REVIEW

Salt hydrates as phase change materials for photovoltaics thermal management

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Abstract

Recently, phase change materials (PCMs) are acquiring much attention for the overall enhancement of photovoltaic (PV) systems′ performance, because of their extraordinary property in temperature management. Many researchers have been incorporating PCMs in PV systems. However, the tested materials are principally organic PCMs. In this review, a comprehensive literature of PV systems with utilization of inorganic PCMs is introduced. Salt hydrates are the focus materials. They, in general, have comparative properties as organic PCMs and are better from safety and environmental standpoints. The characterization, properties, and applications of the salt hydrates in PV-PCM research are discussed in this paper. Indeed, even most research shows promising outcomes, there is still need in data collection for more detailed and accurate system performance evaluation. Therefore, the real-life application of this type of PV-PCM system is still a long way from clear due to the discovered challenges. Finally, the possibilities of future research on PV-PCM systems are highlighted, innovative technologies are to be discovered and addressed to defeat the current issues including system reliability and economic attainability.

KEYWORDS
phase change material, PV-PCM system, salt hydrate, thermal management

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%.[3] 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,[4] PV electricity power systems,[5] solar dryers in agri-industries,[6] 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.[3] 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.[7] 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,[8-11] HVAC system,[12-14] thermal energy storage,[15-17] 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 of two distinct types of thermal energy—sensible and latent heat.[7] Sensible heat is the measure of energy expected to modify the temperature of a substance without changing its physical phase.[18] On the other hand, latent heat is measure of energy that is expected to change the phase of a matter from one to another.[18] 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.[19] 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.[20] 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."[21] The fundamental purpose for paraffin's capability as an energy stockpiling material is its
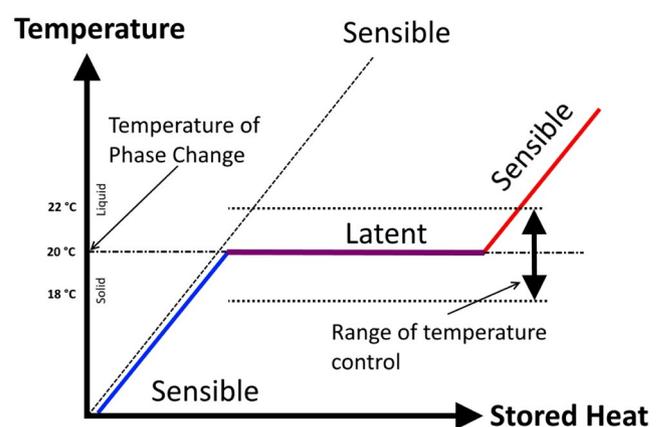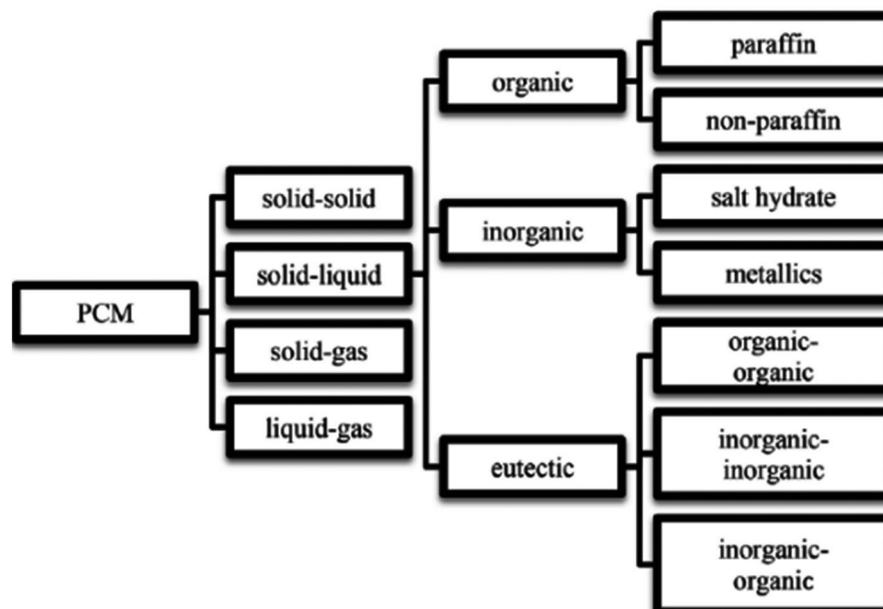

