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Review article

A holistic and state-of-the-art review of nanotechnology in solar cells

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A B S T R A C T

New renewable energy technologies in different designs and forms are emerging every day as a result of the global awareness about the necessity of green transition and strict milestones set for 2050. Among all of the emerging technologies in this area, solar direct electricity generating systems (i.e. photovoltaic [PV], and photovoltaic-thermal [PVT] setups) are more popular not only due to the nature of solar energy, which is abundantly yet limitlessly available worldwide but also due to the recent advances in this field, making solar cells more efficient and cost-effective. The efforts in this framework are still ongoing, and from a research perspective, the use of nanotechnologies for the enhanced performance of such solar systems in various configurations and a wide variety of methods is something probably addressed more than any other approach. This article aims to present a thorough review of research activities in using nanostructures, nano-enhanced materials, nanofluids, and so on for solar direct electricity generating systems including the cells, the panel packages, and the supplementary equipment such as heat storage systems. The article provides the readers a deep understanding of the fundamentals of nanotechnology and how its knowledge has been developed over the years, how it has been integrated into the solar PV and PVT concepts, and what the state-of-the-art nature of this integrity looks like. Finally, our conclusions from the literature review process about the challenges, opportunities, risks, and benefits are presented and some proposals for future research in this area are given.

Introduction

Opening

With worldwide industrialization, population increase, rising energy consumption, utilization and even the introduction of sustainable energy sources have been a top priority. Solar energy is inexhaustible, and when utilized effectively, it may efficiently solve energy challenges. A photovoltaic (PV) cell can absorb photons from solar energy and convert them into electrons. In the past decade, the global weighted average levelized cost of power generated by PV systems has decreased by 85 % [1]. It means that electricity production from PV systems is more cost effective than almost all conventional power production plants in rich solar energy potential areas [2]. Despite this impressive advancement in

techno-economic aspects, investigations show there is still a lot to explore for higher efficiency and better cost-effectiveness [3]. The following has recently become attractive to researchers: using nano-technology for solar PV systems in various ways, including nanoparticles in the PV cell [4], nanofluids for photovoltaic thermal (PVT) panels [5], and nano-enhanced phase change material (PCM) for PV or PVT setups [6].

Necessity of this article

The literature survey shows numerous review articles have been published on various topics of nanotechnology application in solar direct electricity generation over the last 5 years. For example, Mohammad et al. [7] summarized the influence of nanoparticles inclusion in PCM with application in solar systems, Kandeal et al. [8]

Nomenclature

PV	photovoltaic
PVT	photovoltaic-thermal
AFM	Atomic Force Microscope
CNFs	carbon nanofibers
CQDs	Carbon quantum dots
QDs	quantum dots
DSSCs	dye-sensitized solar cells
OSCs	Organic solar cells
PCE	power conversion efficiency
da	designated illumination area
ETL	electron-transporting layer
COP	coefficient of performance
E	energy absorbed from solar cell
α	absorptivity of solar module
W	width of solar cell
r_{ref}	power temperature-coefficient
η_{ref}	efficiency under reference
T_{ref}	characteristic temperature
τ_{PV}	transmittance
η_{PVT}	thermal efficiency of PVT system
$\dot{m}$	mass flow rate
T_0	outlet temperature
η_e	electrical efficiency of PVT
V_m	voltage operating at maximum power
IL	ionic liquid

GNP	graphene nanoplatelets
PCM	phase change material
STM	Scanning Tunneling Microscope
CNTs	carbon nanotubes
GQDs	Graphene quantum dots
SWCNTs	single-walled carbon nanotubes
TMDs	transition-metal dichalcogenides
PSCs	perovskite solar cells
IR	infrared
ap	aperture area
ITO	indium tin oxide
MWCNT	multi-walled carbon nanotubes
GNP	graphene nanoplatelets
τ_a	transmissivity of glass
p	packing factor
dx	elemental length
η_T	efficiency of solar cell
β_{ref}	efficiency temperature-coefficient
P	output PV power
G	solar radiation
A	radiation area
C_P	specific heat
T_i	inlet temperature
I_m	current operating at maximum power
EG50	ethylene glycol-50 % water
AHP	analytical hierarchy process

explored the techniques used in the cooling of PV panels, Amudhalapalli et al. [9] discussed nano-enhanced PCMs synthesis and characterization where these materials could be used in PV/T systems and other solar thermal equipment, Ahmed et al. [10] reviewed the application of metal oxide nanofluids in PVT systems, and Kumar et al. [11] presented a review on the exergy analysis of various solar energy systems including solar collectors and PV/T systems. Having said this, one could see that the literature is critically missing a review paper based on a more holistic approach covering the contribution of nanotechnology to PV & PVT cells, as well as other supplementary facilities of solar direct power generation units. After learning about this gap, this review article is presented to tackle this shortcoming. The article provides a strong

Fig. 1. The co-occurrence map of keywords analysis via VOSviewer.

knowledge basis to anyone who aims to educate thermselves about the state-of-the-art, future perspectives, and additional research possibilities of nanotechnologies for solar direct current power systems in various ways.

Paper structure and statistics

To prepare this article, out of thousands with relevant keywords, 98 research papers, 42 review articles, and four books/chapters were selected, most of which were published in the last 6 years. The VOS-viewer was used to analyze the publications in terms of the frequency of using the keywords (Fig. 1). The type of analysis was chosen to be a co-occurrence. The minimum number of keyword occurrences is 10; among 6389 keywords, 312 met the threshold. As can be seen, keywords such as solar energy, PCMs, energy efficiency, and PV cells appeared more often, which means more publications have focused on this.

This article is organized into seven sections. After the introduction, which aims at providing a clear response to why this article should be done and what its added value to the literature is, section 2 will provide the required basis of nanotechnology and its development history and applications. In section 3, the performance principles of solar cells and their various possible designs are comprehensively discussed. Sections 4 and 5 are indeed the heart of this review article. Section 4 is mainly about nanoparticles introduced into the different layers of PV panels to improve the efficiency of the solar cells. Section 5 is dedicated to discussing several ways to improve PV panel performance using nanoparticles. Section 6 reports the methods that can be used to prepare nanofluids and nano-PCMs. Finally, section 7 presents the main conclusions of the review, and future possible works.

Nanotechnology

The development history of nanotechnology

The first to propose the concept of nanotechnology was Nobel Prize winner and physicist Richard P. Feynman [12]. Norio Taniguchi suggested the term "Nanotechnology" in 1974 to define semiconductor processes occurring on a nanoscale [13]. Taniguchi defined nanotechnology as "something that mainly consists of processing separation, consolidation, and deformation of materials by one atom or one molecule [13]." The rapid development of nanotechnology occurred in the late 1980 s and early 1990 s when the scanning tunneling microscope (STM) and atomic force microscope (AFM) were invented.

Before the 2000 s, the research hotspots were the preparation of nanomaterials and achieving controlled nanostructures growth. During this period, various kinds of nanostructures were fabricated, including solid-state compounds, cylindrical and uniform diameter nanoporous membranes, highly ordered two-dimensional (2D) nanoarrays, carbon nanotubes (CNTs), and carbon nanofibers (CNFs) [14–16]. Various technologies have been used for preparing composite nanostructures [17], for example, the two-step template process sol–gel method was used to fabricate nanowires [18]. The controlling deposition of the nanostructures was realized through the solid-state reaction [19,20]. A considerable effort was also made to realize the commercial applications of nanostructure-based devices. After comparing, Boroditsky et al. [21] found that InGaAs and GaN are the most suitable materials for light-emitting diodes; Yang et al. [22] combined various CNFs and CNTs within the polystyrene matrix to improve the electromagnetic interference shielding characteristic, which approached the target value for commercial applications.

