Energy Sci Eng. 2022;10:1630–1642.

Salt hydrates as phase change materials for photovoltaics thermal management

Yee Min Choo | Wei Wei

Department of Mechanical Engineering, Wichita State University, Wichita, Kansas, USA

Correspondence
Wei Wei, Department of Mechanical Engineering, Wichita State University, 1845 Fairmount St, Wichita, KS 67260, USA.
Email: wei.wei@wichita.edu

Funding information
The Kansas NASA EPSCoR Research Infrastructure Development Program, Grant/Award Number: 80NSSC19M0042; ACS Petroleum Research Fund, Grant/Award Number: 59716-DNI10

1 | INTRODUCTION

Conventional source of energy, for example fossil fuels, are depleting with time. The combustion of fossil fuels also lead to increased carbon emission in environment, causing global warming. To meet the world’s increasing energy demand, the utilization of alternative resources like solar energy must be improved. Solar energy can be harvested directly into electricity by using photovoltaic (PV) module. However, when the solar radiation reaches a PV module, it is not only converted into electricity but also into thermal energy, which increases the PV system temperature.1 There are many factors affecting the solar power output of the PV system. Temperature is one of them. The productivity of a PV-module is the inverse of the temperature. According to the Standard Test Conditions, if a PV module is operated at temperature higher than the ambient temperature, 25°C, at each increase of degree Celsius, the conversion rate of the PV module decreases, up to 0.5%.2 As expected, summer is the season with the highest solar radiation, when a PV system such as solar panel can absorb most solar energy and produce heat or electricity.
for various application. However, the temperature of a day in summer usually goes from 40 to 70°C, which is 2-3 times of the ideal operating temperature of solar panels. It causes threats to the overall performance of PV system—a potential drop in the conversion rate by 7.5%-22.5%. In the other words, the PV module’s efficiency is negatively impacted principally in view of the loss in radiation when the liquid temperature is above normothermia.

As the surface temperature of the PV module is a dependent factor to its power generation, the operating conditions and environment including location coordination (latitude and longitude), humidity and shadiness have a degree of influence to the performance of the installed PV system. Overheating of the PV modules will ultimately shorten their lifespan due to the increase of function degradation.

Modification on the panel’s layers to ingest the excessive heat involves new design concept and architecture development. That would be a long journey of discovery and development. A straightforward solution to bring down the surface temperature of current PV system is free cooling (via convection) on the rear of the PV panels, by incorporating a phase change material (PCM). PCMs are materials that go through reversible progress of stage contingent upon their temperature. They could either uptake or reject heat. The use of PCM has filled gradually in the solar industries, for example, solar cooling and power plants, PV electricity power systems, solar dryers in agrindustries, and so forth.

The working principle of PCMs in PV module is simple. The excess heat from the panel’s surface caused by the rising surrounding temperature will be consumed by the attached PCM, until the physical phase of the PCM has totally converted (for example, from solid phase to liquid phase). At the point during dropping of the panel’s temperature, the PCM solidification process ought to release heat to the working fluid in PV panel, to the structure or it will act as an insulator in the system. This PCM arrangement is relied upon to be extremely valuable for the rooftop or façade integrated PV system where space for ventilation is restricted. The overall PV-PCM architecture sounds easy; however, only a couple studies have been explicitly dedicated to passive cooling function of PCMs in PV systems due to the complex properties and characteristic of PCMs.

2 | PHASE CHANGE MATERIAL

PCMs are the type of materials that can assimilate and delivery energy during the phase changing processes, involving liquefying and solidifying. The processes of gaining and releasing heat or thermal energy are due to the latent heat of PCMs. This unique property makes PCMs constantly work in a cycle. As a result, PCM is an ideal candidate for an assortment of daily applications that require temperature regulation and management, for instance, building construction, HVAC system, thermal energy storage, etc. PCMs are utilized in these applications mainly for energy saving, but they are also eco-friendly.

The driving forces of PCM can be categorized into two distinct types of thermal energy—sensible and latent heat. Sensible heat is the measure of energy expected to modify the temperature of a substance without changing its physical phase. On the other hand, latent heat is measure of energy that is expected to change the phase of a matter from one to another. Latent heat can be further classified into latent heat of fusion and latent heat of vaporization. Ice cube is a classic example of latent heat fusion where it changes phase from solid to liquid (vice versa) during the absorption or release of heat. At the point when sensible and latent heat cooperate in a substance, the time for such substance maintaining at a specific temperature will be extended (Figure 1). PCMs use the same concept to decrease temperature swings, keeping a particular temperature for broadened timeframes.

Each PCM is different in properties. In the PV-PCM system, thermo-physical properties play an essential role in the overall performance and efficiency. Nevertheless, different properties like dynamic, chemical and economic properties ought to be additionally considered to ensure an optimal PV-PCM framework for safety and cost viability purposes. There are three main categories in PCMs—organic, inorganic and eutectic (Figure 2). Organic PCMs are further characterized into paraffin and nonparaffin PCMs. Since the cost of pure paraffins are not proportional to its practical value, most industrial use PCMs is the "technical class paraffins." The fundamental purpose for paraffin’s capability as an energy stockpiling material is its
availability in a wide scope of temperatures. They are predictable, safe, and noncorrosive. Nonparaffin PCMs are all the other organic compounds, including esters, alcohols, and unsaturated fats (fatty acids). They are combustible, and thus ought not to be presented to high temperature and oxidizing agents that could cause flames. Inorganic PCMs such as salt hydrates, metals, and alloys have comparable monetary and environmental properties as paraffin; however, they are noncombustible, inexpensive, and high in latent heat. Eutectics are mixtures of inorganics (generally hydrated salts) and potentially organics PCMs. They melt at temperature that is generally lower than that of any of the constitutive mixtures. One of the main qualities of eutectics is their ability of congruent melting or freezing without having segregation between phases.

