Available on https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.10 Issue 2 Page No 168-180

Reducing Surface Temperature of Photovoltaic Panel using Phase Change Material: A Comprehensive Review

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Abstract

It is possible to improve the performance of photovoltaic (PV) systems and increase energy security through the utilization of energy storage systems. For the purpose of cooling a photovoltaic panel and ensuring that it continues to operate at a high efficiency, energy storage systems can be attached to the back surface of the panel. Using nanoparticles in phase transition materials for the purpose of storing thermal energy can improve the latent heat storage capacity of the material. In this study, a bibliometric and thematic analysis of photovoltaic (PV) cooling systems that are paired with an energy storage system is presented. The analysis focuses on publishing patterns, the most cited publications, sources, and keywords in this subject during the course of the twenty-first century. The effectiveness of solar photovoltaic (PV) panels is negatively impacted when they are frequently exposed to extremely high temperatures. To reduce the amount of heat generated by photovoltaic panels, a great number of cooling solutions have been designed and used. A few examples of these include heat sinks, heat pipes, phase change materials, air-cooled systems, and water-cooled systems. Since phase change material possesses exceptional optical and thermal qualities, it has been found that it is a good material that may be utilized in solar photovoltaic panels for the purpose of reducing the surface temperature of the PV panels.

Keywords: Phase Change Material, Solar Panel, Renewable Energy, Thermal Energy Storage

1. Introduction

Energy utilization is growing exponentially in this era of rising population, and the demand for renewable energy is increasing significantly from the last decade onwards. Solar energy, which is derived from the sun, is the most abundant renewable energy that can easily meet today's demands. With the help of solar photovoltaics, solar energy from the sun that falls on the earth's surface can be transformed into electrical energy [1]. Photovoltaics (PV), also referred to as solar cells, are solid-state devices that directly converts solar energy into electricity. Depending on the PV cell material and climatic conditions, a standard PV converts 6-20% of the incident solar radiation into electricity, and the remainder is converted to thermal energy, which increases the temperature of the PV cell to 33℃-50℃ above ambient temperature. The temperature coefficient of power is an important differentiator in solar PV efficiency, particularly in hot climates [2-3].

The efficiency of PV cells degrades as the temperature of the cells increases passive temperature regulation of PV using phase change material (PCM) has

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received much attention in this regard. At a current scenario only 15–20% of the total incoming solar radiation on a PV panel can be utilized as an electricity and rest part of solar radiation reflected by the panel [4]. The reflected radiation generates heat and raises the temperature of the panel. Various factors, such as tilt angle, varying atmospheric conditions, and dust build-up, will affect the panel surface temperature (17℃–22℃). Increasing the temperature of the photovoltaic surface will reduce the voltage drop in the photovoltaic panel, which will also affect the structural integrity [5].Due to the higher surface temperature, the conversion rate of photovoltaic panels is reduced by approximately 0.5%/℃ above the nominal operating temperature of the panel which is 25°C defined by the industry standard. Summer time temperatures vary between 40°C -70°C, causing the conversion rate to fall from average. Therefore, some techniques have been practiced on photovoltaic panels to control their temperature as minimal as possible. To increase the rate of heat transfer, the most widely used cooling technology in thermal engineering is adopted [6].

Storing renewable energy is the best way to utilize it. Energy storage is very economical because it can reduce costs and energy consumption. Even after storing energy, we are not able to fully utilize sources due to losses [7].Temperature-controlled heat storage systems are categorized as sensible heat storage (SHS), phase-changing heat as a latent heat storage (LHS), and thermos-chemically based thermo-chemical heat storage (TCHS). When compared to SHS & LHS systems, LHS has a higher capacity for storing heat at the same temperature rise, and on comparing LHS and TCHS gives high heat storage capacity but it is not controllable and takes too much time for the reverse process [8]. So latent heat storage (LHS) gives the best result for the thermal storage system, therefore, latent heat storage is mostly used in thermal management in many applications. PCM is the best example of a latent heat storage system. During its phase transition, PCM stored a significant amount of heat.