Over the last 2 decades, researchers have focused on the fabrication of 3D hybrid nanostructures [23,24]. Nanostructure materials have been very widely used in many fields, such as the anode materials in lithium and sodium-ion batteries [25,26]. They can also be used to improve the efficiency of solar cells or gas sensors [27,28]. The most important part is that highly ordered ultralong nanowire arrays up to 20 cm long and 50 nm in diameter can be used in flexible electronics, photonic applications, biochemical sensors, and solar cells [29]. When it comes to nanostructures, the WO$_3$ films can improve the efficiency of solar water splitting [30]. In 2020, Mariappan et al. [31] used 3D Ni core for energy storage [31].

The structures of nanomaterials

Generally, nanostructures can be defined as systems in which at least one dimension is no more than 100 nm. This can include 0D, which means the material is on a nanometer scale in all dimensions; 1D which means the material is on a nanometer scale in two dimensions; 2D, which is one dimension on a nanometer scale; and 3D which means the material is out of nanoscale in any dimension. Besides these, there is another class of nanostructures called 3D-like nanostructures that can be formed through the assembly of 0D,1D, and 2D nanostructures [32–36]. In principle, there are two methods of nanotechnology: a "bottom-up" strategy and a "top-down" strategy. The "bottom-up" approach creates nanodevices out of atomic or molecule components. Using an electron beam, extreme ultraviolet, or X-ray lithography, the "top-down" technique aims to directly build nanodevices on silicon or other semiconductor chips.

Considering the inherent structural properties of 0D nanomaterials, such as the surface-to-volume ratio and the ultra-small sizes, the edge and quantum confinement effects are further enhanced [37]. Up to now, different kinds of 0D nanomaterials have been proposed. Graphene quantum dots (GQDs) are carbon-based nanoscale particles with exceptional physical, chemical, and biological properties, especially photoluminescence properties, allowing them to shine in a variety of biological applications [38]. Carbon quantum dots (CQDs) were first reported in 2004 by Xu et al. [39] when they were purifying single-walled carbon nanotubes (SWCNTs) from arc-discharged soot and unintentionally discovered fluorescent CQDs. Because of the extraordinary light emission properties, CQDs have excellent properties such as wide tunability, bright luminescence, single-photon emission, biocompatibility, low toxicity, chemical inertness, and ease of biomolecule functionalization, which can be used in bioimaging, drug delivery [40,41], and so on. The CQDs are also widely used in lasing, PVs, and sensing [42–44]. Research on fullerene first began in 1985 [45]. Fullerene is composed of 60 carbon atoms, including 12 pentagons and 20 hexagons, which can also be marked as C$_{60}$ [46]. Fullerene can be used in PVs, biomedicine, and catalysis [47–52]. The other 0D nanoparticles include noble metal nanoparticles, upconversion nanoparticles, polymer dots, and quantum dots (QDs) [53–56].

Solar cells

Fundamentals

Solar PV energy conversion is a process that converts light into electrical energy [57]. The light composed of photons irradiates on the surface of the semiconductor; when the frequency reaches a specific value, the electrons escape entirely from the semiconductor surface. The semiconductor can be divided into p-type and *n*-type. A p-n junction is formed at the interface of the two semiconductor types. When the photoelectric effect occurs, it will generate electron-hole pairs. The PV influence, which means the trapping, generation, recombination, and transport of electron holes throughout the semiconductor material and within the contact electrodes, is central to solar cell physics [58]. The total energy absorbed at the solar cell top surface is as follows:

$$E = \tau_g \alpha p G W dx \tag{1}$$

where τ_g is the glass transmissivity, G is the solar radiation, α is the solar module absorptivity, p is the solar module packing factor, W is the solar cell width, and dx is the elemental length [59]. The solar cell

temperature-related efficiency is as follows:

$$\eta_T = \eta_{ref}\left[1 - \beta_{ref}\left(T - T_{ref}\right)\right] \tag{2}$$

where η_{ref} is the efficiency under the reference temperature that can be marked as 12 %, β_{ref} is the efficiency temperature-coefficient which is 0.45 %/K, and T_{ref} is the characteristic temperature which is 25°C.

The output PV power could be

$$P = G\tau_{PV}\eta_{ref}A[1 - r_{ref}(T - T_{ref})] \tag{3}$$

where τ_{PV} is the outside layers transmittance in the PV cell, A is the radiation area, and r_{ref} is the power temperature-coefficient [60].

The solar cell can be regarded as a two-terminal device that creates photovoltage during the daytime when charged by the sun and that conducts like a diode at night without the sun. The cells are connected in a series and encapsulated into modules to produce enough DC voltages. A photovoltage power generation system contains several components, such as cells, mechanical and electrical connections, mountings, and ways of monitoring and modifying the electrical output [61]. Three main factors should be considered when the solar cell can be commercially used, cost, efficiency, and operating lifetime [62]. The most effective way to improve solar cells' efficiency is to reduce area-related costs. These include module materials and system costs, such as the cell fabrication semiconductor, cell interconnection, packaging material, transport, support structures, cabling, and module mounting [63].

Solar cell generations

Three types of solar cell generations have been developed so far. The first generation is composed of crystalline Si solar cells, the second is composed of thin-film solar cells such as CdTe, CIGS, and AsGa, and the third is composed of emerging solar cells such as dye-sensitized solar cells (DSSCs), perovskite solar cells (PSCs), and polymer solar cells [64]. Crystalline silicon-based solar cells are the leaders in the world PV market by up to 90 %. This is due to their appropriate bandgap, nontoxic nature, material abundance, and complete technology master. The single-junction solar cell can reach the highest efficiency when the energy gap is 1.35–1.5 eV [65]. Shockley and Queisser calculated that a single solar cell's most outstanding theoretical efficiency is 33 % [66]. Due to surface recombination, lattice defects, incomplete incident light absorption, and nonideal contacts, the commercial solar cells' efficiencies are below the theoretical levels [67]. After seven decades, crystalline silicon's power efficiency reached 26.7 %. The second-generation thin-film solar cells' advantages, disadvantages, and methods of improvement are summarized in Table 1.

The third-generation solar cells are based on PSCs, DSSC, organic solar cells (OSCs), and hybrid multiple-junction solar cells [75]. The PSCs with a maximum efficiency of above 25 % have emerged as promising next-generation PV devices. Because of their simple structure and low cost, DSSC can be a possible replacement for silicon solar cells. However, the efficiency is limited by their inability to use light in the infrared. The first reported DSSC efficiency was 7.1 % [76]. Now, the research hotspots include how to improve their efficiency and make them environmentally friendly, nontoxic, and long-lasting green. Their efficiency is now up to 11.9 % [77,78]. OSCs have various advantages, including simple structure, the ability to be produced for large-area applications, low-cost solution-processing, and the ability to be used in flexible electronics and semitransparent devices [79]. The recently announced power conversion efficiency (PCE) has reached 15.2 %, although it can present harmful halogenated solvents, sensitivity to the thickness of PV layers, and stability issues [80].

One way to enhance the efficiency of solar cells is to make two or multi-junction cells with different absorber layers. In theory, infinite junctions can reach 68 % [81]. So far, the latest literature has reported the highest efficiency of 47.1 % (six multi-junctions) [82]. Table 2 represents a summary of several third-generation solar cells' efficiencies, advantages, disadvantages, and so on.

