yearly ambient temperature during summer is 30 to 33°C. Therefore, the selection of PCM on melting point should be greater than ambient, and its solidification should occur at the environment at nighttime.

\[ T_{pv} = T_a + \left( \frac{0.32}{8.91 + 2V_w} \right) G \]  

(1)
Figure 2. PCM heat stored Vs temperature behavior [11]

Figure 3. Different melting point of PCM based on previous experiments [8]

Figure 4. (a) Experimental setup of PV with and without PCM [9] (b) Experimental setup for PV-PCM [12]
2.2 Selection criteria based on latent heat of PCM

PCM can store more amount of heat during its latent heat period, at a peak solar irradiance PCM will regulate the rise in surface temperature of PV by holding the latent heat duration. The thermal regulation time mainly depends on the volume of PCM and latent heat value. The high latent heat value of PCM maintains the surface temperature of solar cell constant. The energy storage behavior of PCM with respect to temperature has shown in the fig 2. Always high latent heat value provides longer time thermal regulation compared to low latent value. The temperature differences between the surface temperatures of PV for different latent heat value have shown in fig 5. The maximum temperature difference observed was 26.2°C for different latent value of PCM [13]. The different PCM used by the previous researchers have shown in the table 2. The latent heat value and depth of PCM will be choose by based on irradiance and irradiation on the particular location [14]. Hasan et al. [15] studied with different PCM, the study reveals that high latent heat regulate the PV surface temperature for long duration compared to low latent heat PCM. Adibpour et al. [16] experimented on PV with sun tracker and PCM for summer conditions. Tracking the solar radiation yield maximum conversion efficiency but on the other hand surface temperature of PV will increase. This surface temperature will regulate by using PCM. The maximum temperature reduction and yield efficiency compared to without PCM observed is 16.3°C and 6.8% respectively. Karthick et al. [17] reported with glauber salt as PCM in building integrated photovoltaics, the results revealed that 12% of temperature reductions help to enhance the electrical efficiency 8%. Emam et al. [18] numerically reported with multiple PCM with different cavities for concentrated photovoltaic cooling. The calcium chloride Hexahydrate phase change material provides good thermal regulation and maintained CPV cell temperature about 96°C for 137 minutes. Selection of latent heat is a important criteria for thermal management applications. The salt-based inorganic phase change materials have a high latent heat but it is not suitable for photovoltaics thermal regulation due to less thermal stability over the number of cycles and containment issues. Tariq et al. [27] developed mathematical model for selection of PCM for Mexico climatic condition for photovoltaic air collector with phase change materials. The study reveals that using PCM the temperature of PV has been significantly reduced 20% and electrical efficiency and thermal efficiency has been improved 37.5% and 32% respectively. The electrical efficiency for RT35HC shows good results.

| PCM   | Organic/Inorganic | Melting temperature (°C) | Latent heat value (kJ/kg) | References |
|-------|-------------------|--------------------------|---------------------------|------------|
| RT21  | organic           | 21                       | 134                       | [19]       |
| PEG 600 | organic        | 23                       | 146                       | [13]       |
| RT31  | organic           | 31                       | 165                       | [20]       |
| OM32  | organic           | 32                       | 191                       | [21]       |
| OM35  | organic           | 35                       | 145                       | [10]       |
| RT35  | organic           | 35                       | 240                       | [22]       |
| RT40  | organic           | 40                       | 180                       | [23]       |
| RT55  | organic           | 51                       | 170                       | [23]       |
| Paraffin | organic      | 56                       | 200                       | [13]       |
| TH-SL35 | organic        | 37                       | 216                       | [24]       |
Figure 5. (a). Paraffin and PEG600 as phase change materials for thermal regulation of PV  
(b) Temperature difference between high and low latent heat value of PCM [13]

Figure 6. Commercially available PCM based on melting point and enthalpy

Table 3. Temperature reduction with PCM in PV compared to without PCM

| PCM        | Temperature reduction (°C) | Time period (hrs) | References |
|------------|----------------------------|-------------------|------------|
| RT35       | 10                         | 5                 | [25]       |
| Inorganic  | 16.3                       | 4                 | [16]       |
| CaCl$_2$.6H$_2$O | 10                      | 3.5               | [15]       |
| RT40       | 13                         | 2.2               | [26]       |
| OM32       | 50                         | 0.0416            | [21]       |