However, solar energy harvested by solar photovoltaic systems is the most plentiful, inexhaustible, and environmentally friendly form of energy generation. Different types of photovoltaic (PV) systems, which turn solar power into usable energy, are available. In general, the two major types of PV systems used today can be summarized as PV panels and hybrid photovoltaic thermal (PVT) systems. However, a hybrid PVTs system can produce thermal and electrical energy together simultaneously [9]. PV cells are semiconductors that transform direct current (DC) discharged and concentrated solar radiation with conversion efficiency varying from 4% to 32%, depending on the properties of the material from which they are manufactured. The wide use of solar cells faces many challenges, and the most important obstacle is their low efficiency resulting from their high temperature. In reality, most arriving solar radiation is transformed into heat, raising the PV panel's temperature and lowering the output power, electrical conversion efficiency, and fill factor.

It is also desirable to increase PV module heat dissipation whenever possible. In recent years, some researchers have discussed the applications of PCM systems in PV modules, as they have been reported for cooling PV cells or modules efficiently [10]. PCMs have a few simple advantages in comparison with cooling using forced or natural convection of air: higher heat-absorbing performance with no mobile equipment and low maintenance costs and electrical consumption.

A few attempts were made to incorporate PCMs producing unique PVT panels. Containers containing phase-change material are placed on the solar panel's back surface and fixed there. The harmful excess heat from the solar cells is transferred to be stored in the phase-changing matter in the form of latent heat [11]. The application of materials to absorb the excess heat released by PV modules is the basis for passive cooling strategies. The relationship between solar cell efficiency and temperature in recent years, some researchers have discussed the applications of PCM systems in PV modules, as they have been reported for cooling PV cells or modules efficiently [12]. PCMs have a few simple advantages in comparison with cooling using forced or natural convection of air: higher heat-absorbing performance with no mobile equipment and low maintenance costs and electrical consumption. A few attempts were made to incorporate PCMs into PV panels, producing unique PVT panels [13].

The phase-change material is very interesting for thermal environmental control and storage of energy. It efficiently stores and releases a huge quantity of latent processes of melting and solidification, respectively. It can maintain the PV temperature during the full stage of heat transfer. Several numerical and experimental studies of temperatures of the keys that have been considered as a problem is the low thermal conductivity of PCMs, which provides greater cooling and maintains better thermal control of the board. Nanomaterials were added to PCMs to obtain improved thermal properties compared to the original materials. The type and concentration of nanoparticles in nano-PCMs indicated their thermal characteristics. Furthermore, with the use of selective paint over the solar cell, it was observed that heat loss was greatly reduced, and air was passed as a coolant in a designed stream with ease and greater safety. PVTs provide low thermal conductivity and specific heat, resulting in low efficiency. This review paper has the potential to be a valuable contribution to the current literature in the subject field, offering a clear and different perspective. This research provides a comprehensive analysis of the improvements

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made to solar panel efficiency and their incorporation with energy storage systems. Furthermore, the limitations of these systems have been examined in order to determine the necessary method for enhancing solar panel efficiency and reducing panel temperature by phase change material.

2. Literature Review

Solar energy is one of the major renewable energy sources. Solar PV panels receive solar incident radiation and convert it into electrical energy with an efficiency factor of 10–16%. Electrical efficiency is decreased by 0.4–0.6% for each increased degree of panel surface temperature. Many researchers performed experiments for removal of heat from the solar PV panels for improving the efficiency by passive cooling or forced convection cooling, hydraulic cooling, refrigerant cooling and heat pipes. Hussein M. Maghrabie et al. [14] experimentally examined the low-concentrated solar PV cell cooling, using loop heat pipe passive cooling technique Phase-change material (PCM)-based solar PV cooling method draws more attention of researchers, because it is a passive cooling without using any power [15]. Researchers used solid–liquid phase-change materials also for cooling of solar PV panels. The temperature of the PV cell is cooled to 37.53 °C even at midday. Kumar, Y et al. [16] analyzed the thermal performance of the PCM incorporated a solar PV panel and concluded that harvesting 13.6% electrical energy output is possible by using PCM layer, having a melting point of 30 °C. Mehmet Ali Yildirim et al. [17] mixed aluminum nanoparticles to paraffin wax and observed the improvement in fluid and thermal properties of PCM. Thermal conductivity of PCM is improved compared to the dynamic viscosity. Neda Azimi et al [18]. explained the use of CuO nanoparticle-embedded paraffin wax for enhancement of thermal conductivity and thermal performance of a storage system [19].