Nanomaterials for solar panels

Perovskite-based solar cells

Perovskite solar cells were rapidly developed since their first proposition in 2009 [83], and the PSCs could efficiently sensitize TiO_2 to improve the energy conversion efficiency by 3.8 %. Since then, different groups have made numerous efforts to improve efficiency. The perovskite structure is ABX_3, where A represents inorganic cations such as cesium (Cs +) and organic cations such as $CH_3NH_3^+$, $C_2H_5NH_3^+$ and HC $(NH_2)_2^+$, B stands for metal cations such as Ge^{2+}, Pb^{2+}, and Sn^{2+}, X stands for halide anions such as I^-, Cl^-, and Br^-.

Three main factors could affect PSCs' business application prospects: PCE, cost, and stability. For the PCE part, the most effective method is PSCs-based tandem solar cells, because, in theory, the photons can be absorbed only if their energy is higher than the semiconductor material bandgap. The excess energy will be released as thermalization. To enhance PCE solar cells above the Shockley-Quiesser limit, various absorbers with complementary bandgaps can be combined in a multi-junction or integrated solar cell to maximize sunlight use while reducing thermalization loss [84,85]. The PSC's efficiency is mainly dependent on their architecture, which indicates the materials used, and methods for depositing the material. The PSCs have two significant

Table 1
The single-junction terrestrial cells' efficiency and submodules at 25 °C [68].

Classification	Efficiency (%)	Area¹ (cm²)	Advantage	Disadvantage	Improvement
CIGS (cell) (Cd-free)	23.35 ± 0.5	1.043 (da)	Adjustable bandgap, low-cost, high open-circuit voltage	Uniformity over large areas, standardizing fabrication process, long processing time, toxic, indium scarcity	Barrier layer between the bilayer structure back contact [69]
CIGSSe (submodule)	19.6 ± 0.5	670.6 (ap)	High efficiency, potential applications for flexible and lightweight solar panels	High-cost	Employing solution-processed technique [70].
CdTe (cell)	21.0 ± 0.4	1.062 (ap)	Low-costs, recyclable, high scalability	The toxic, open-circuit voltage needs improvement	Grain boundaries passivation, back-contact quality, stability, doping [71].
CZTSSe(cell)	11.3 ± 0.3	1.176 (da)	Cheap in large scale, Non-toxic, earth-abundant,	Low photon conversion , voltage deficit of ~0.62 V	Layer materials development , novel growth techniques [72]
CZTS (cell)	10.0 ± 0.2	1.113 (da)	Non-toxic, earth-abundant, cost-effective	Structure related properties, low open circuit	Doping, adjust bandgap [73].
GaAs (thin-film cells)	29.1 ± 0.6	0.998 (ap)	Highest efficiency, low-temperature coefficient, minimal external conditions effect	High-cost	Reusing the GaAs substrate[74].

¹ (ap) = aperture area, (da) = designated illumination area

Table 2
The third-generation solar cells' efficiencies at 25°C [68].

Cell class	Efficiency (%)	Area (cm^2)	Advantage	Disadvantage	Improvement
Perovskite	22.6 ± 0.6	1.019 (da)	low cost, tunable bandgap, high absorption coefficient, carrier mobility	instability	employing novel materials, improving the design
Dye	11.9 ± 0.4	1.005 (da)	simple structure, low-cost	low photon conversion	using different counter electrodes
organic	15.2 ± 0.2	1.015 (da)	simple structure, produced for large-area applications, low-cost solution-processing, flexible electronics, semitransparent devices	harmful halogenated solvents, sensitivity to material layers, unstable	all-polymer-based photoactive layer materials, self-doped strategy

forms mesoscopic and planar structures. Depending on the electric current direction, the planar structures can exist in either a conventional *n*-i-p or inverted p-i-n arrangement.

For more than ten years, efforts have been made to improve the PCE of PSCs. The latest report on PSCS efficiency is 25.2 % [86]. The cost of PSCs is complicated; it contains energy cost, energy payback time, and raw materials selection. One of the most effective methods is the low-temperature solution technique. PSCs' instability is caused by moisture, UV radiation, and temperature. Humidity is considered a complex challenge. There are some thoughts about what causes perovskite films to deteriorate, and the metal electrodes could have moisture-assisted interaction with perovskite, which can break the stability. The temperature increases during the synthesis process and an annealing treatment is used to form a perovskite structure; it was found that perovskite decomposes at high temperatures. This could be resolved by using thermally resistant materials. The TiO$_2$ layer is used as the PSCs' electron transport layer; when under the ultraviolet, the layer degrades. To reduce this, encapsulated devices with an ultraviolet filter could be used, or a novel and stable complex can be doped, which can extend the spectral absorption range to the ultraviolet region [87]. An effective way to reduce the moisture and Pb leakage is PSCs encapsulation.

Carbon nanotubes for solar cells

CNTs are ideal nanomaterials for carrier-selective transport and for collecting layers in solar cells because of their exceptional photonic, electrical, and mechanical capabilities, and they are abundant. Inside the solar cell, the transparent conducting layer is used as the top electrode, which is always indium tin oxide (ITO). The ITO advantage is its excellent transparency and conductivity. However, the substance includes indium, a rare metal. They have other disadvantages, such as short flexibility, more crystal defects, high cost, and instability (high temperatures). As a result, indium-free solar cells have become a primary research target for next-generation PV technologies [88]. Due to their unique nature, CNTs have emerged as attractive indium-free alternatives for use as transparent and conducting materials.

In 2005, researchers began to replace ITO for SWCNTs in OSCs. Compared to ITO-based devices, the PCE of SWCNTs-based solar cells is better. This is meaningful for the deposition technique; the SWCNTs are synthesized through the solution-processed, cheaper than vacuum-deposition of ITO [89]. Some factors can influence the SWCNTs' performance in the solar cell. The cell needs maximum transparency and conductivity, but usually, the reduced conductivity of SWCNTs-electrodes is proportional to their transparency. The best way to solve this is to choose suitable dopants [90,91].

Research on CNTs in solar cells has been focused on PSCs due to their flexibility. An electron-transporting layer (ETL) plays a vital role in improving the PCE. Until now, in n–i–p structured PSCs, TiO$_2$ and SnO$_2$ are the most preferred ETLs, but they have low electron mobility. The most practical approach to solve this issue is incorporating carbon-based nanoparticles; it was reported that a small amount of CNTs doped into TiO$_2$ ETL will improve the PCE. However, the doping concentration needs to be precisely controlled; if excess CNTs is introduced, the device's performance will be decreased [92]. CNTs can be used in the perovskite layer. During the deposition process, the perovskite crystallization always has many grain boundaries with several defects and charge traps. If doped with appropriate functionalization of CNTs, the film morphology is optimized.

Summary of findings

The most promising nanomaterial for a solar cell is perovskite and CNTs. Three main factors block PSCs' commercial application: PCE, cost, and stability. CNTs can be used as transparent and conducting materials instead of ITO. The best way to improve PCE and PSC stability is using CNTs as interlayers and back electrodes in PSCs. CNTs have proven to be reliable replacements for traditional noble metal electrodes for achieving highly efficient and stable PSCs.

Nanotechnologies for PVT systems

One recent innovation in direct solar power generation, beyond PV systems, is taking advantage of the increased temperature of PV cells under the solar rays to generate low-grade heat. This has two positive impacts. First, the temperature rise in solar cells causes a reduction in their efficiency and damage to the cells [93], and in this way, the panel's temperature is reduced by withdrawing its heat and thereby increasing its efficiency. Second, a certain amount of thermal energy can be generated for heating applications, such as space heating, domestic hot water, heat source for heat pumps, and so on. Interestingly, quantitatively, the generated heat by such panels (so-called PVT panels) is far larger than their electric energy output [94]. Fig. 2 shows a schematic of a PVT panel and its components.