FIGURE 1 Difference between sensible and latent heat in temperature during phase change[52]

FIGURE 2 Classification of phase change materials[34]

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).[22] 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.[23] 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.[24]

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.[25,26] 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.[27]

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.[28] 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%.[29]

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 $AB \cdot nH_2O$, where A and B stand for 2 different chemical elements.[30] 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/m^3, while solid salt hydrates is slight higher, around 2180 kg/m^3.[31-34] The pioneering research using salt hydrates as the principal materials was first conducted by Telkes.[35,36]

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.[31-33,37] 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 $20/kWh. For instance, average material expense for calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$) is from $0.13 to $0.46/

kg.[38] However, paraffins with practically identical melting points cost from \$20 to \$30/kWh.[39]

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 ($Na_2SO_4 \cdot 10H_2O$), 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 ($CaCl_2 \cdot 6H_2O$) and sodium hydrogen phosphate dodecahydrate ($Na_2HPO_4 \cdot 12H_2O$), might be feasible options as the material replacement.[39]

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.[31,40]

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.[41] 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 ($MgSO_4 \cdot 7H_2O$) into Sodium Carbonate Decahydrate ($Na_2CO_3 \cdot 10H_2O$),[42] 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.[43] In this experiment, another hydrated salt—calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$) 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 insolating (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

TABLE 1 Inorganic salt hydrates history and application

Application	System	Salt hydrate	Year of study	References
TES	Greenhouse heating system	$Na_2SO_4 \cdot 10H_2O$	1983	55
	Solar cooker	$Mg(NO_3)_2 \cdot 6H_2O$	2000	56
			2008	57
		$MgCl_2 \cdot 6H_2O$	2009	58
			2001	59
			2018	60
	Solar collector system	$Na_2SO_4 \cdot 10H_2O$	1991	61
		$CaCl_2 \cdot 6H_2O$	2008	62
		$Na_2CO_3 \cdot 10H_2O$	2010	63
		$CH_3COONa \cdot 3H_2O$	2021	64
	Solar space heating	$CaCl_2 \cdot 6H_2O$	1997	65, 66
			1998	67
			2004	68
			2009	69, 70
		$Na_2HPO_4 \cdot 12H_2O$	1979	71
		$Na_2S_2O_3 \cdot 5H_2O$	1983	72
	Solar water heating	$Na_2HPO_4 \cdot 12H_2O$	1983	73
		$Na_2SO_4 \cdot 10H_2O$	1983	73
			1989	74
		$Ba(OH)_2 \cdot 8H_2O$	1983	72
		$Na_2S_2O_3 \cdot 5H_2O$	2005	75
		$CH_3COONa \cdot 3H_2O$	2009	76
		Delta cool DC58	2016	77
		Thermusol HD60		
		Pure temp PT58		
	Underfloor heating	$CaCl_2 \cdot 6H_2O$	2001	78
	Thermochemical storage	$MgCl_2 \cdot 6H_2O$	2018	79
	TES cooling system	$Mn(NO_3)_2 \cdot 6H_2O$	2003	80
	Air-conditioning systems	Climsel C-18 ($NaNO_3/H_2O$)	2012	81
		$CaCl_2 \cdot 6H_2O$	2018	82
		$Na_2HPO_4 \cdot 12H_2O$		
Phase change material for thermal regulation	PCM-façade-panel	S27	2005	83
	Composite PCM concrete system	$Na_2S_2O_3 \cdot 5H_2O$	2000	84
		$CaCl_2 \cdot 6H_2O$	2017	85, 86
	Photovoltaic-phase change material (PV-PCM) system	$CaCl_2 \cdot 6H_2O$	2008	80
			2010	43
			2014	87, 88
			2015	44
		$Na_2SO_4 \cdot 10H_2O$	2015	81
			2015	82
			2018	41
		$Na_2CO_3 \cdot 10H_2O$	2020	42
		$MgSO_4 \cdot 7H_2O$	2020	42
		$Na_2HPO_4 \cdot 12H_2O$	2016	45
			2016	83

Abbreviations: PCM, phase change material; PV, photovoltaic; TES, thermal energy storage.