The majority studies in PV-PCM systems in the past decade have focused on organic PCMs, especially RT-series paraffin waxes by Rubitherm, because of their performance stability within a great scope of melting points. Notwithstanding, the greatest disadvantage of paraffins is low thermal conductivity (around 0.2 W/mK), drawing limitations to heat extraction and dissipation from PV when necessary, at different time of a day. Since some of the organic PCMs are highly flammable, which increases danger level to the environment and society, incorporation of PCMs in building construction requires careful material selection and architecture design housing, which leads to overall cost addition. Therefore, salts hydrates are considered as effective substitutes, and they have been successfully utilized in bricks.

Along with these lines, scientists and researchers began testing the inorganic (mostly salt hydrates) or eutectics PCMs for all kind of applications. In PV modules, PCMs diminishes the temperature variation during PV charging and discharging mode, resulting enhancement in the overall electric conversion efficiency and lengthening PV serving lifespan. Studies have discovered that PCMs can be adequately utilized for restricting the temperature ascent of the PV cell, subsequently expanding the effectiveness of the PV cell up to 10%.

3 | SALT HYDRATES AND APPLICATIONS

Salt hydrates, a type of inorganic salts contain one or more water particles. The general formula of salt hydrates is written as AB·nH₂O, where A and B stand for 2 different chemical elements. The temperature range where phase transitions occur in most salt hydrates is between 40°C to a little more than 100°C. Salt hydrates have high density in general—fluid salt hydrates is about 1937 kg/m³, while solid salt hydrates is slight higher, around 2180 kg/m³. The pioneering research using salt hydrates as the principal materials was first conducted by Telkes.

Salt hydrates show high values in latent heat, roughly (100-300) J/g and thermal conductivity (~0.7 W/mK, beyond twofold of paraffins and fatty acids) due to their excellent chemical properties. Indeed, even salt hydrates are inorganic, they are eco-friendly since they are not combustible and are biodegradable and recyclable. Most importantly, salt hydrates are considered the least expensive among all PCMs. Most salt hydrates with melting temperature higher than 20°C typically cost $1 to $20/kWh. For instance, average material expense for calcium chloride hexahydrate (CaCl₂·6H₂O) is from $0.13 to $0.46/
kg. However, paraffins with practically identical melting points cost from $20 to $30/kWh. Inorganic salt hydrates were first used as thermal storage units, and now are common materials in thermal regulation related studies (Table 1). For instance, sodium sulfate decahydrate (Na$_2$SO$_4$·10H$_2$O), otherwise called Glauber’s salt, has a melting temperature of 32.4°C, and is regularly considered for space applications. Nonetheless, the problem of Glauber’s salt melting incongruently and supercooling inconsistently causes instability in the system performance. In that case, different materials with identical melting temperature, for example, calcium chloride hexahydrate (CaCl$_2$·6H$_2$O) and sodium hydrogen phosphate dodecahydrate (Na$_2$HPO$_4$·12H$_2$O), might be feasible options as the material replacement.

Most of the recent experiments on salt hydrates in the PV systems generally focus on their latent heat of fusion—the thermal energy absorption capability for phase transition of a substance from solid to liquid stage (Table 2). This benefits in temperature regulation as salt hydrates help in passive cooling in PV modules. Metals have not been a genuine applicant due to their heavy atomic weight. Nonetheless, in conditions when volume is considered, metals are logical competitors as they have higher thermal conductivities, as well as latent heat of fusion per unit volume, compared to salt hydrates.

3.1 Building coordinated PV system

Karthick et al incorporated Glauber salt in the building coordinated photovoltaic (BIPV) system, which was introduced as the façade of the test room located at Kovilpatti, India. The purpose of the study was to assess the improvement in electrical and thermal energy outcome. Glauber salt was stuffed and sealed tight with tedlar sheet, then attached right behind each polycrystalline PV cell (Figure 3). To create a single BIPV module, the cells are sandwiched between additional e-glazing materials with low iron content (Figure 3).

Parameters including power output and efficiency were analyzed. As solar radiation and the ambient temperature vary each day, the investigation was rehashed couple weeks for performance assessment. Notwithstanding, only daytime condition, specifically from 6:00 AM to 6:00 PM is considered in this case. Other variables such as the module and test room orientation that could affect the system surface temperature were also considered to determine the solar heat gain through the façade. Result showed a 10% enhancement in electrical proficiency with utilization of PCM. It was because of an 8°C reduction of the system’s instantaneous peak temperature. The overall temperature of the PV cells drop by 12%. This study further aides in picking the ideal orientation of the establishment of BIPV-PCM in the building’s façade, which is the East for the test location in Kovilpatti, India.

Pichandi et al considered eutectic PCMs by adding Magnesium Sulfate Heptahydrate (MgSO$_4$·7H$_2$O) into Sodium Carbonate Decahydrate (Na$_2$CO$_3$·10H$_2$O), hoping to eliminate the issues of supercooling and phase separation of the sodium carbonate salt hydrate in the PV application. The binary eutectic was prepared via a heating-mixing strategy. Through the estimation of DSC, the ratio of 70% sodium carbonate decahydrate to 30% magnesium sulfate heptahydrate tends to result the best in terms of thermal conductivity and stability, latent heat of fusion, melting temperature, etc. This eutectic PCM was coordinated on the posterior of the 25 W polycrystalline silicon PV module (Figure 4). The experiment was conducted in two specific days chosen based on the solar insolation outdoor conditions in Kovilpatti, Tamil Nadu, South India.