The application of nanoparticles in the systems can help to improve the overall optical properties, thus increasing the spectrum of solar radiation that can be absorbed by the system [96]. Beyond such efforts for increasing the solar cells' efficiency and other physical features by nanotechnology measures, a significant portion of research works in this field have recently focused on enhancing the PVT systems' efficiency by nano techniques. For this, the majority of efforts include either using nanofluids for better heat collection throughout the collectors or using nano-enhanced PCMs for more efficient heat storage or stability in the panel's temperature. PVT systems' thermal efficiency could be as following:

$$\eta_{PVT} = \frac{\dot{m} C_P (T_0 - T_i)}{AG} \tag{4}$$

where η_{PVT} is the PVT system thermal efficiency, $\dot{m}$ is the mass flow rate, C_P is the specific heat, T_0 is the collector outlet temperature, T_i is the inlet temperature, A is the collector area, G is the beam irradiation. PVT system's electrical efficiency is:

$$\eta_e = \frac{I_m V_m}{AG} \tag{5}$$

where I_m and V_m are the current and the voltage operating at maximum power [97].
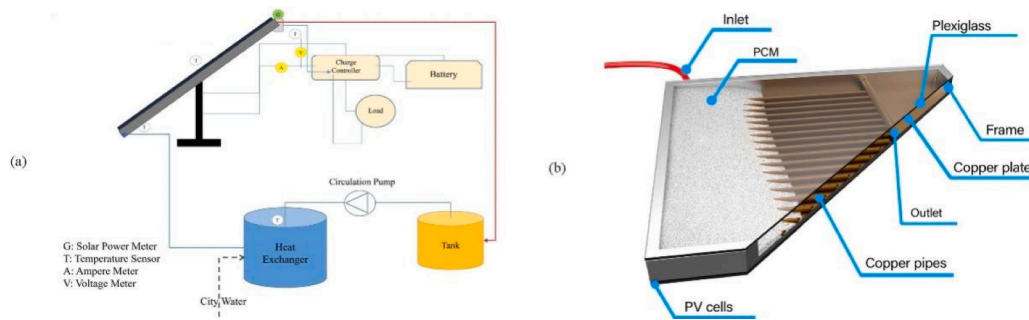
Fig. 2. PVT panel schematic and its main components [95] (Reprinted with permission from Elsevier).

Nanofluids

Characteristics and classification

Nanofluids are composed of a regular fluid mixed (e.g. water, thermal fluid) with colloid nanomaterials that have a minimum and maximum size of 1 nm and 100 nm, respectively [98,99]. The nanoparticles' mixture into the fluid changes the general properties (thermal conductivity, viscosity, and specific heat), and increases the thermal properties and thereby reducing the required heat transfer area throughout the panel's back. They can also present high solar radiation absorption and have a small size and large surface area that help in the absorption of solar energy [96,100]. However, nano-powders for nanofluids can also present thermal instability (suspensions or agglomeration)chemical compatibility issues with other elements, difficulties in the manufacturing process, and high cost (material and preparation) [101]. The nanofluids can be classified based on three categories: types of nanomaterial, nanomaterial composition, and the base fluid type [102]. Based on the nanomaterial and its composition most used for thermal applications, the nanofluids can be classified into mono-nanofluids (pure metal, metal oxide, carbide, nitride, and carbon) or hybrid nanofluids (nanomaterial mixture and nanocomposite). The mono-nanofluids have been diversely investigated in the thermal process. Table 3 summarizes the nanofluids' characteristics.

For the nanomaterial mixture (CNTs and Au, CNTs and Cu), there is a simple mixture between the nanoparticles and base fluid. On the other hand, for the nanocomposite (Graphene-Multi-walled CNTs MWCNT, Al_2O_3-Cu), there is a combination of two or more nanoparticles in the nanoscale [102]. Table 4 presents a properties summary of nanoparticles and fluids used as the base fluid in PVT systems.

Applications

A regular PVT configuration includes a glass over the PV cells, a conductive plate under the PV cells, a thermal collector serpentine under the plate, and insulation under the thermal collector. An experimental indoor investigation in a PVT system was made by applying a magnetic during the use of Fe_3O_4-water with concentrations of 1 % and 3 % [116]. Four system configurations were compared, and it turns out the 3 % concentration with no magnetic field presented an efficiency increase of 24 % and the case alternating the magnetic field with 50 Hz frequency presented an efficiency increase of 27.6 % when compared to the case with just water as the cooling medium [116].

A comparison between different nanoparticles (Al_2O_3 and Cu), in distinct base fluids (water and EG) with different concentrations (0.1/0.2/0.4 wt%) for a PVT system, was conducted in [117]. The tests indicate a higher performance of PVT for cases using water (base fluid), Cu (nanoparticle), and 0.4 wt% concentration. The increase of nanoparticle concentration generates a slight decrease of the nanofluid specify heat. Using Cu-water with 0.4 wt%, a maximum thermal efficiency of 76.8 % and electrical efficiency of 13.7 % were found. The case using Al_2O_3-water with 0.4 wt% reached a maximum thermal efficiency of 46.7 %, reporting an increase of 2.7 % in the thermal efficiency

Table 3
Mononanofluids characteristics summary [102,103].

Type/Base	Advantages	Disadvantages	Examples-Base fluid
Pure metal	Easy to manipulate and achieve the particle size; Can be developed using "green" synthesis method; High thermal properties;	Using high particle concentrations can present a reduction in performance; Noble metal costs;	Au- Water, thermal fluid; Ag- Water, ethanol; Cu- Water, kerosene; Fe- Water, EG;
Metal oxide	Less likely to occur atmospheric oxidation; Lower density than pure metal; Better stability;	Lower thermal conductivity than pure metal;	Al_2O_3-Water; CuO- EG, water; TiO$_2$- Water; ZnO- Alcohol, EG, water;
Carbide	Environmentally friendly; Chemically stable; Provide high surface area;	Few materials have higher thermal conductivity; SiC presented small settling of particles; Requires less pump power than metal-oxide	SiC- Water; ZiC- Water;
Nitride	Hexagonal 1D possesses a good conductor of heat;		BN-Water;
Carbon	Low weight; High conductivity,solar absorption, availability;	Cost;	Graphene- Water, EG; Graphite- EG, water; Carbon black- Water, thermal oil; Nanodiamond- Water, EG.

compared with the use of just water [117]. Al-Waeli et al. [113] made an experimental investigation in PVT using SiC-ionized water as a nanofluid in different concentrations (0, 1, 1.5, 2, 3, 4 wt%). During the nanofluids preparation, it was reported that the increase of 3 wt% SiC, increased the nanofluid density by 8.2 %, viscosity by 5.18 %, and thermal conductivity by 4.3 %. After 6 months of continuous examination, the nanofluid was still stable, reducing the thermal conductivity by only 0.003 W/mK. Using 3 wt% as the concentration, the maximum increase in the electrical efficiency of 24 % was obtained when compared to PVT using only water.

PVT can have different arrangements concerning the coupling between the PV cells and the thermal system. The type of arrangement can also influence its performance. Hussain et al. [118] investigated numerically the PVT system with two heat exchangers using different fluids in each one of them. The system has a parallel serpentine heat exchanger and a single-pass air heater that are independent of each other. It also has a series of baffles responsible for reducing thermal resistance. The simulations were made for different nanoparticles (CuO,

Table 4
Nanoparticles and base fluid properties for nanofluid applications in PVT systems (25–35 °C).