TABLE 2 Thermo-physical properties of salt hydrates PCMs in different PV research

Types	T_m (°C)	Latent heat of fusion (kJ/kg)	Thermal conductivity (W/mC) [solid]	Specific heat capacity (kJ/kg·K) [solid]	Specific heat capacity (kJ/kg·K) [liquid]	Refs.
$CaCl_2 \cdot 6H_2O$	29.8	191	1.08	1.4	2.1	43, 44, 89
$Na_2SO_4 \cdot 10H_2O$	32	251	0.7	1.76	3.30	41, 90, 91
$Na_2CO_3 \cdot 10H_2O$	33	247	0.876	1.88	—	42
$MgSO_4 \cdot 7H_2O$	48.5	202	0.645	1.546	—	42
$Na_2HPO_4 \cdot 12H_2O$	40	280	0.514	—	—	45, 92

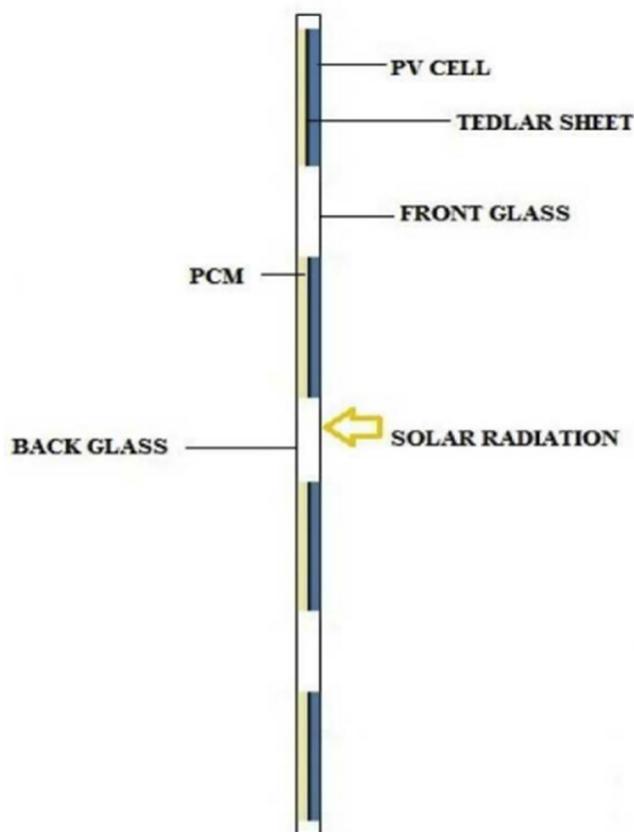Abbreviations: PCMs, phase change materials; PV, photovoltaic.

FIGURE 3 Schematic view of the BIPV module[41]

(Figure 6). In the BIPV-PCM system, at 750 W/m^2, the PV cell surface temperature reduced up to 18°C, and the temperature held constant for about 30 minutes. However, at 1000 W/m^2, 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/m^2.

The same salt hydrate, $CaCl_2 \cdot 6H_2O$ was further tested by Hasan et al again for thermal and electrical energy generation and efficiency analysis.[44] 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-PCM$_1$ system was capric-palmitic corrosive, while PV-PCM$_2$ utilized the salt hydrate $CaCl_2 \cdot 6H_2O$.

Focusing on the PV-PCM$_2$ 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-PCM$_2$ (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.[45] However, only two types—sodium sulfate decahydrate ($Na_2SO_4 \cdot 10H_2O$) and sodium dihydrogen phosphate dodecahydrate ($Na_2HPO_4 \cdot 12H_2O$) 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