Various researchers have recommended different cooling strategies, such as active and passive cooling like water cooling, air cooling, heat pipe, phase change material (PCM), nanofluid, geothermal, etc., to reduce the operating temperature of the photovoltaic panel. However, the variable nature of the sunlight, freezing of heat transfer fluid (HTF) in particularly cold regions, and difficulty to store thermal energy act as barriers to the widespread use of PV cooling systems. To overcome these difficulties, energy storage systems such as phase change materials (PCMs) provide a clear alternative solution [20].

Based on the summary of bibliometric entities the most frequently used document on PV cooling through PCM, nano-enhanced PCM, and nanofluid is shown graphically in Fig. 1. Subsequently, more and more research has been conducted in the field of photovoltaic cooling through energy storage systems[21]. Annual publication volumes and average citations in this domain during the last decade are shown in Fig. 2. Since 2017, the number of publications in the field has significantly increased and as on 31st December 2022, there were 85 publications in a single year, in this area [22].

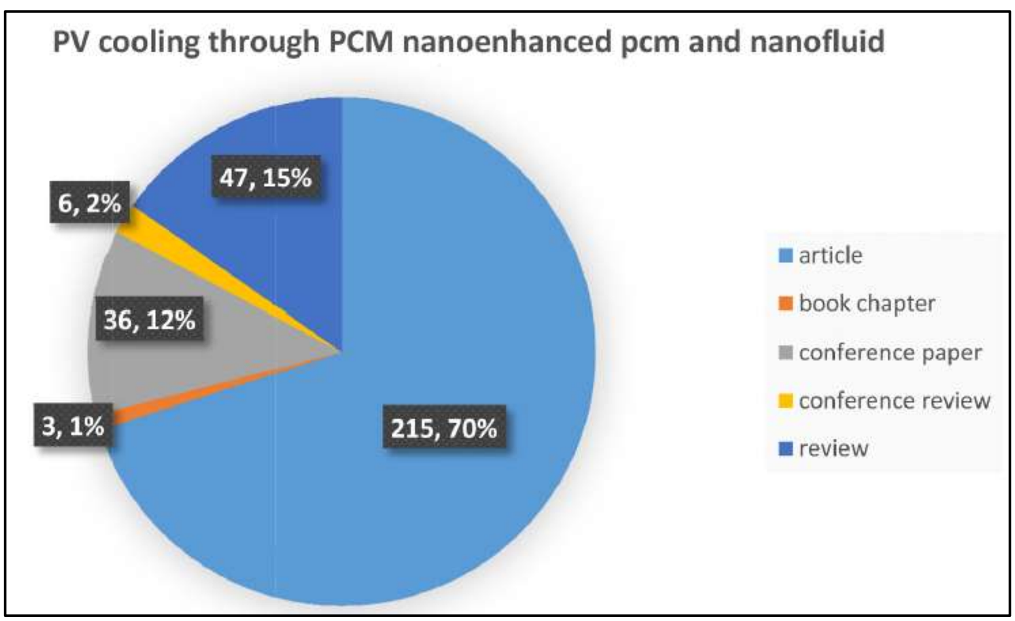

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Fig. 1. Most frequent type document of PV cooling through PCM, nano-enhanced PCM and nanofluid. [23]