Substance	Thermal conductivity (W/m.K)	Thermal capacity (J/kgK)	Density (kg/m^3)	Diameter (nm)	Viscosity (Ns/m^2)	Reference
Soybean oil	0.154–0.1873	1974	920	–	0.0409	[104,105]
Pure water	0.613	4179	997.1	–	0.001003	[106]
Ethylene glycol (EG)	0.258	2470.2	1113.2	–	0.0161	[106]
50 %EG + 50 %water (EG50)	0.4140	3488	1051	–	0.0028	[95]
Sunflower oil	0.161	2153	916.7	–	0.04167	[104]
Cu	401	385	8933	–	–	[106]
Ag	429	235	10,500	–	–	[106]
Fe	80	–	–	–	–	[103]
Al	273	–	–	–	–	[103]
Al$_2$O$_3$	40	765	3912	35–55	–	[107,108]
CuO	76.5		6320	33	–	[109]
TiO$_2$	9.2	686.2	4250	35–50	–	[106,110]
ZnO	23.4	514	5606	35–45	–	[111]
SiO$_2$	1.4	745	2220	40	–	[112]
SiC	370–490		3220	45–65	–	[113]
MXene (Ti$_3$C$_2$)	–	–	3700	Lateral:1–10 μm Thickness:1	–	[105]
C$_{60}$–C$_{70}$ (Fullerenes)	0.4		1600	10	–	[109]
MWCNT	3000		2100	45–50	–	[110]
CNT	3000	796	2100	30	–	[114]
Carbon nanofiber	13	–	–	–	–	[103]
Graphite	2000				–	[115]
Nanodiamond	~900	–	3500	–	–	[115]
Graphene	1000–1400	–	–	16–52	–	[115]

Al$_2$O$_3$, and SiO$_2$), with different concentrations and using water as a based fluid. Results indicated that the best concentration is 0.75 %; too-high concentrations generate aggregation nanoparticles. The CuO presented the best thermal stability and highest thermal conductivity for the nanofluid. The overall maximum efficiency of the case with CuO-water (0.75 wt%) and air system was 90.3 %, whereas it was 79.8 % for the case with water and air. The authors accentuated that even with higher costs related to pumping both systems, the gains from decreasing the PV cells' temperature are bigger concerning the system efficiency [118].

Tests in PVT systems were made using a nanofluid composed of a base fluid mixture made of ionic liquid (IL) and water and two-dimensional MXene (Ti$_3$C$_2$) nanoparticles in several concentration ratios (0.05/0.1/0.2 wt%) [119]. The optimum concentration of 0.2 wt% was found using the thermal physical properties as parameters. The tests related to the thermal stability showed that of all concentrations the samples were stable at up to 45 °C. The results showed a maximum electrical efficiency achieved 14 % and a maximum thermal efficiency achieved 81.2 % [119]. Rubbi et al. [105] studied the PVT system performance by applying soybean oil as a base fluid and MXene nanoparticles in three concentration ratios 0.025, 0.075, and 0.125 wt%. Tests related to the thermal stability showed that for the range of 30–80 °C, there were no significant changes for all concentration levels. The use of soybean oil with 0.125 % of MXene reached 84.3 % overall thermal efficiency, with a surface temperature dropping by 14 °C compared with water. The MXene-soybean oil nanofluid also presented a superior performance to MXene-palm oil and Alumina-water nanofluids.

Different nanofluids, such as water-based MWCNT, Al$_2$O$_3$, and TiO$_2$, with a concentration of 0.3 wt% were experimentally investigated for the PVT system. Using nanofluids, the PV cells' temperature was reduced by 48 %, 37 %, and 36 %, respectively for the system with MWCNT, Al$_2$O$_3$, and TiO$_2$ water-based nanofluids. Maximum electrical efficiencies of 18 %, 17.8 %, 16 %, and 9.5 % for MWCNT-water, Al$_2$O$_3$-water, TiO$_2$-water, and pure water units were achieved, respectively. The highest overall efficiency was about 47 %, 33 %, and 27 % with systems using MWCNT, Al$_2$O$_3$, and TiO$_2$ water-based nanofluids [110]. Sohani et al. [120] made a selection of the best nanofluid type based on efficiency, energy gain, reliability, economic, and environmental criteria using an analytical hierarchy process (AHP) for the PVT system.

It evaluated the nanofluids using Al$_2$O$_3$, TiO$_2$, and ZnO in water with a concentration ratio of 0.2 wt%. In terms of annual energy delivered, electrical efficiency, thermal efficiency, reliability, and CO$_2$ emissions reduction the best one is the use of ZnO-water nanofluid. ZnO-water loses only in terms of the payback period for both of the other nanofluids. The score of the nanofluids using the AHP is 33.1 for ZnO-water, 26.0 for TiO$_2$-water, and 13.9 for Al$_2$O$_3$-water, concluding that the best ones are ZnO-water and TiO$_2$-water. The electrical and thermal efficiencies of ZnO-water and TiO$_2$-water are 14.7 %-47.6 % and 14.6 %- 46 %, respectively.

Abdelrazik et al. [121] performed an investigation using Ag-water nanofluid (range of 0.0005–0.05 wt%) in a PVT system by means of an optical filtration channel. The nanofluid in this case flows through over the PV cells and is used as an optical filtration (see Fig. 3). Comparing the PV unit and the PVT system with optical filtration, the PV system showed a higher electrical efficiency, for low/medium solar concentrations and climatic temperatures. On the other hand, the PV system presents low electrical efficiency for high solar concentrations and climatic temperatures. They recommended the use of PVT using Ag-water with optical filtration for applications where thermal and electrical energies are needed in high climatic temperatures and solar concentrations. For solar concentrations of 5 and and environmental temperature of 45 °C, the PVT using Ag-water with optical filtration reached 66.7 % and 8.4 % of thermal and electrical efficiencies, respectively.

Nanotechnology and PCMs in solar cells

PCM characteristics and classification.
A material absorbs or releases energy at a constant temperature along the physical phase change process. The amount of energy required to make this phase change in the material is usually quite significant compared to that required for changing the temperature in a certain phase. This phenomenon has been used for decades as an efficient way to store thermal energy, and the materials used to complete this process are known as PCMs, which can be categorized into three wide categories of organic (paraffin, and non-paraffin), inorganic (metallics, and salt hydrate), and eutectic (organic-organic, inorganic-inorganic, and inorganic–organic).
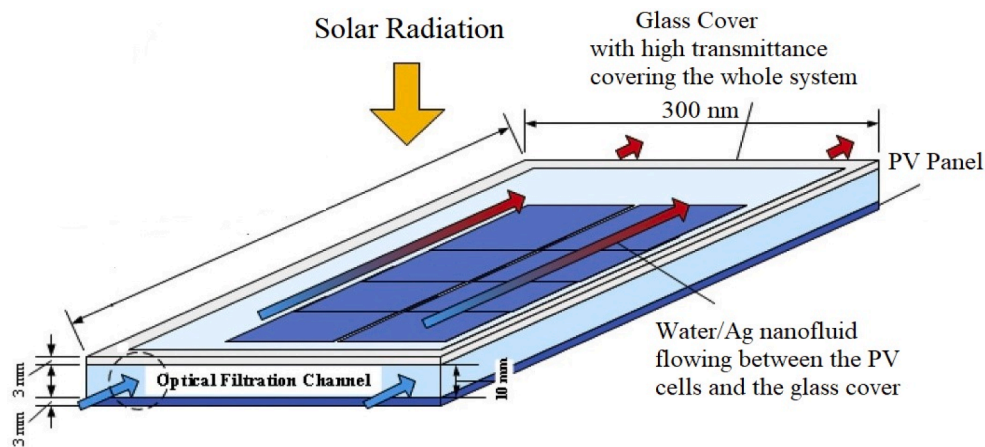Table 5 summarizes the advantages and disadvantages of each class

Fig. 3. PVT system with optical filtration channel [121] (Reprinted with permission from Elsevier).

Table 5
Summary of PCM characteristics [122,123].