Equipment including temperature data logger, voltmeter, ammeter, solar radiation sensor, and thermocouple wire were used to evaluate the PV-PCM system performance. According to the collected data, the system showed the temperature decrease maximally 7°C, resulting a 1.21% increase of efficiency. In terms of the system’s power output, it was 17.63 W higher with the application of eutectic PCM, improving the produced electrical energy by 12.5%. Nonetheless, by comparing the cost of this PV-PCM system to the monetary payback in long term, the economic benefit is very little to none, as the PCM material preparation and setup cost extra, even in mass production. Therefore, different salt hydrates with similar properties to the magnesium sulfate heptahydrates are potential substitute to the study. Overall, this study contributes to the findings of binary eutectic salt hydrates in PV systems.

Another BIPV related research was conducted by Hasan et al. In this experiment, another hydrated salt—calcium chloride hexahydrate (CaCl$_2$·6H$_2$O) was studied, in 4 distinctive PV-PCM systems at both low and high solar intensity for the complete performance evaluation. Polycrystalline silicon PV cells with Perspex as the encapsulation were placed at the front of 4 containers made of different materials (Figure 5).

The materials and sizes of the system containers were carefully chosen to study the impact of thermal conductivity (for system A and C made of aluminum) and insulating (for system B and D made of perspex), wall thickness, and PCM’s thermal mass in temperature regulation. While the ambient temperature stayed constant (~20°C ± 1°C), the test result showed that the calcium chloride hexahydrate reduced the temperature of the cell at solar intensity >750 W/m$^2$, expanding the duration of the temperature deviation...
| Application                  | System                          | Salt hydrate                        | Year of study | References |
|------------------------------|---------------------------------|-------------------------------------|---------------|------------|
| TES                          | Greenhouse heating system       | Na$_2$SO$_4$·10H$_2$O               | 1983          | 55         |
| Solar cooker                 |                                 | Mg(NO$_3$)$_2$·6H$_2$O               | 2000          | 56         |
|                              |                                 | MgCl$_2$·6H$_2$O                     | 2008          | 57         |
|                              |                                 |                                     | 2009          | 58         |
|                              |                                 |                                     | 2001          | 59         |
|                              |                                 |                                     | 2018          | 60         |
| Solar collector system       |                                 | Na$_2$SO$_4$·10H$_2$O               | 1991          | 61         |
|                              |                                 | CaCl$_2$·6H$_2$O                     | 2008          | 62         |
|                              |                                 | Na$_2$CO$_3$·10H$_2$O                | 2010          | 63         |
|                              |                                 | CH$_3$COONa·3H$_2$O                  | 2021          | 64         |
| Solar space heating          |                                 | CaCl$_2$·6H$_2$O                     | 1997          | 65, 66     |
|                              |                                 |                                     | 1998          | 67         |
|                              |                                 |                                     | 2004          | 68         |
|                              |                                 |                                     | 2009          | 69, 70     |
|                              |                                 | Na$_2$HPO$_4$·12H$_2$O               | 1979          | 71         |
|                              |                                 |                                     | 1983          | 72         |
| Solar water heating          |                                 | Na$_2$HPO$_4$·12H$_2$O               | 1983          | 73         |
|                              |                                 | Na$_2$SO$_4$·10H$_2$O                | 1989          | 73         |
|                              |                                 |                                     | 1983          | 74         |
|                              |                                 | Ba(OH)$_2$·8H$_2$O                   | 1983          | 72         |
|                              |                                 | Na$_2$S$_2$O$_3$·5H$_2$O             | 2005          | 75         |
|                              |                                 |                                     | 2009          | 76         |
|                              |                                 | Delta cool DC58                      | 2016          | 77         |
|                              |                                 | Thermoul HD60                        |               |            |
|                              |                                 | Pure temp PT58                       |               |            |
| Underfloor heating           |                                 | CaCl$_2$·6H$_2$O                     | 2001          | 78         |
| Thermochemical storage       |                                 | MgCl$_2$·6H$_2$O                     | 2018          | 79         |
| TES cooling system           |                                 | Mn(NO$_3$)$_2$·6H$_2$O                | 2003          | 80         |
| Air conditioning systems     |                                 | Climsel C-18 (NaNO$_3$/H$_2$O)      | 2012          | 81         |
|                              |                                 | CaCl$_2$·6H$_2$O                     | 2018          | 82         |
|                              |                                 | Na$_2$HPO$_4$·12H$_2$O               |               |            |
| Phase change material        | PCM-façade-panel                | S27                                 | 2005          | 83         |
| for thermal regulation       |                                 |                                     |               |            |
| Composite PCM concrete system|                                 | Na$_2$S$_2$O$_3$·5H$_2$O             | 2000          | 84         |
|                              |                                 | CaCl$_2$·6H$_2$O                     | 2017          | 85, 86     |
| Photovoltaic-phase change    |                                 | CaCl$_2$·6H$_2$O                     | 2008          | 80         |
| material (PV-PCM) system     |                                 |                                     | 2010          | 43         |
|                              |                                 |                                     | 2014          | 87, 88     |
|                              |                                 |                                     | 2015          | 44         |
|                              |                                 | Na$_2$SO$_4$·10H$_2$O                | 2015          | 81         |
|                              |                                 |                                     | 2015          | 82         |
|                              |                                 |                                     | 2018          | 41         |
|                              |                                 | Na$_2$CO$_3$·10H$_2$O                | 2020          | 42         |
|                              |                                 | MgSO$_4$·7H$_2$O                     | 2020          | 42         |
|                              |                                 |                                     | 2016          | 45         |
|                              |                                 | Na$_2$HPO$_4$·12H$_2$O               | 2016          | 83         |

Abbreviations: PCM, phase change material; PV, photovoltaic; TES, thermal energy storage.
In the BIPV-PCM system, at 750 W/m², the PV cell surface temperature reduced up to 18°C, and the temperature held constant for about 30 minutes. However, at 1000 W/m², although the reduction of surface temperature was lower (10°C), the duration increased to 5 hours long. This positive outcome makes salt hydrate a decent choice for PV application in hot climates with ambient temperature of 34°C and high solar insolation of 1000 W/m².