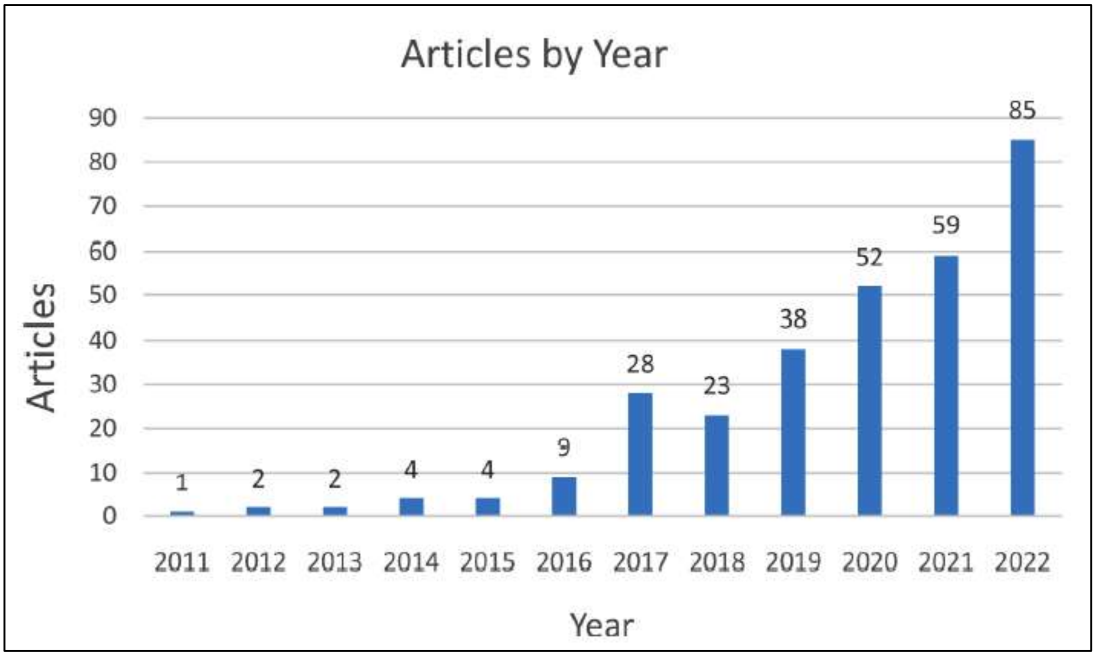

Fig 2. Year-wise distribution of published papers. [24]

2.1. Analysis of high-frequency keywords

A bibliophagy tool is used to retrieve and count the authors' most frequently used keywords in order to better understand the themes covered in the reviewed research papers. Using this technique, a word tree map is drawn for keywords with word frequencies greater than 10 and is represented in Fig. 3. The keywords phase change material, photovoltaic, thermal management, nanofluids, nano-enhanced PCM, solar energy, PV cooling, nanoparticles, renewable energy, exergy analysis, and electrical efficiency account for 29%, 8%, 6%, 5%, 5%, 4 %, 4%, and 3%, respectively, of the high-frequency keywords in the research field. This finding shows that PV cooling research has relatively extensively focused on phase change material, passive cooling, and nanofluids. This observation also indicates that thermal management is required for improving performance such as the electrical and thermal efficiency of the photovoltaic system. Table 1 Comparative features of different PV cooling methods [26-27].