PCM	Advantage	Disadvantage
Organic	Thermally and chemically stable (paraffin); Elevated latent heat (fusion); Suitable with metal (paraffin); Does not present supercooling (paraffin and fatty acids); It is not toxic and corrosive.	Could be toxic and unstable at high temperatures (nonparaffin); Flammable; Present low thermal conductivity and melting enthalpy; Can affect plastics (paraffin).
Inorganic	Not flammable; Present a high latent heat and thermal; conductivity (metallic); Cheap.	Salt hydrate: can present corrosion, phase separation, supercooling, and be thermally unstable. Metallic: It is heavy.
Eutectics	Large range of temperature of phase change; Thermally and chemically stable; Present an elevated heat capacity; Does not present supercooling.	Present low thermal conductivity; Can present problems during the phase change.

of PCMs. For cooling applications, all main groups presented good characteristics; however, paraffin was the most used PCM.

The coupling of the thermal system in the PV panel (PVT) is used to reduce the PV cells' temperature, which increases its efficiency. PCMs are used in the PVT to help the thermal system absorb the heat released by the PV cells. As the energy is absorbed by the PCM, the material melts at a constant temperature, which helps to not only reduce but also stabilize the PV cells' temperature [124]. The process duration and performance depend on the properties and amount of PCM and materials involved [124]. Table 6 presents several PCMs and their properties, which can be used in PVT applications.

Application of nanofluids for PCMs

Nanotechnology can be used in various ways to improve the thermophysical performance of PCMs. When nanoparticles are used in PCMs, the material is called nano-enhanced PCM. Before jumping into the literature on nano-enhanced PCMs, hereunder, some of the recent works on PVT systems equipped with PCMs and the use of nanofluids as the cooling medium are briefly reviewed. Generally, PCM is inserted under the solar cells, among the thermal collector tubes, and above the insulation. The use of PCM in PVT can enhance 8 % of the electrical efficiency, and 25 % of the thermal efficiency considering the same operations conditions, as Ref. [112] claimed. Hassan et al. [129] studied

experimentally the performance of a PVT system using PCM (RT-35HC) with graphene/water as a nanofluid. It was tested at several concentrations (0.05/0.1/0.15 %wt) and flow rates (20, 30, and 40 LPM). The concentration of 0.1 %wt presents the best electrical and thermal efficiency for all tested flow rates. The maximum overall, electrical and thermal efficiency, as well as the PV temperature reductions achieved were 61.6 %, 14 %, 42.2 %, and 29.3 °C, respectively (for 40LPM). A similar study performed an exergetic analysis for those same conditions [134]. The maximum overall, electrical and exergetic efficiency, achieved were 14.62 %, 13.02 %, and 1.68 %, respectively (for 0.1 %wt and 40LPM). Al-Musawi et al. [112] studied the use of SiO_2/water (1 and 3 % wt) as nanofluid and paraffin wax as PCM for PVT/PCM systems. The electrical and thermal efficiencies were 14.3 %, and 40 %, respectively (3 % wt). It also tested the effects of the PCM melting temperature (31, 34, and 54 °C) for the PVT/PCM system. An increase in the PCM melting temperature leads to a high increment in the thermal efficiency (30 %) and a small decline in the electrical (0.03 %) efficiency.

Naghdbishi et al. [95] compared the use of water, and 50 % ethylene glycol-50 % water (EG50), as the base fluid for the MWCNT nanoparticle (0.1 and 0.2 %wt) in a PVT system with PCM (paraffin wax). The best performance was found using 0.2 % MWCNT/water. For that case, the electrical and thermal efficiencies of the system were 16.1 % and 63.4 %, respectively. Using pure water in the PVT system with PCM presented a better performance than using MWCNT/EG50. Experiments were also made to understand the performance of the PVT/PCM system with ZnO/ water (0.2 %wt) nanofluid and paraffin wax PCM [111]. The average electrical output power (W/m^2) was 92.2 for the PV, 99.6 for the PVT, and 104.4 for the PVT/PCM, which represents an increase of 13.3 % in the electrical output power.

Rahmanian et al. [114] investigated a PVT/PCM system where the nanofluid flows all over aluminum packs of PCM. The used PCM was RT35-HC, the nanofluid was CNT/water (0.1 %vf), and the solar concentration was 5. Active (nanofluid speed of 0.05 m/s) and passive cooling were investigated. The authors concluded that for passive cooling, using a single pack can reduce the PV temperature by 18 °C, and increase the electrical and thermal efficiency by 12 % and 23 %, respectively.

Basalike et al. [132] studied a multilayer PVT refrigerator with PCM (n-octadecane and caprice-palmitic acid) and nanofluid (Al_3O_2-water 0.02 %). They analyzed the coefficient of performance (COP) and stored energy in the PCM. It was concluded that the use of paraffin generates a high COP in comparison with the use of caprice-palmitic acid. The best-obtained COP and energy storage capacities were 5 and 2.9 kJ, respectively.

PCM and nanofluid were investigated as spectral filters in a concentrated PVT/PCM system [127], as shown in Fig. 4. The system used RT25 and S27 as PCMs, Ag/water (0.05 %wt) as the nanofluid,

Table 6
PCM properties for PVT applications (melting temperature 20–58 °C).

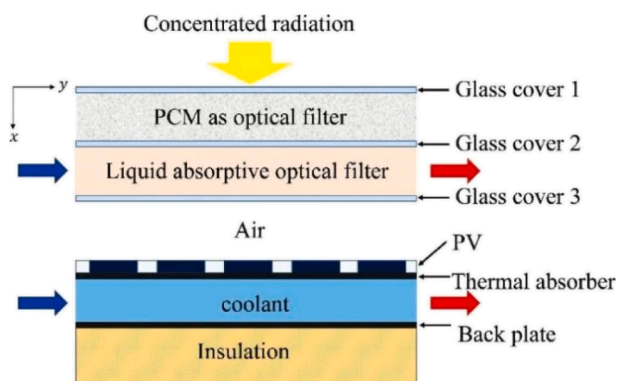| Material		Melting temperature (°C)	Latent heat fusion (kJ/kg)	Density (kg/m^3)	Specific heat (kJ/kg.K)	Thermal conductivity (W/m.K)	Reference
Organic- Paraffin	Paraffin C$_{16}$-C$_{18}$	20–22	152	–	–	–	[125]
	Paraffin C$_{13}$-C$_{24}$	22–24	189	900 solid 760 liquid	2.1	0.21 solid	[126]
	RT-25	25	147	804 solid 763 liquid	2.9 solid 2.11 liquid	0.19 solid 0.17 liquid	[127]
	n-Octadecane	28	244	814 solid 774 liquid	2.16	0.15 solid	[126]
	n-Nonadecane	32	222	–	–	–	[128]
	RT-35HC	35	240	804.55	5.0 solid 2.1 liquid	0.65 solid 0.166 liquid	[129,130]
	n-Eicosane	38	283	779	–	–	[122]
	Paraffin C$_{16}$-C$_{28}$	42–44	189	910 solid 765 liquid	2.1	0.21 solid	[126]
	Paraffin C$_{20}$-C$_{33}$	48–50	189	912 solid 769 liquid	2.1	0.21 solid	[126]
Organic -Fatty acids	Polyethylene glycol 600	20–25	146	–	–	–	[128]
	Capric acid	32	153	886 liquid 1004 solid	–	0.14 liquid	[122]
	Lauric acid	42–44	178	870 liquid 1007 solid	–	0.14 liquid	[122]
	Eladic acid	47	218	–	–	–	[128]
Inorganic-Salt hydrates	S27	27	190	1700 solid 1530 liquid	1.5 solid 2.22 liquid	0.79 solid 0.48 liquid	[127]
	CaCl$_2$·6H$_2$O	29–30	171–190	1562 liquid 1710 solid	–	0.54 liquid 1.088 solid	[122]
	LiNO$_3$·2H$_2$O	30	296	–	–	–	[122]
	Na$_2$SO$_4$·10H$_2$O	32	254	1485 solid	–	0.554	[122]
	KFe(SO$_4$)$_2$·12H$_2$O	33	173	–	–	–	[128]
	Na$_2$HPO$_4$·12H$_2$O	35–44	280	1442 liquid 1522 solid	–	0.47 liquid 0.514 solid	[122]
	Fe(NO$_3$)$_3$·9H$_2$O	47	155	–	–	–	[128]
	Na$_2$S$_2$O$_3$·5H$_2$O	48	201	1670 liquid 1730 solid	1.46 solid 2.39 liquid	–	[126]
	PT58	58	225	810 liquid 890 solid	2.71 liquid 2.47 solid	0.15 liquid 0.25 solid	[131]
Eutetics	C$_{14}$H$_{28}$O$_2$ 34 %+ C$_{10}$H$_{20}$O$_2$ 66 %	24	147.7	–	–	–	[128]
	caprice-palmitic acid	22.35	173	870 solid 790 liquid	2 solid 2.3 liquid	0.14 solid/ liquid	[132]
	coconut oil 82 % + sunflower oil 18 %	25–26	308	911	2.35 solid 2.38 liquid	0.2606	[133]
	Triethylolethane 62.5 % +urea 37.5 %	29.8	218	–	–	–	[128]
	Ca(NO)$_3$·4H$_2$O 47 %+ Mg (NO)$_3$·6H$_2$O 53 %	30	136	–	–	–	[128]