The same salt hydrate, CaCl₂·6H₂O was further tested by Hasan et al again for thermal and electrical energy generation and efficiency analysis. Three 65 W polycrystalline PV panels encapsulated with EVA were utilized in the investigations; one served as reference PV for comparison purpose, and the other two were manufactured with different PCMs (Figure 7). The PCM in PV-PCM₁ system was capric-palmitic corrosive, while PV-PCM₂ utilized the salt hydrate CaCl₂·6H₂O.

Focusing on the PV-PCM₂ system, the salt hydrate was softened in a particular temperature to achieve steady and uniform solution. It was then filled in coordinated PV-PCM system, leaving a 100-mm gap on top in case of volume change during phase transition. Prior testing, the PV-PCM system must be kept at low temperature to ensure complete solidification of the PCM solution. A pyranometer and a weather station were used for measurement of solar intensity, surrounding temperature wind speed, respectively. The test output—open circuit voltage and short circuit current were measured simply by a multimeter. The results are summarized in Table 3.

To determine the economic feasibility of this PV-PCM system, several factors were considered in the investment—cost of PCM and control materials and holders’ production cost. With the formulated cost and energy saving analysis, considering large scale manufacturing of PV-PCM₂ (salt hydrate) system, the expense is expected to be high in Ireland (€98 for one system); however, it is only €62 in Pakistan. The analysis was only based on the date collected in a single day. A longer test period could help in producing a more accurate long-term cost analysis. Overall, this research further supports that utilization of salt hydrate in PV system is monetarily suitable in climate with high temperature and solar radiation climate.

On the other hand, in Royo et al’s research, distinctive salt hydrates were thought of in BIPV systems. However, only two types—sodium sulfate decahydrate (Na₂SO₄·10H₂O) and sodium dihydrogen phosphate decahydrate (Na₂HPO₄·12H₂O) were eventually chosen due their fitting thermo-physical properties for the climate conditions in various areas in Spain. This study was aiming to discover new directions of PV applications, for example, material development, design innovations, power output optimization, etc. The impacts of PCM to BIPV system

| Types                  | T_m (°C) | Latent heat of fusion (kJ/kg) | Thermal conductivity (W/m°C) [solid] | Specific heat capacity (kJ/kg·K) [solid] | Specific heat capacity (kJ/kg·K) [liquid] | Refs. |
|------------------------|----------|------------------------------|-------------------------------------|----------------------------------------|------------------------------------------|-------|
| CaCl₂·6H₂O             | 29.8     | 191                          | 1.08                                | 1.4                                    | 2.1                                      | 43, 44, 89 |
| Na₂SO₄·10H₂O           | 32       | 251                          | 0.7                                 | 1.76                                   | 3.30                                     | 41, 90, 91 |
| Na₂CO₃·10H₂O           | 33       | 247                          | 0.876                               | 1.88                                   | —                                        | 42    |
| MgSO₄·7H₂O             | 48.5     | 202                          | 0.645                               | 1.546                                  | —                                        | 42    |
| Na₂HPO₄·12H₂O          | 40       | 280                          | 0.514                               | —                                      | —                                        | 45, 92 |

Abbreviations: PCMs, phase change materials; PV, photovoltaic.
were explicitly contemplated to expand the electrical transformation, enhance the valuable duty lifetime and at the same time avoid problem areas. Numerical models of BIPV system involved silicon polycrystalline PV cells and a layer of salt hydrates PCMs in different thicknesses (Figure 8).

The behavior of this novel PCM-BIPV was studied through mathematical analysis. The result outcomes showed an overall system improvement; the surface temperature of the PV cell decreased by 8°C, contributing to 3% increase of system efficiency. It is additionally discovered that the system was more efficient in disseminating heat in days with higher wind speed. The heat rejected via convection could further diminish the operating temperature of the system. As a result, this study affirms that the utilization of salt hydrate PCMs could forestall generation of hot spots besides mitigating system degradation. It is estimated that this BIPV-PCM system has a longer lifespan, up to the scope of 28-48 years. Both types of salt hydrates show positivity in real-life BIPV applications. An outdoor or lab experiment could further support this diagnosis, making the system feasible and valuable in the market.

3.2 | Challenges

While salt hydrates are extremely alluring PCMs from the perspective of energy storage system and temperature regulation, they do have weaknesses.\textsuperscript{31,32,46} One of the biggest challenges is incongruent melting issue (Figure 9). During the heating process before the salt hydrate starts melting, some parts in the structure gets dried out, becoming less
FIGURE 6 Duration of each PV-PCM system with surface temperature maintained as 10°C below the reference temperature at different solar insolation. (A), 500 W/m², (B) 750 W/m², and (C) 1000 W/m².

FIGURE 7 Schematics of a PCM container.

TABLE 3 Summary of measured data in Dublin, Ireland on September 12, 2009, and Vehari, Pakistan on October 30, 2009.

| Measured data           | Time       | Reference PV | PV-PCM₁ | PV-PCM₂ |
|-------------------------|------------|--------------|---------|---------|
|                         |            | Dublin       | Vehari  | Dublin  | Vehari  |
| Insolation G (W·m⁻²)    | At peak    | 970          | 950     | 970     | 950     |
|                         | At average | 674          | 660     | 674     | 660     |
| Temperature (°C)        | At peak    | 49           | 63      | 43      | 51      |
|                         | At average | —            | —       | 7       | 17      |
| Temperature regulation (°C) | At peak | —               | —       | 7       | 17      |
|                         | At average | —            | —       | 10      | 21      |
| Fill factor (%)         | Average    | —            | 69.64   | 72.82   | 71.26   |
|                         |            | —            | —       | 73.22   | 72.24   |
| $V_{oc}$ (V)            | At peak    | 20.10        | 18.32   | 20.81   | 19.71   |
|                         | At average | 20.41        | 18.71   | 20.52   | 19.42   |
| $I_{sc}$ (Amp)          | At peak    | 3.74         | 3.42    | 3.70    | 3.35    |
|                         | At average | 2.82         | 2.45    | 2.77    | 2.41    |