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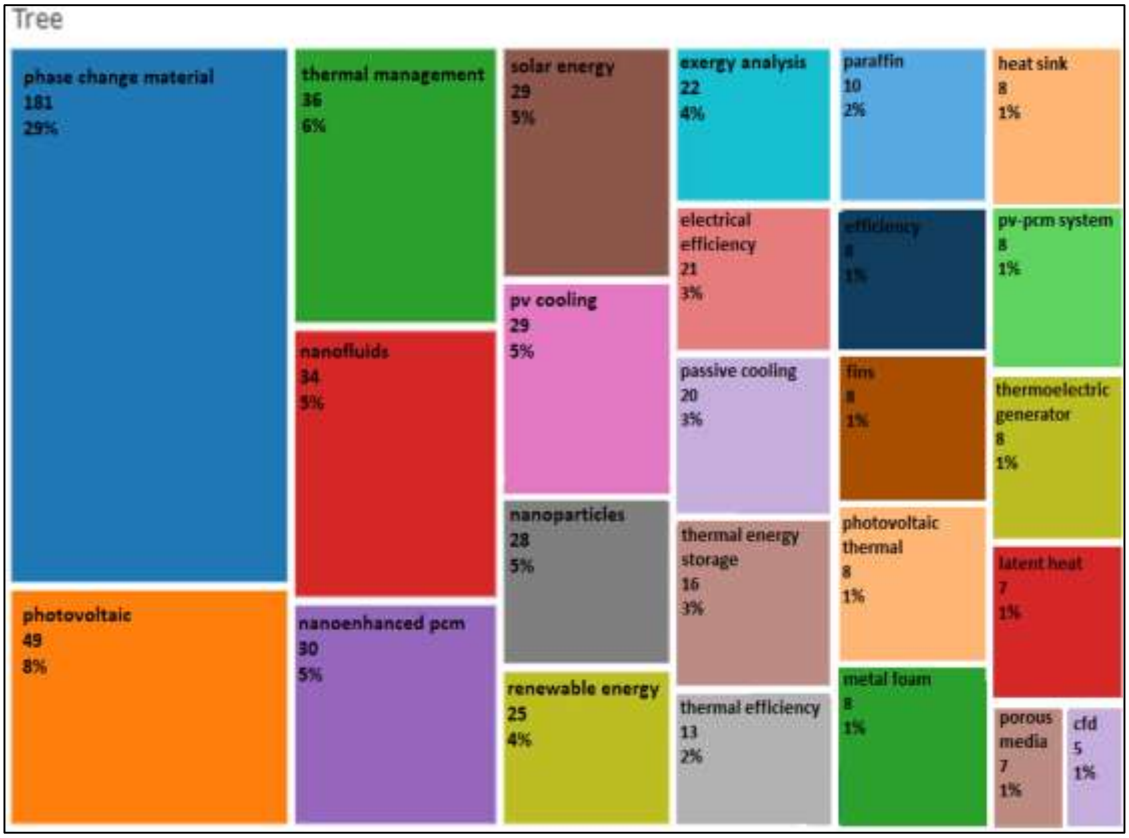

Fig. 3. A word tree map is drawn for keywords with word frequencies greater than 10[25]

Table 1 Comparative features of different PV cooling methods [26-27].

Cooling Technologies	Merits	Demerits
Natural Convention of air	• Low investment • No maintenance • Easy to integrate • Longer Life • Noiseless • No Power Supply • Passive heat Exchange	• Low heat transfer rates • Due to low thermal conductivity and heat capacity of air • Accumulation of dust in inlet grating further deteriorates heat transfer • Depend on wind speed and direction • Low mass flow rates of air • Limited temperature reduction
Forced Convention of Air	• Higher heat transfer rates compared to natural convention • Independent of wind direction and speed • Higher mass flow rates compared to natural convention • Higher temperature reduction compared to natural convention	• High investment on fans, ducts, etc. • Extra power consumption • Noisy • High maintenance cost • Difficult to integrate with PV module

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Water cooling	• Higher heat transfer compared to both natural & forced convention • Higher mass flow r and tate, heat capacity and thermal conductivity of water compared to natural and forced convention of air. • Higher temperature reduction	• Higher investment due to use of pumps • Higher maintenance cost compared to natu- ral and forced convection. • Higher electricity consumption compared to forced convection. • Less life due to corrosion
Heat Pipe Cooling	• Passive heat exchange • Low cost • Easy to integrate	• Low heat transfer rates • Dust accumulation on inlet grating • Dependent on wind speed and direction.
PCM Cooling	• Higher heat Transfer rate as compare to both air and water cooling • Higher heat storage capacity due to latent heat • Isothermal heat removal • No electricity needed • Passive heat Excahnge • Noise less • No maintenance cost • Heat supply on demand	• High PCM cost • Some PCMs are toxic • Some PCMs are corrosive • Some PCMs are flammable • Disposal issue after life cycle completion
Thermoelectric cooling	• No moving parts • Noiseless • Compact size • Easy to integrate • Low maintenance cost	• Heat transfer depends on ambient conditions • Active system • Electricity consumption • Low reliability • No heat storage capacity • Requires efficient heat removal from hot side

A comparative merits and demerits of organic PCM, inorganic PCM and eutectics, adapted from [28,29,30,31] have been compiled in Table 2.