FIGURE 4 (A), Experimental setup with temperature data log, (B) Rear view of the PV-PCM system, (C) Cross-sectional schematic of the PV-PCM system[42]
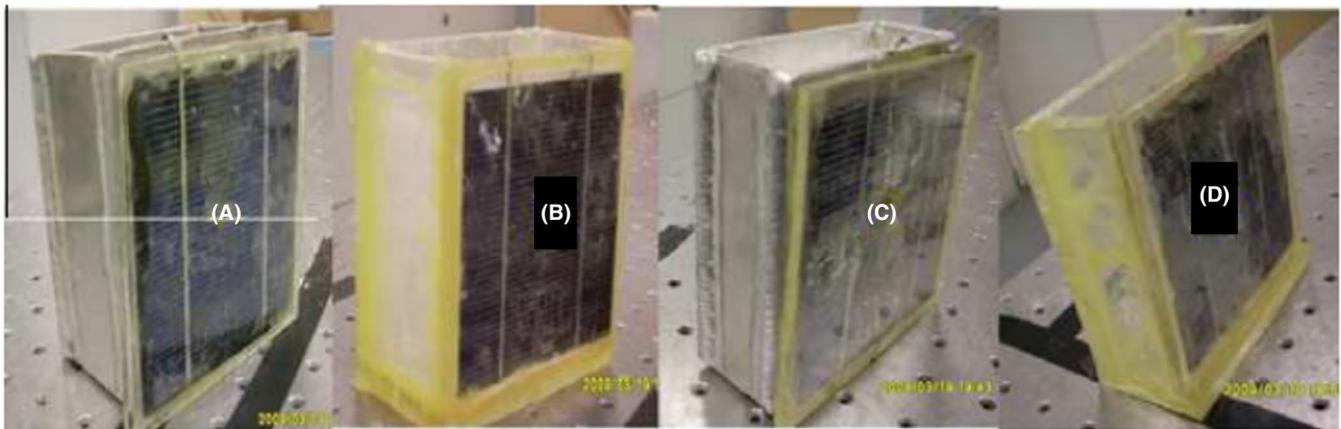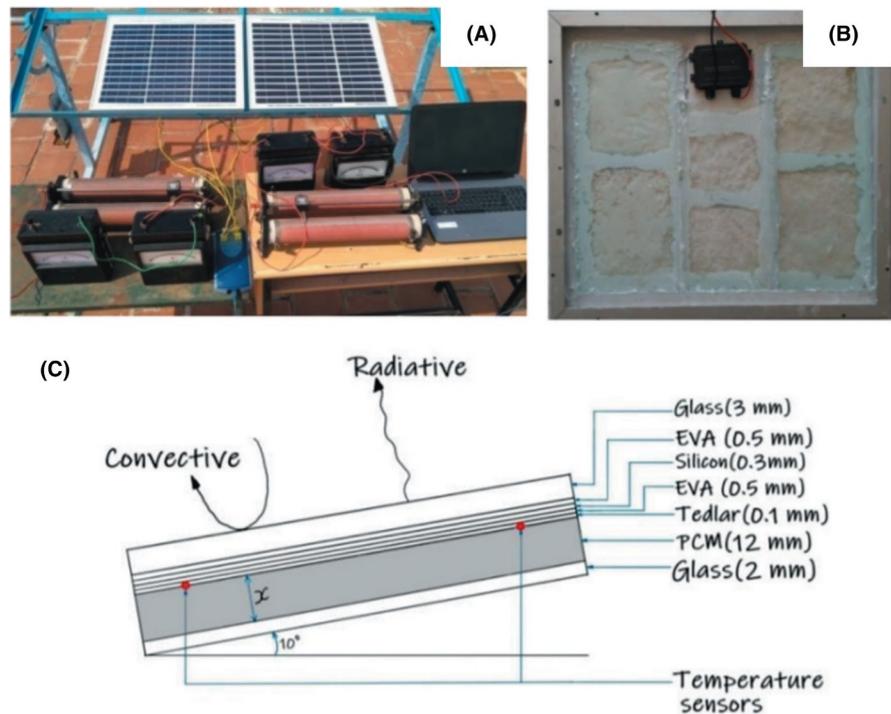

FIGURE 5 The overlook of PV-PCM systems (A-D)[43]