Abbreviations: PCM, phase change material; PV, photovoltaic.
Choo and Wei hydrated. In a phase diagram, this phase transition phenomena is noted as a peritectic point. At this point, the less hydrated parts of the structure are not dissolvable even when the operating temperature is within appropriate range. As the results, the less hydrated salt will sink as its density is higher than the melted solution, and is difficult to rehydrate while cooling.\textsuperscript{46,47} The inconsistency of solution due to phase separation problem eventually causes irreparable performance loss. A cheaper solution to this issue is mechanical mixing and blending, forcing recombination of both solid and liquid phases of salt hydrates upon cooling. Besides, addition of chemical to thicken the solution will act as an adhesive or binding agent, preventing the solid (less hydrated) structures from isolating to the floor of the container or holder.\textsuperscript{48} Also, smaller size of containers is preferred to reduce the chances of irreversible phase separation upon heating and expand the likelihood of rehydration in cooling.\textsuperscript{47}

Supercooling of salt hydrates is another big problem to overcome (Figure 10). The stored latent heat is not able to be released as supercooling hinder the crystallization process. With nucleating agents adding to the salt hydrate, it helps the formation of crystal nuclei; however, noting that its physical phase (solid phase) must not be affected by other variables, such as operating temperature.\textsuperscript{35,49} Furthermore, “cold finger” also aids in crystallization. It is a method of extending a cold material, which is thermally conductive into the salt hydrate solution. Due to the huge temperature difference at the cold region of the inserted material, it promotes crystallization.\textsuperscript{50}

The potential solutions mentioned above should be included in future research of PV-PCM systems to increase the accuracy of result data. Otherwise, new strategies or techniques of material handling should be discovered. Besides, more data collected from practical outdoor experiment on the salt hydrates PV-PCM system would help in the study of the system’s long-term stability. Also, focus of system’s performance and efficiency at nighttime will better address the supercooling issue of salt hydrates. There are many more kinds of salt hydrates to be the possible ideal candidates in the PV-PCM system; different salt hydrates could be combined in various ratios as eutectic PCMs to obtain desired properties such as specific melting point and thermal conductivity. It could possibly draw the production cost down while enhancing the overall performance.

4 | CONCLUSION AND OUTLOOK

In this review article, salt hydrate as a PCM material is introduced. It has high potential in boosting the latest and current PV applications available in the market. All experiment of PV-PCM systems discussed above have shown positive results in energy saving as well as efficiency improvement. However, all systems were tested for a short period of time. It is important to investigate the discharging and charging PCM for extended period of time. Moreover, the solutions to the major issues such as phase separation and supercooling of salt hydrates are neglected. In most cases, addition of a thickening agent or additional process of mixing and stirring in the material preparation could overcome the phase separation issue.

To stifle supercooling, an appropriate nucleating material
added to the salt hydrates can make sure gradual crystal-
ization upon material cooling.

Suitable packaging or containers for salt hydrate PCM
are also important to reduce the risk of leakage and water
evaporation. Again, by adding corrosion inhibitors or
using tightly sealed containers, the effect of corrosion can
be eliminated. For instance, stainless steel and plastic are
good material candidates as the PCM holders for long-
term storage of most salt hydrate PCMs. Most importantly,
the financially effective salt hydrate PCM type is yet to be
found and explored. Enhancing heat transfer within the
PCM and between the PV and PCM should be investigated
to evaluate the applicability of PCM in the thermal man-
agement of PV.

Furthermore, DSC is the commonly chosen equip-
ment in most research for investigation of PV-PCM sys-
tem performance. In any case, this expensive method
may not be the most fitting one for portraying PCM tests,
since DSC uses only about 10 mg mass of PCM sample. It
creates difficulties in determining issues associated with
larger samples during phase isolation, dispersion, high
subcooling, etc during the test. After all, the small size
of research samples tested in the studies are usually not
illustrative of the real-life engineering systems or indus-
trial applications, which requires huge amounts of PCM,
particularly for inhomogeneous materials. Subsequently,
other techniques that allow bigger mass of test samples in
the investigation should be considered, such as T-History
strategy.

It increases the overall measurement reliability of the
phase change enthalpies of PCM. This will not only
improve the precision and accuracy of the estimation of
PCM phase transition temperatures but decrease the in-
strumentation cost.

ACKNOWLEDGMENT
This work was partially supported by the ACS Petroleum
Research Fund (PRF #59716-DNI10) and The Kansas
NASA EPSCoR Research Infrastructure Development
Program (#80NSSC19M0042).

CONFLICT OF INTEREST
The authors declare no competing financial interest.