Table 2 Comparative merits and demerits of organic PCM, inorganic PCM and eutectics [32,33,34,35].

Organic	• Available in wide temperature range • Low or no super cooling • High heat of fusion • Self nucleating property • Congruent melting • Good physical and chemical stability • Non-reactive, recyclable • Good compatibility with other materials	• Low volumetric latent heat storage capacity • Low thermal conductivity • Large volume change on phase transition • Flammable

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Inorganic	• High heat of fusion • High thermal conductivity • High volumetric latent heat storage • Sharp melting point • Low volume change on phase transition • Non-flammable • Ample availability • Low price	• Super cooling • Quick phase separation • Lack of thermal stability • Incongruent melting • Corrosiveness
Eutectics	• Sharp melting point • High volumetric heat storage density • No segregation on melting or freezing	• Lack of test datum of thermo-physical properties

2.2. Problem Identification

1. The electrical efficiency and power output are highly influenced by the surface temperature of PV.
2. Increasing the surface temperature of PV highly influences the performance and its electrical conversion efficiency.
3. Depending on the PV cell material and climatic conditions, a standard PV converts 6-20% of the incident solar radiation into electricity, and the remainder is converted to thermal energy, which increases the temperature of the PV cell to 50°C above ambient. The temperature coefficient of power is an important differentiator in solar PV efficiency, particularly in hot climates.
4. Increasing the temperature of the photovoltaic surface will reduce the voltage drop in the photovoltaic panel, which will also affect the structural integrity. Due to the higher surface temperature, the conversion rate of photovoltaic panels is reduced by approximately 0.5%/°C above the nominal operating temperature of the panel which is 25°C defined by the industry standard.
5. Summertime temperatures vary between 40-70°C, causing the conversion rate to fall from average. Therefore, some techniques have been practiced on photovoltaic panels to control their temperature as minimally as possible

2.3. Phase change material a promising heat storage material

Phase Change Materials (PCMs) have the ability to store and release latent heat, maintaining a stable temperature during the processes of heat absorption or dissipation [36,37]. The Latent energy storage by PCM with temperature changes and schematic classification of PCM based on chemical composition as discussed in Figure 4, and 5 respectively. The phase change process involves transitioning between different states of matter, such as liquids and gases through condensation and evaporation, or solids and liquids through melting and freezing. When the temperature around a PCM rises to its melting point, an endothermic process occurs, breaking chemical bonds and allowing the PCM to absorb energy, transitioning from a solid to a liquid state. Conversely, when the temperature drops to the PCM's freezing point, these bonds reform in an exothermic process, releasing heat and returning the PCM to its solid state. This ability to store and release heat classifies PCMs as thermal reservoirs [38]. During these phase changes, PCMs typically experience a volume reduction of about 10% from their initial volume [39].

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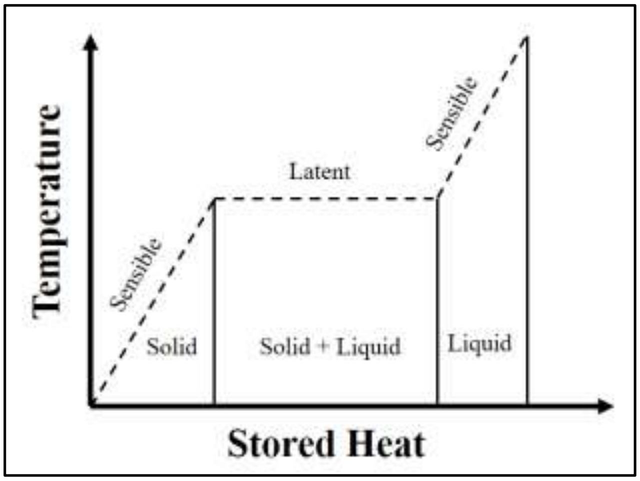

Fig. 4. Latent energy storage by PCM with temperature changes [40, 41].