2.3 Selection criteria based on the thermal conductivity enhancement of PCM

Generally, phase change material has a low thermal conductivity material. There are many techniques to enhance the thermal conductivity of PCM adding fins [49], adding nano particles [10], metal matrix [11], and porous structure [28]. Among the various techniques, adding fins and nano particles has a more attention in the researchers. Fins in the heat sink used to maintain a uniform temperature distribution in the PCM. Thermophysical properties of PCM has been improved by adding nano inclusion, for thermal energy storage system to store more energy and higher heat dissipation system such as electronic devices, fuel cell and photovoltaic performance needs passive thermal management techniques. The nano enhanced PCM (n-PCM) plays a vital role on energy storage and passive thermal regulation [29-
Yang L et al. [42] reviewed the nano enhanced phase change materials for different applications. The study reveals that adding nano particles enhance the thermal conductivity and provides less solidification time in thermal energy storage applications and provides better thermal regulation in thermal control unit. Thermophysical properties of PCM are improves by adding nano particles and sonication provides long stability time. Bahiraei et al. [43] experimentally investigated nano enhanced PCM for thermal management application. The study reveals that enhancement in thermal conductivity of phase change materials by adding nano particles leads to higher temperature in the PCM leads to higher heat transfer, which in turn base temperature of heater will reduce. A composite (PCM and Graphite) provides better thermal regulation compared to carbon nano filler and graphene nano particles. The reason behind this is increasing the nano loading leads to increase the viscosity, which is suppress the convection in liquid nano enhanced PCM. Yang R et al. [44] experimentally investigated the PCM by adding ZnO and CuO nanoparticles to enhance the photo thermal conversion efficiency. CuO-paraffin absorbs more light energy. The thermal conductivity enhancement for ZnO/paraffin and CuO/paraffin observed was 8.44% and 13.12% at 1.5 x 10$^{-3}$ vol%. Karthikeyan et al.[45] has done a simulation on composite PCM to improve the performance of PV, study reveals that composite PCM with thickness of 5cm gives better thermal regulation compared to pure PCM with same thickness. The temperature reduction and efficiency enhancement observed for composite PCM is 11°C and 5% compared to pure PCM. Shastry et al. [11] experimentally studied the effect of aluminum metal matrix in PCM for thermal management of PV. Due to its porous structure, heat diffusion rate is higher leads to reduce the temperature about 11.1% and enhance the conversion efficiency 8.6% compared to PCM on PV/T. Ali et al. [46] experimentally investigated the copper foam with three different PCM for electronic cooling, the study reveals that at higher heat flux RT54HC provides better thermal regulation, the maximum temperature reduction was observed 15% at 2400 W/m² compared to other PCM. Kant et al. [47] numerically studied with different volume concentration of nano particles in PCM. The study reveals that nano enhanced PCM provides better results due to its superior thermo physical properties, the maximum time taken to reach 40°C of PV surface temperature is 60 minutes for Cu 5% in PCM, 40 minutes for TiO₂. Sivashankar et al. [10] experimentally analysed the thermal regulation for the concentrated photovoltaic application with different concentration ratio and different volume concentrations of nano-enhanced phase change materials. The maximum reduction in temperature about 20°C and enhanced electrical efficiency about 6% for nano enhanced phase change materials compared to without PCM. Sharma et al. [48] reported experimentally thermal management of building integrated photovoltaic application using nano enhanced phase change materials with micro fins. The reduction in temperature observed 18.5% in micro fins with nano enhanced phase change materials study.

| Reference | PCM / Nature of study | Peak temperature difference after cooling ∆T (°C) | Enhancement Findings |
|-----------|----------------------|-----------------------------------------------|----------------------|
| [50]      | OM35/Experimental     | 5.3                                           | Continuous water circulation by thermo syphon behind PV-PCM significantly enhance the power output and electrical efficiency. |
| [10]      | OM35/Experimental     | 20                                            | For 0.5 vol% of nano enhanced PCM (GnP+OM35) provides efficiency enhancement 6% at CR5. |
| [21]      | OM32/Numerical        | 32                                            | The power output and electrical efficiency of concentrated |
photovoltaic at CR3 enhanced by 27% and 22% respectively.

- Maximum temperature reduction is 45°C at CR3 with height of PCM 3mm.
- The power output for PV-PCM has been enhanced by 9.7% and 7.6% on day 1 and day 2 respectively.
- PCM coupled with building integrated photovoltaics provides annual increase power output of 7.98% compared to reference.
- Electrical conversion efficiency improved by 13.2% for PCM-Al₂O₃.
- Attained electrical efficiency gain was 5.18% compared to reference.
- Proposed electrical sum can gain about 30.4% by combining thermo electric generator in PV-PCM.
- The maximum temperature reduction helps to enhance the power output 2.8%.

| Phase Change Material | Improvement | Reference |
|-----------------------|-------------|-----------|
| Eutectic (calcium chloride hexahydrate + ferric chloride hexahydrate) | 9 | [51] |
| Binary (Sodium Sulfate Decahydrate + Zinc Nitrate Hexahydrate) | 12 | [52] |
| RT55/Experimental | 10.6 | [53] |
| Paraffin/Experimental | 23 | [54] |
| Lauryl alcohol and Ethyl alcohol (75:25) | 10.3 | [55] |

3. Conclusion
In this work concisely reviewed the recent research in the field of phase change materials and nano enhanced phase change materials for photovoltaic applications.

- Melting point of PCM has been choose by based on the climatic condition and photovoltaic material. The phase change temperature should be greater than ambient then only it will undergo a melting cycle during daytime and solidify during nighttime.
- High latent heat phase change materials can hold the surface temperature of photovoltaic constantly for long duration compared to low latent value. The high latent heat salt hydrate based phase change materials corrode the heat sink container. Paraffin is a good choice for thermal stability over a number of cycles.
- Nano enhanced phase change materials provides superior thermo physical properties such as thermal conductivity, thermal diffusivity and specific heat especially thermal conductivity is an important parameter. By adding nano particles provides a significant improvement in thermal conductivity there by an increase in temperature during a phase change provides a greater temperature gradient it helps to regulate the base temperature by natural convection.

4. Recommendations for future work:
The enhancement in the performance of photovoltaic and concentrated photovoltaic system by using phase change materials and nano enhanced phase change materials still there are many challenges that need to address as follows

- The factors such as nano inclusion and concentration ratio how it is affects the melt front behavior of phase change material and nano enhanced phase change materials study has been enlarged.
- Combining air heating system and water heating system with photovoltaic cooling needs more investigations
Further investigation needed on nano enhanced phase change materials stability and its thermo physical properties.
Optimization of fins in the PCM heat sink such as fin height and width are to be analysed.
Feasibility, Economic and environmental factors are to be considered more for nano enhanced phase change materials

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