ORCID
Wei Wei  https://orcid.org/0000-0002-9701-3742

REFERENCES
1. Ingersoll JG. Simplified calculation of solar cell temperatures
in terrestrial photovoltaic arrays. J Sol Energy Eng. 1986;108:95-
101. https://doi.org/10.1115/1.3268087
2. Voller VR, Cross M, Markatos N. An enthalpy method for
convection/diffusion phase change. Int J Numer Methods Eng.
1987;24:271-284.
3. Biwole PH, Eclache P, Kuznik F. Phase-change materials to im-
prove solar panel’s performance. Energy Build. 2013;62:59-67.
4. Aydin D, Casey SP, Riffat S. The latest advancements on ther-
ochemical heat storage systems. Renew Sustain Energy Rev.
2015;41:356-367.
5. Ma T, Yang H, Zhang Y, Lu L, Wang X. Using phase change
materials in photovoltaic systems for thermal regulation and
electrical efficiency improvement: a review and outlook. Renew Sustain
Energy Rev. 2015;43:1273-1284.
6. Shalaby S, Bek M, El-Sebaii A. Solar dryers with PCM as en-
ergy storage medium: a review. Renew Sustain Energy Rev.
2014;33:110-116.
7. Raoux S. Phase change materials. Annu Rev Mater Res.
2009;39:25-48.
8. Essid N, Edibahak-Ousni A, Neji J. Experimental and numerical ther-
mal properties investigation of cement-based materials modified with
PCM for building construction use. J Archit Eng. 2020;26:04020018.
https://doi.org/10.1061/(ASCE)AE.1943-5568.0000399
9. Kuznik F, Virgone J, Johannes K. Development and validation
of a new TRNSYS type for the simulation of external building
walls containing PCM. Energy Build. 2010;42:1004-1009.
https://doi.org/10.1016/j.enbuild.2010.01.012
10. Konuklu Y, Ostry M, Paksoy HO, Charvat P. Review on using
microencapsulated phase change materials (PCM) in building
applications. Energy Build. 2015;106:134-155. https://doi.
org/10.1016/j.enbuild.2015.07.019
11. Mahdaoui M, Hamdaoui S, Ait Msaad A, et al. Building bricks
with phase change material (PCM): thermal performances.
Constr Build Mater. 2021;269:121315. https://doi.org/10.1016/j.
conbuildmat.2020.121315
12. Fiorentini M, Cooper P, Ma Z. Development and optimization of an innovative HVAC system with integrated PVT and PCM thermal storage for a net-zero energy retrofitted house. *Energy Build.* 2015;94:21-32. https://doi.org/10.1016/j.enbuild.2015.02.018

13. Promoppatnum P, Yao S-C, Hultz T, Agee D. Experimental and numerical investigation of the cross-flow PCM heat exchanger for the energy saving of building HVAC. *Energy Build.* 2017;138:468-478. https://doi.org/10.1016/j.enbuild.2016.12.043

14. Real A, García V, Domenech L, et al. Improvement of a heat pump based HVAC system with PCM thermal storage for cold accumulation and heat dissipation. *Energy Build.* 2014;83:108-116. https://doi.org/10.1016/j.enbuild.2014.04.029

15. Cabeza LF, Castell A, Barreneche C, de Gracia A, Fernández AI. Materials used as PCM in thermal energy storage in buildings: a review. *Renew Sustain Energy Rev.* 2011;15:1675-1695. https://doi.org/10.1016/j.rser.2010.11.018

16. Huang X, Zhu C, Lin Y, Fang G. Thermal properties and applications of microencapsulated PCM for thermal energy storage: a review. *Appl Therm Eng.* 2019;147:841-855. https://doi.org/10.1016/j.applthermaleng.2018.11.007

17. Rathore PKS, Shukla SK. Potential of microencapsulated PCM for thermal energy storage in buildings: a comprehensive review. *Constr Build Mater.* 2019;225:723-744. https://doi.org/10.1016/j.conbuildmat.2019.07.221

18. Prigogine I, Defay R. Chemical thermodynamics. 1958.

19. Serway RA, Jewett JW. *Physics for Scientists and Engineers.* Independence, KY 41051, USA: Cengage Learning. 2018.

20. Pielichowska K, Pielichowski K. Phase change materials for thermal energy storage in buildings: a review. *Renew Sustain Energy Rev.* 2011;15:1675-1695. https://doi.org/10.1016/j.rser.2010.11.018

21. Hamja A, Rahman M. *Performance analysis and applications of phase change materials.* *Appl Therm Eng.* 2014;65:67-123. https://doi.org/10.1016/j.applthermaleng.2014.03.005

22. Hamja A, Rahman M. *Paper on phase change materials.* 2013.

23. Hasnain S. Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques. *Energy Convers Manag.* 1998;39:1127-1138.

24. Wahid MA, Hosseini SE, Husseen HM, et al. An overview of phase change materials for construction architecture thermal management in hot and dry climate region. *Appl Therm Eng.* 2017;121:1240-1259. https://doi.org/10.1016/j.applthermaleng.2016.07.032

25. Gunasekara SN, Martin V, Chiu JN. Phase equilibrium in the design of phase change materials for thermal energy storage: state-of-the-art. *Renew Sustain Energy Rev.* 2017;73:558-581. https://doi.org/10.1016/j.rser.2017.03.108

26. Sam MN, Caggiano A, Mankel C, Röser F, Koenders E. In: Pereira EB, Barros JAO, Figueiredo FP eds. Thermal Energy Storage Characterization of Environmental-Friendly Bio-based PCMs as an Alternative to Petroleum-Based Paraffin Waxes. *Proceedings of the 3rd RILEM Spring Convention and Conference (RSCC 2020).* RILEM Bookseries. New York City, USA: Springer International Publishing. 2021;32:191-203.

27. Cabaleiro D, Agresti F, Barison S, et al. Development of paraffinic phase change material nanoemulsions for thermal energy storage and transport in low-temperature applications. *Appl Therm Eng.* 2019;159:113868. https://doi.org/10.1016/j.applthermaleng.2019.113868

28. Abdelrahman HE, Wahba MH, Refaey HA, Moawad M, Berbish NS. Performance enhancement of photovoltaic cells by changing configuration and using PCM (RT35HC) with nanoparticles Al2O3. *Sol Energy.* 2019;177:665-671. https://doi.org/10.1016/j.solener.2018.11.022

29. Waqas A, Jie J. Effectiveness of phase change material for cooling of photovoltaic panel for hot climate. *J Sol Energy Eng.* 2018;140. https://doi.org/10.1115/1.4039550

30. Casini M. *Smart Buildings: Advanced Materials and Nanotechnology to Improve Energy-Efficiency and Environmental Performance.* Sawston, United Kingdom: Woodhead Publishing. 2016.