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.[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
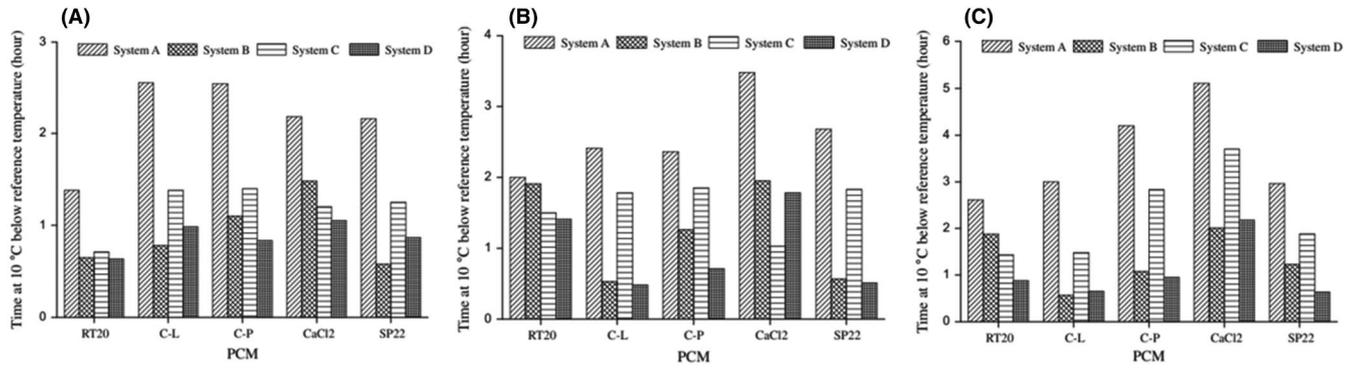
FIGURE 6 Duration of each PV-PCM system with surface temperature maintained as 10°C below the reference temperature at different solar insolation. (A), 500 W/m², (B) 750 W/m², and (C) 1000 W/m²[43]
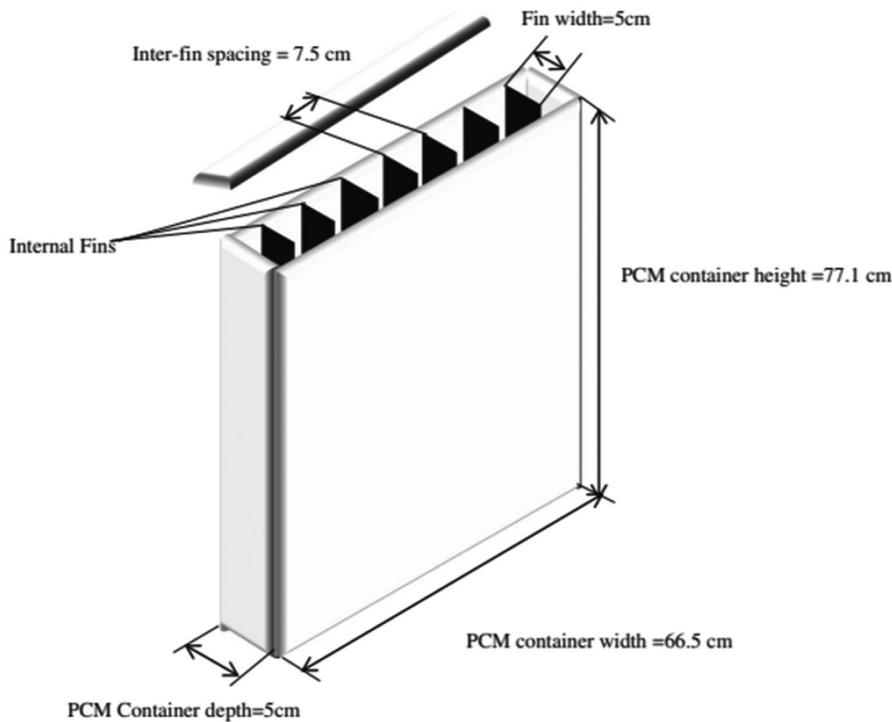

FIGURE 7 Schematics of a PCM container[44]

TABLE 3 Summary of measured data in Dublin, Ireland on September 12, 2009, and Vehari, Pakistan on October 30, 2009[87]

Measured data	Time	Reference PV		PV-PCM₁		PV-PCM₂	
		Dublin	Vehari	Dublin	Vehari	Dublin	Vehari
Insolation G (W·m⁻²)	At peak	970	950	970	950	970	950
	At average	674	660	674	660	674	660
Temperature (°C)	At peak	49	63	43	51	40	42
Temperature regulation (°C)	At peak	—	—	7	17	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	20.95	20.15
	At average	20.41	18.71	20.52	19.42	20.81	19.92
I_{sc} (Amp)	At peak	3.74	3.42	3.70	3.35	3.68	3.33
	At average	2.82	2.45	2.77	2.41	2.78	2.39

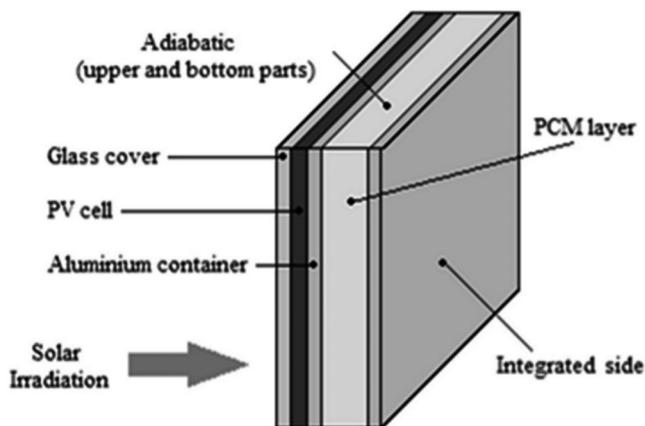Abbreviations: PCM, phase change material; PV, photovoltaic.