Fig. 4. PVT system using PCM and nanofluid optical filter [127] (Reprinted with permission from Elsevier).

water as the coolant, and a concentration ratio of 20. The best performance was observed using S27 due to its optical properties, and when the nanofluid was positioned on the PCM filter top. For this case, the electrical and thermal efficiencies were 21.5 % and 64.9 %, respectively.

Application of nano-enhanced PCMs

As mentioned in previous sections, PCM has great potential to help the performance of PVT systems, although most of them present a low thermal conductivity, which is not a good parameter for the heat transfer. To improve PCMs' thermal conductivity and other parameters, many research pieces have applied nanoparticles to PCMs (nano-enhanced PCMs or simply nano-PCMs).

Al-Waeli et al. [135] performed some experiments in the PVT/PCM system using nanofluid (SiC-water 3 %) and nano-enhanced PCM (SiC-paraffin 0.1 %). The nano-PCM obtained a thermal conductivity of 2.09 times higher than pure PCM. The experiments were made for a flow rate range of 0.083–0.175 kg/s, and an environment temperature range of 30–33 °C. The work compared the proposed system with the same PV modules but with a conventional design. The maximum electrical efficiency of PVT/PCM was 13.7 % and the PV in the same conditions was 7.1 %. The optimum concentration ratio for the nanofluid SiC-water and nano-PCM SiC-paraffin was also investigated in a range of 0–4 %, and the optimal ratio was 0.3% for the nanofluid and 0.1% for the nano-PCM [136]. It was applied to this optimized nanofluid as a coolant and nano-enhanced PCM as a heat sink into a PVT/PCM system was tested experimentally and modeled using an artificial neural network. The results showed that the electrical and thermal efficiencies reached 13.3

% (whereas it was only 8.1 % for the PV) and 72 %, respectively [136]. Al-Waeli et al. [137] also investigated the technical and economic aspects of this system using the same characteristics, considering a lifetime of 25 years and all effective parameters of the system. The results showed an electricity cost of 0.112 USD/kWh and a payback period between 4.4 and 5.3 years, which indicates great economic viability.

Fu et al. [138] studied experimentally the behavior of a multilayer PVT/PCM system with water and nano-PCM (expanded graphite-paraffin). The nano-PCM was encapsulated in an aluminum vacuum bag, and it was investigated with three concentration ratios of expanded graphite (EG), i.e. 5, 10, and 15 % wt. The work assesses the effect of the PCM layer thickness too. The higher performance was obtained with the ratio concentration of 15 % in the nano-PCM and PCM layer thickness of 1 cm, reaching a maximum value of 18.8 % and 67.1 % for the electrical and thermal efficiencies, respectively.

MWCNTs were also used to prepare the nano-PCM (paraffin-based PCM) and nanofluid (EG50-based fluid), which are used in PVT/PCM systems [139]. An improvement of 19 % in the PCM thermal conductivity was found using 0.3 %wt, and various concentration ratios were tested for the nanofluid (0.1, 0.2, and 0.3 %wt). The higher electrical power generated by the PVT/PCM system was 307.9 W/m^2 for the MWCNT concentration of 0.2 %wt in the nanofluid.

Khodadadi and Sheikholeslami [130] investigated the influence of fins in a multilayer PVT/PCM system with nanofluid and nano-PCMs. The used nanofluid was SiC-water at 0.04 % volume fraction (vf), the nano-PCM was Al$_2$O$_3$-RT35-HC at 0.04 % vf, and the system was tested using 0, 10, 14 and 18 fins. The electrical and thermal efficiencies were 13.2 % and 70.1 % for 0 fin, 13.2 % and 76.6 % for 10 fins, 13.3 % and 77.1 for 14 fins, and 13.3 % and 79.5 % for 18 fins, respectively.

Jamil et al. [131] made a comparison of three nano-PCMs for PV modules. Using the salt hydrate PT58 as the base PCM and two concentration ratios (0.25 and 0.5 %wt), they prepared the nano-PCM with MWCNTs, graphene nanoplatelets (GNP), and MgO nanoparticles. For these tests, the configuration of the PVT system is different. The nano-PCMs are located directly under the PV cells, without a serpentine system The concentration ratio of 0.5 %wt obtained a better performance among all nano-PCMs. Compared with PV panels, the maximum temperature drop of PV cells was 9.9 °C for GNP-PT58, 9.8 °C for MWCNT-PT58, and 8.4 °C for MgO-PT58. The electrical efficiency reached 12.1 % for GNP-PT58, 12.1 % for MWCNT-PT58, and 11.9 % for MgO-PT58. The best nano-PCM in this configuration is the 0.5 %wt GNP-PT58.

Salem et al. [140] studied the use of channels to cool down the PV panels using nano-PCMs and water (Fig. 5). The channels can be filled with just water, partially with water and nano-PCMs, and with just nano-PCMs, shown in Fig. 5. The used base PCM was calcium chloride

hexahydrate, and several concentration levels of the nanoparticle Al$_2$O$_3$ (0.25, 0.5, 0.75, and 1 % wt) in the PCM were investigated. The best electrical efficiency of 13.3 % was found for the concentration ratio of 1 % and $\lambda_{PCM} = 25\%$. For the same conditions (1 %wt and 1 L/min water flow) the electrical efficiency found was 13 %, 12.7 %, 12.2 % and 11.4 % for $\lambda_{PCM} = 0\%$, $\lambda_{PCM} = 50\%$, $\lambda_{PCM} = 75\%$, and $\lambda_{PCM} = 100\%$, respectively.

Summary of findings

A lot of research has focused on testing different geometry configurations to improve the thermal and optical characteristics of PVT systems. Different nanoparticles under different base fluids for several concentrations were reported to improve the thermal and electrical efficiency of the system. The nanoparticles' concentration dramatically influences the thermal conductivity and specific heat of the liquid. Nano-enhanced PCM is an effective way to augment heat transfer properties. However, there are also some drawbacks to the nanoparticles added; for example, the distribution of nanoparticles is difficult to realize uniform, and this may be a problem for long-term use. Because of the aggregation and sedimentation of nanoparticles, the thermal conductivity can decrease a lot. The use of ionized water as the base fluid has reported a thermal conductivity more stable with time. Additional research should investigate other methods to present a more stable nanofluid concerning these trepidations.