31. Sharma A, Tyagi VV, Chen C, Buddhi D. Review on thermal energy storage with phase change materials and applications. *Renew Sustain Energy Rev.* 2009;13:318-345.

32. Zalba B, Marin JM, Cabeza LF, Mehling H. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. *Appl Therm Eng.* 2003;23:251-283.

33. Cabeza LF, Castell A, Barreneche C, de Gracia A, Fernández AI. Materials used as PCM in thermal energy storage in buildings: a review. *Renew Sustain Energy Rev.* 2011;15:1675-1695.

34. Rathod MK, Banerjee J. Thermal stability of phase change materials used in latent heat energy storage systems: a review. *Renew Sustain Energy Rev.* 2013;18:246-258.

35. Telkes M. Nucleation of supersaturated inorganic salt solutions. *Ind Eng Chem.* 1952;44:1308-1310.

36. Telkes M. Thermal energy storage in salt hydrates. *Sol Energy Mater.* 1980;2:381-393.

37. Kenisarin M, Mahkamov K. Solar energy storage using phase change materials. *Renew Sustain Energy Rev.* 2007;11:1913-1965.

38. Kosny J, Shukla N, Fallahi A. Cost analysis of simple phase change material-enhanced building envelopes in southern US climates. Golden, CO: National Renewable Energy Laboratory (NREL); 2013.

39. Hirschey J, Gluesenkamp KR, Mallow A, Graham S. Review of inorganic salt hydrates with phase change temperature in range of 5 to 60°C and material cost comparison with common waxes. 2018.

40. Oré E, De Gracia A, Castell A, Farid MM, Cabeza LF. Review on phase change materials (PCMs) for cold thermal energy storage applications. *Appl Energy.* 2012;99:513-533.

41. Karthick A, Murugavel KK, Ramanan P. Performance enhancement of a building-integrated photovoltaic module using phase change material. *Energy.* 2018;142:803-812.

42. Pichandi R, Murugavel Kulandaivelu K, Alagar K, Dhevaguru HK, Ganesamoorthy S. Performance enhancement of photovoltaic module by integrating eutectic inorganic phase change material. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects.* 2020:1-18.

43. Hasan A, McCormack S, Huang M, Norton B. Evaluation of phase change materials for thermal regulation enhancement of building integrated photovoltaics. *Sol Energy.* 2010;84:1601-1612.

44. Hasan A, McCormack S, Huang M, Sarwar J, Norton B. Increased photovoltaic performance through temperature regulation by phase change materials: materials comparison in different climates. *Sol Energy.* 2015;115:264-276.

45. Royo P, Ferreira VI, López-Sabirón AM, Ferreira G. Hybrid diagnosis to characterise the energy and environmental enhancement of photovoltaic modules using smart materials. *Energy.* 2016;101:174-189.
46. Farid MM, Khudhair AM, Razack SAK, Al-Hallaj S. A review on phase change energy storage: materials and applications. Energy Convers Manag. 2004;45:1597-1615.

47. Lane G. Solar Heat Storage: Latent Heat Materials. Volume 1. Background and Scientific Principles. Journal of Solar Energy Engineering. 1983:105:467.

48. Ryu HW, Woo SW, Shin BC, Kim SD. Prevention of supercooling and stabilization of inorganic salt hydrates as latent heat storage materials. Sol Energy Mater Sol Cells. 1992;27:161-172.

49. Lane GA. Phase change materials for energy storage nucleation to prevent supercooling. Sol Energy Mater Sol Cells. 1992;27:135-160.

50. Noël JA, Kahwaji S, Desgrosseilliers L, Groulx D, White MA. Storing Energy. Amsterdam, Netherlands: Elsevier. 2016;249-272.

51. Yinping Z, Yi J, Yi J. A simple method, the-history method, of determining the heat of fusion, specific heat and thermal conductivity of phase-change materials. Meas Sci Technol. 1999;10:201.

52. Skovajsa J, Koláček M, Zálešák M. Phase change material based accumulation panels in combination with renewable energy sources and thermoelectric cooling. Energies. 2017;10:152. https://doi.org/10.3390/en10020152

53. Bruno F, Belusko M, Liu M, Tay N. Advances in Thermal Energy Storage Systems. Amsterdam, Netherlands: Elsevier. 2015:201-246.

54. Goswami M, Kumar N, Li Y, et al. Understanding supercooling mechanism in sodium sulfate decahydrate phase-change material. J Appl Phys. 2021;129:245109. https://doi.org/10.1063/5.0049512

55. Nishina H, Takakura T. III International Symposium on Energy in Protected Cultivation 148. 751-754.

56. Sharma S, Buddha D, Sawhney R, Sharma A. Design, development and performance evaluation of a latent heat storage unit for evening cooking in a solar cooker. Energy Convers Manag. 2000;41:1497-1508.

57. Chen C, Sharma A, Tyagi S, Buddha D. Numerical heat transfer studies of PCMs used in a box-type solar cooker. Renew Energy. 2008;33:1121-1129.

58. El-Sebaii AA, Al-Amir S, Al-Marzouki FM, et al. Fast thermal cycling ofacenanilide and magnesium chloride hexahydrate for indoor solar cooking. Energy Convers Manag. 2009;50:3104-3111.

59. El-Sebaii A, Al-Heniti S, Al-AgeI F, Al-Ghamdi A, Al-Marzouki F. One thousand thermal cycles of magnesium chloride hexahydrate as a promising PCM for indoor solar cooking. Energy Convers Manag. 2011;52:1771-1777.

60. Bhave AG, Thakare KA. Development of a solar thermal storage cum cooking device using salt hydrate. Sol Energy. 2018;171:784-789.

61. Ghoeime A, Klein S, Duffie J. Analysis of collector-storage building walls using phase-change materials. Sol Energy. 1991;47:237-242.

62. Koca A, Oztup HF, Koyun T, Varol Y. Energy and energy analysis of a latent heat storage system with phase change material for a solar collector. Renew Energy. 2008;33:567-574.