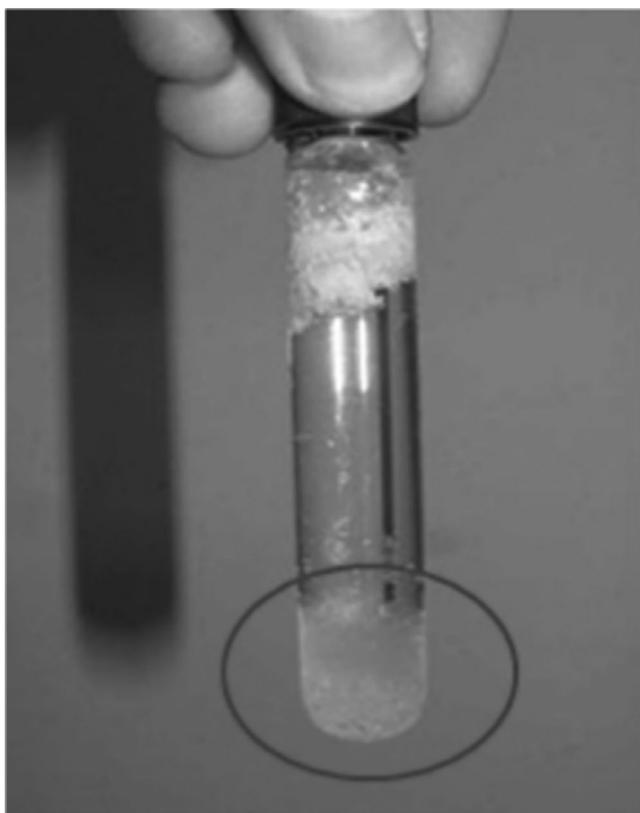**FIGURE 8** Schematics of BIPV-PCM system[45]

FIGURE 9 Incongruent melting issue of salt hydrates[53]

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.[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.[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.[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.[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.[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 slat 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
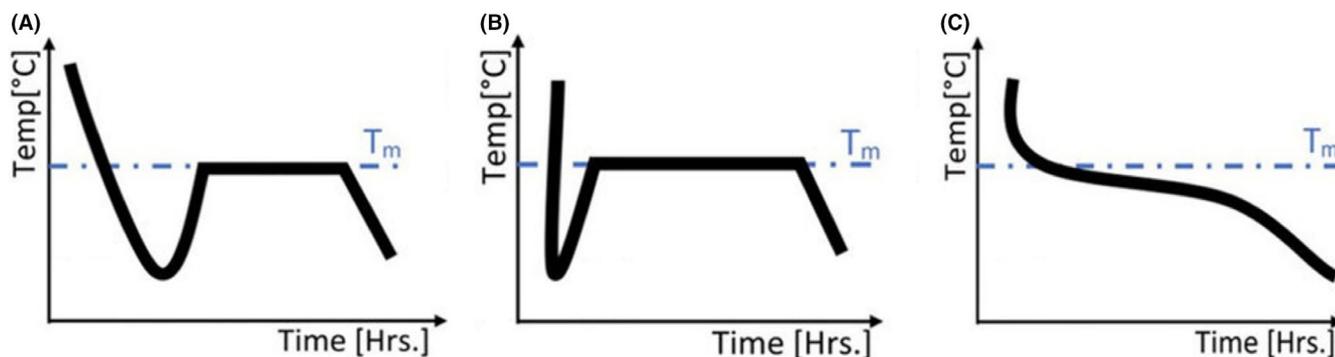
FIGURE 10 Supercooling curves of Na$_2$SO$_4$·10H$_2$O salt hydrates. (A), Low rate of nucleation and thermal diffusivity, (B) low rate of nucleation, but higher thermal diffusivity, and (C) restrained nucleation due to supercooling[54]

added to the salt hydrates can make sure gradual crystallization 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 management of PV.

Furthermore, DSC is the commonly chosen equipment in most research for investigation of PV-PCM system 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 industrial 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.[51] 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 instrumentation cost.

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CONFLICT OF INTEREST
The authors declare no competing financial interest.

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