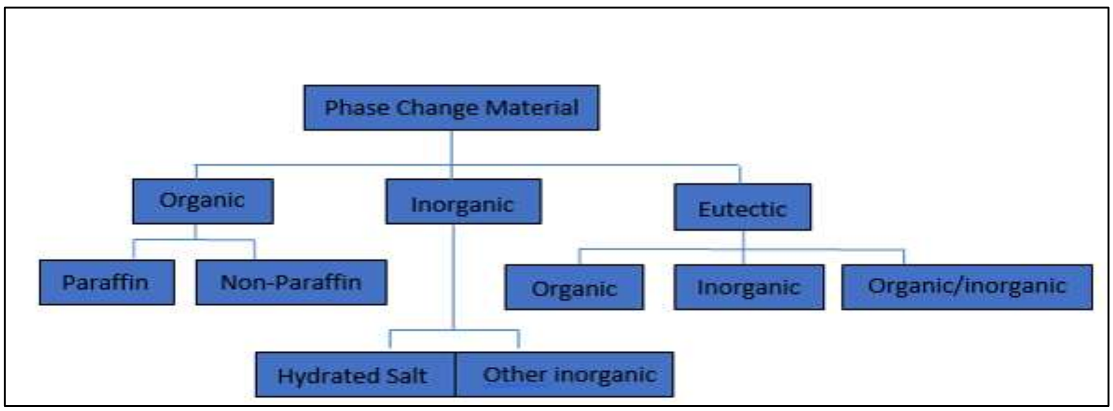

Fig. 5. Schematic Classification of PCM Based on Chemical Composition.

2.4. Selection of PCM Material

Selecting the ideal Phase Change Material (PCM) involves considering several key factors. The PCM must have a high latent heat capacity, high thermal conductivity, a melting temperature within the practical range of operation, minimal supercooling, and should be non-toxic, non-corrosive, chemically stable, and cost-effective [42,43]. When cooling a PV module using PCM the melting point of the PCM must align with the operating temperature range of the PV module. PCMs with excessively low melting points are not recommended [44]. One major issue with PCMs is their typically low thermal conductivity, which can limit efficient heat dissipation [45]. A property requisites for PCM selection in PV thermal application and the important properties of the PCMs mostly used in PV systems is summarized in Table 3 and Table 4.

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Table 3. Property requisites for PCM selection in PV thermal application [46-47].

Properties	Requisite	Argument
Thermal	High latent heat	Maximum heat absorption
	High heat capacity	Minimum sensible heating
	High thermal conductivity	Efficient heat removal
	Reversible phase change	Diurnal response
	Fixed melting point	
	Phase change temperature in desired range	Consistent behavior Confirm phase transition
Kinetic	High nucleation rate	To avoid supercooling
	No super cooling	Easy to freeze
	High crystal growth rate	Faster solidification and to meet demands of heat recovery
Physical	Favorable phase equilibrium	Stable thermal storage
	Small volume change on phase transition	Avoid overdesign
	High density	To ensure low containment
	High specific heat	
Chemical	Chemical stability	Minimum thermal gradient Non-corrosive Long container life
	Long PCM life cycle	
	Congruent melting	
	Non-flammable and non-explosive	To ensure safety

Table 4. The important properties of the PCMs mostly used in PV systems [47-53].

PCM (Organic/Inorganic) [Ref.]	Density (kg/m^3 or kg/L or kg/dm^3)	Melting temperature (C)	Latent Heat of Fusion (kJ/kg)	Thermal conductivity (W/m K)
Rubitherm RT20 (organic) [47]	0.88 kg/L (solid) 0.77 kg/L (liquid)	21.23 (onset) 25.73 (peak)	140.3	0.2
Rubitherm RT21 (organic) [48]	840 kg/m^3 (solid) 760 kg/m^3 (liquid)	21	134	0.2
Rubitherm RT25 (organic) [49]	785 kg/m^3 (solid) 749 kg/m^3 (liquid)	26.6	232	0.19 (solid) 0.18 (liquid)
Rubitherm RT27 (organic) [50]	880 kg/m^3 (solid) 750 kg/m^3 (liquid)	26–28	184 (179)	0.2
Rubitherm RT31 (organic) [51]	840 kg/m^3 (solid) 750 kg/m^3 (liquid)	29	169	0.2
Rubitherm RT35 (organic) [52]	880 kg/m^3 (solid) 760 kg/m^3 (liquid)	35	157	0.2 (solid& liquid)
Rubitherm RT44 (organic) [53]	780 kg/m^3 (solid) 760 kg/m^3 (liquid)	41–45	255	0.2