63. Varol Y, Koca A, Oztup HF, Avci E. Forecasting of thermal energy storage performance of Phase Change Material in a solar collector using soft computing techniques. Expert Syst Appl. 2010;37:2724-2732.

64. Mehrali M, Johan E, Shahi M, Mahmoudi A. Simultaneous solar-thermal energy harvesting and storage via shape stabilized salt hydrate phase change material. Chem Eng J. 2021;405:126624.

65. Manz H, Egolf P, Suter P, Goetzberger A. TIM–PCM external wall system for solar space heating and daylighting. Sol Energy. 1997;61:369-379.

66. El-Dessouky H, Al-Juwayyel F. Effectiveness of a thermal energy storage system using phase-change materials. Energy Convers Manag. 1997;38:601-617.

67. Esen M, Durmuş A, Durmuş A. Geometric design of solar-aide latent heat store depending on various parameters and phase change materials. Sol Energy. 1998;62:19-28.

68. Khalifa A, Abbas E. World Renewable Energy Congress VIII (WREC).

69. Khalifa AJN, Abbas EF. A comparative performance study of some thermal storage materials used for solar space heating. Energy Build. 2009;41:407-415.

70. Veerappan M, Kalaiselvam S, Iniyan S, Goic R. Phase change characteristic study of spherical PCMs in solar energy storage. Sol Energy. 2009;83:1245-1252.

71. Jurinak JJ, Abdel-Khalik S. On the performance of air-based solar heating systems utilizing phase-change energy storage. Energy. 1979;4:503-522.

72. Abhat A. Low temperature latent heat thermal energy storage: heat storage materials. Sol Energy. 1983;30:313-332.

73. Bhargava AK. A solar water heater based on phase-changing material. Appl Energy. 1983;14:197-209.

74. Ghoneim A. Comparison of theoretical models of phase-change and sensible heat storage for air and water-based solar heating systems. Sol Energy. 1989;42:209-220.

75. Canbazoglu S, Sahinaslan A, Ekmekeyapar A, Aksoy YG, Akarsu F. Enhancement of solar thermal energy storage performance using sodium thiosulfate pentahydrate of a conventional solar water-heating system. Energy Build. 2005;37:235-242.

76. Castell A, Solé C, Medrano M, Nogués M, Cabeza L. Comparison of stratification in a water tank and a PCM-water tank. J Sol Energy Eng. 2009;131:024501.

77. Porteiro J, Miguez JL, Crespo B, De Lara J, Pousada JM. On the behavior of different PCMs in a hot water storage tank against thermal demands. Materials. 2016;9:213.

78. Farid M, Kong W. Underfloor heating with latent heat storage. Proc Inst Mech Eng A: J Power Energy. 2001;215:601-609.

79. Mamani V, Gutiérrez A, Ushak S. Development of low-cost inorganic salt hydrate as a thermochemical energy storage material. Sol Energy Mater Sol Cells. 2018;176:346-356.

80. Nagano K, Mochida T, Takeda S, Domanśki R, Rebow M. Storing Energy. Amsterdam, Netherlands: Elsevier. 2015:201-246.

81. Oró E, Miró L, Farid M, Cabeza L. Improving thermal performance of freezers using phase change materials. Int J Refrig. 2012;35:984-991.

82. Iryay M, Suwono A, Indarto NY, Pasek AD, Pradiparta MA. Phase change materials development from salt hydrate for application as secondary refrigerant in air-conditioning systems. Sci Technol Built Environ. 2018;24:90-96.

83. Weinländer H, Beck A, Fricker J. PCM-facade-panel for daylighting and room heating. Sol Energy. 2005;78:177-186.
84. Hadjieva M, Stoykov R, Filipova T. Composite salt-hydrate concrete system for building energy storage. Renew Energy. 2000;19:111-115.
85. Ye R, Lin W, Yuan K, Fang X, Zhang Z. Experimental and numerical investigations on the thermal performance of building plane containing CaCl₂·6H₂O/expanded graphite composite phase change material. Appl Energy. 2017;193:325-335.
86. Fu L, Wang Q, Ye R, Fang X, Zhang Z. A calcium chloride hexahydrate/expanded perlite composite with good heat storage and insulation properties for building energy conservation. Renew Energy. 2017;114:733-743.
87. Hasan A, McCormack SJ, Huang MJ, Norton B. Energy and cost saving of a photovoltaic-phase change materials (PV-PCM) system through temperature regulation and performance enhancement of photovoltaics. Energies. 2014;7:1318-1331.
88. Hasan A, McCormack S, Huang M, Norton B. Characterization of phase change materials for thermal control of photovoltaics using Differential Scanning Calorimetry and Temperature History Method. Energy Convers Manag. 2014;81:322-329.
89. Tyagi V, Buddhi D. Thermal cycle testing of calcium chloride hexahydrate as a possible PCM for latent heat storage. Sol Energy Mater Sol Cells. 2008;92:891-899.
90. Qu S, Ma F, Ji R, Wang D, Yang L. System design and energy performance of a solar heat pump heating system with dual-tank latent heat storage. Energy Build. 2015;105:294-301.
91. Iranzo A, Boillat P, Biesdorf J, Salva A. Investigation of the liquid water distributions in a 50 cm² PEM fuel cell: effects of reactants relative humidity, current density, and cathode stoichiometry. Energy. 2015;82:914-921.
92. Khan Z, Khan Z, Ghafoor A. A review of performance enhancement of PCM based latent heat storage system within the context of materials, thermal stability and compatibility. Energy Convers Manag. 2016;115:132-158.

How to cite this article: Choo YM, Wei W. Salt hydrates as phase change materials for photovoltaics thermal management. Energy Sci Eng. 2022;10:1630–1642. https://doi.org/10.1002/ese3.1007