The basic rules for nanofluids selection are thermal conductivity and cost, and numerous nanoparticles have excellent thermal conductivity, but they are challenging to realize in a commercial application because of their high prices. For instance, the cost of 100 g of aluminum oxide is 126 €, whereas the cost of Au or CNTs nanoparticles is higher. CuO has better thermal conductivity, but because of its prohibitive cost, it should be chosen carefully. Table 7 shows some nanoparticles' thermal conductivity and costs.

In assessing this brief literature survey-one could note there are still some challenges in using nanofluids. The interaction between nanoparticles may cause clustering which will change the fluid thermal property. At the present stage, the main challenges of the nanofluid commercial application are the preparation and cost of nanoparticles. Researchers are now working on developing a model of colloidal particles that can overcome the challenges [142].

Preparation of nanofluids and nano-enhanced PCMs

There are two main categories of methods to prepare nanofluids and nano-PCMs, namely, one and two-step methods. For the former, the
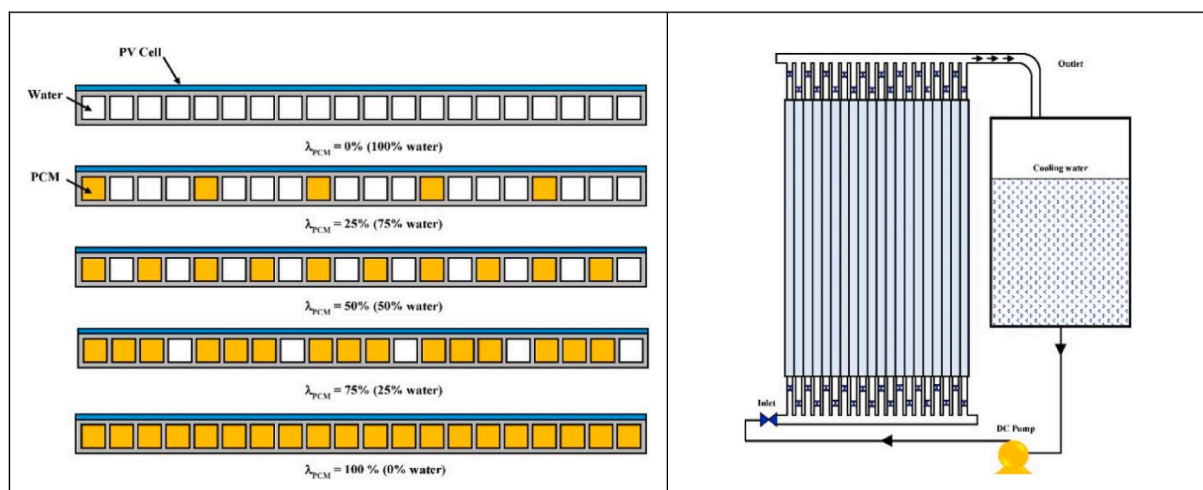

Fig. 5. PVT system that uses PCM and water channels [140] (Reprinted with permission from Elsevier).

Table 7
Nanoparticles' thermal conductivity and cost [141] (with permission from Elsevier).

Nanopowders	Thermal conductivity (W/m·K)	Quantity	Cost (EUR)
Aluminum Oxide (Al_2O_3)	40	100 g	126
Zinc Oxide (ZnO)	29	100 g	24
Tin Oxide (SnO_2)	36	100 g	95
Iron Oxide (Fe_2O_3)	7	100 g	110
Gold nanopowder (Au)	315	1 g	552
Titanium Dioxide (TiO_2)	8.5	100 g	203
Copper Oxide (CuO)	76	5 g	49
Carbon nanotubes	3000–6000	250 mg	308
Zirconium (IV) Oxide (ZrO_2)	2	100 ml	167
Silicon nitride (Si_3N_4)	29–30	100 g	720
Boron nitride (BN)	30–33	100 g	156
Aluminum nitride (AlN)	140–180	100 g	164
Diamond nanopowder (C)	900	1 g	138
Silver nanopowder (Ag)	424	5 g	204

nanoparticles' preparation and dispersion are done at the same time, whereas for the latter, the nanoparticles' preparation and dispersion are made in two different stages [103]. The most frequently used method in the literature and for large-scale applications is the two-step approach due to the commercial availability of powdered nanoparticles [103,131]. The common two-step methods used to produce nanofluids/nano-PCMs are ultrasonic vibration, magnetic stirring, ultra-high-shear mixing, ball milling, and homogenizing [143].

The chemical and kinetic influences determine the nanofluid/nano-PCM stability. The kinetic influences in the nanoparticles are the Brownian motion, which influences the small sized nanoparticles to ensure they are well distributed and in movement inside the fluid/PCM, and gravity, which influences the nanoparticles to settle to the bottom. The Van der Waals attraction forces and the electric double layer repulsive force cause the chemical influences [143,144]. The non-stability between those forces can generate a loss of nanofluid/nano-PCM thermophysical properties and nanoparticles' sedimentation. In this way, nanofluid/nano-PCM stability is a key theme, and a lot of research has been devoted to enhancing nanofluids' stability. There are four effective ways for this [144]:

- Physical, mechanical, and ultrasonic agitation and stirring can be used to provide a good nanoparticle dispersion inside the fluid.
- Use of surfactants: introducing small amounts of a surfactant helps to promote continuity within the fluid, thus reducing the superficial tension. It can also generate contamination, and reduce the nanofluid performance. The surfactant must be compatible with the base fluid.
- Control of nanofluid pH: the nanofluid pH can change the nanoparticles' surface, and this can help the nanoparticles' dispersion stability. The nanofluid pH can be modified using a nonreactive alkaline or acid solution.
- Functionalization: the introduction of functionalization in the nanofluid modifies the nanoparticle surface and assists with the nanoparticles' reorganization and dispersion.

Conclusions and perspectives

This review article presents an overview of the state-of-the-art and most recent works on the application of nanotechnology in solar cells. For this, a short discussion about the fundamentals and development of nanotechnology was presented; various generations of solar cells were introduced, and various possible methods of integrating and incorporating nanotechnology for improved performance in solar cells were discussed. Further, the preparation and application of nanofluids were listed, especially nano-enhanced PCMs, and the challenges and advances were discussed. All in all, the following main conclusions could be made

from the conducted review of the literature.

- Nanoparticles in solar cells can effectively improve the performance of cells in PCE, but there must be certain stress on stability, toxicity, and low cost when choosing the right particle types.
- During the last five years, a great effort has been made to commercialize non-silicon solar cells, but some issues have not been resolved, especially stability, large-area growth, further improvement of PCE, and extended service life problems.
- CNTs could effectively improve the PCE of solar cells and the efficiency of PCMs, but the cost of CNTs is a big challenge.
- There are two methods to prepare nanofluids, and the main challenges of nanofluids application are stability, sedimentation, and high cost of production.

Based on this, the possible future works could be:

- A combination of different nanoparticles in solar cells.
- Morphology engineering of nanoparticles such as the diameter and shape for applications in PVT systems.
- Development of the device architecture and optimization of the chemical composition of constituent materials.
- Studies on the behavior of PVT integrated nanofluids and PCM where novel and eco-friendly nanoparticles are used; and
- Investigation of the performance of new configurations of PVT systems using multiple thermal/optical layers, many of which are related to solar concentration ratios in PVTs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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