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3. Research Gap

1. The enhancement in the performance of photovoltaic and concentrated photovoltaic systems by using phase change materials and Nano-enhanced phase change materials are difficult challenges that need to be addressed.
2. Reducing the cell's temperature by using Nano-Phase change material but among the problems of this material are its high cost and the problem of uniform distribution of Nano particles into the PCM is a difficult challenge therefore, more studies are needed in the future.
3. The photovoltaic-Nano-phase change material with a hybrid optimization system is very rarely developed.
4. Silicon is the best semiconductor material used in the manufacture of photovoltaic cells. But the search continues to find another material better than silicon that does not suffer from a lack of voltage when its temperature rises.
5. Around 12% higher electrical power is experimentally achieved by phase change material.
6. The exergy efficiency of the PVT unit by using phase change material is improved only up to 15% at noon.
7. Nanofluid-PCM PVT system showed 9% higher overall efficiency than the water-PCM PVT system.
8. Recent research focused on implementing phase change materials (PCMs) to solve the overheating issue in solar systems, via pure PCM, composite PCM, finned PCM, and hybrid PCM systems.
9. To limit and manage the temperature of photovoltaic panels, the scientific community has devised a variety of novel solutions; one of them is passive cooling with phase change materials (PCM).
10. Renewable energies still face some challenges related to their usage criteria since they are highly dependent on the location where they are employed, on the weather conditions, and always need enhancements and technological improvements. To maintain the continuity of benefiting from renewables, continuous research studies for their improvements are required.
11. To be able to control the temperatures of solar PV modules and optimize their performance output, research and development (R&D) of cooling techniques for solar PV modules are increasingly gaining attention.
12. From the available literature, several studies have been conducted on the performance improvement of solar PV modules in terms of their efficiencies and power output, with different cooling techniques. However, not much is known on the optimization of energy performance and the levelized cost of energy (LCOE) of solar PV modules integrated with different nano-phase change material.
13. PCM cooling is considered one of the successful future methods in photovoltaic cooling, but due to the low thermal conductivity of the PCM, this method gives a low enhancement. The thermal conductivity of the PCM should be improved by adding another component to improve the cooling performance.
14. Adding the nanoparticles to the PCM is an innovative way to improve the performance of the PCM better than adding the fans and gives better results, but due to the high price of the nanoparticles, this method is considered uneconomic

4. Discussion

The findings suggest that the number of research publications on photovoltaic (PV) cooling combined with energy storage systems such nano-enhanced photovoltaic (PCM) and photovoltaic (PCM) has continued to increase. This is based on the patterns that have been seen in publishing. There has been a significant increase in the number of articles that have been published in recent years, notably after the year 2016. When it comes to passive cooling in solar systems, the utilization of polycrystalline molybdenum (PCM) and nanoenhanced PCM energy storage materials has been demonstrated to have the highest number of articles.

5. Conclusion

The photovoltaic (PV) system is the most promising renewable source when it comes to meeting the need for electricity rather than using fossil fuels. There are various restrictions associated with photovoltaic (PV) systems, which might be solved by utilizing a cooling system to make use of the extra waste thermal energy that is generated by the PV surface. This paper examines the current and future trends in the cooling of photovoltaic (PV) systems through the utilization of energy storage materials such as polycrystalline methanol (PCM) and nano enhanced PCM. PCM shows promise as an effective cooling solution for PV modules; however, each type of PCM has its own strengths and weaknesses. Common issues include liquid leakage and low thermal conductivity. While PCM offers potential, it is not the most economical or preferred cooling solution. Selecting the appropriate type of PCM remains a significant challenge. Therefore, further research is necessary to optimize PV cooling with PCM, aiming to achieve maximum efficiency at a more economical cost.

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