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Progress in research and technological developments of phase change materials integrated photovoltaic thermal systems: The allied problems and their mitigation strategies

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ABSTRACT

The efficiency of solar cells and photovoltaic (PV) panels are lacking significantly due to its surface overheating by the incident solar radiation. Indeed, the generated heat energy is harnessed by integrating a thermal system into PV panel, which introduces a photovoltaic thermal (PVT) system. Phase change materials (PCM)s are a class of energy material that is intended to facilitate thermal regulations of photovoltaic (PV) panel. Despite, PVT systems are allied with numerous problems like, integration technique, increase in overall weight of the system, dust accumulation, complication of tracking etc., which are of utmost importance to be resolved. The foremost aim of the review is to analyze the current technologies and allied problems of PVT system, the impact of the overall weight of the system on the PVT systems, detailed assessment of recent advancements in soil mitigation techniques, and the economic benefit of the PVT systems. Also, this review article is specifically intended to discuss on a) concerns allied with PV and PVT system integrated with PCM for thermal regulation; b) framework intimidating the performance of PCM-integrated PVT system; and c) mitigation techniques to resolve the problems and enhanced the performance of PCM integrated PVT system. A elaborative technical exploration on common issues associated with both PV and PVT systems in terms of surface cleaning towards dust mitigation via advanced mechanisms and futuristic technologies is comprehensively presented. A new possible sustainable solution towards enhancing the performance of PV and PVT systems is also provided. A summary of numerous research works conducted on enhancing the performance of PVT system integrated with PCM at different global locations is summarized. Furthermore, this review also discusses the economic analysis of PVT system integrated with PCM along with a summary of technical challenges and future outlook of PCM integrated PVT system to boost sustainable development.

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Nomenclature

Abbreviations

A	Area of cell
AC	Alternate current
Al_2O_3	Aluminium dioxide
ALCC	Annualized life cycle cost
ALCS	Annualized life cycle savings
AM	Air mass
BIPVT	Building integrated photovoltaic thermal system
$C_{capital}$	Total capital
CFD	Computational fluid dynamics
CI	Capital investment
$C_{O\&M}$	Annual operating and maintenance cost
COE	Cost of energy
CPBT	Cost payback time
CRF	Capital recovery factor
ECS	Electricity savings
EDS	Electrodynamic screens
EG	Ethylene glycol
F_{loss}	Financial loss due to reduced energy output
FTR	Filtering facepiece respirators
GHG	Greenhouse gas
GW	Giga watts
Imax	Maximum current
IPBT	Investment payback time
IRR	Internal rate of return
LCS	Life cycle cost savings
LHS	Latent heat storage
LPM	Liter per minute
MC	Maintenance cost
ML	Machine learning
MPPT	Maximum power point tracking
MWCNT	Multi-walled carbon nanotubes
NIOSH	National institute for occupational safety and health
NPCM	Nano phase change materials
NPV	Net present value
PBT	Payback time
PCM	Phase change materials
PEG	Polyethylene glycol
PET	Polyethylene terephthalate
PLC	Programmable logic controller
PPE	Personal protective equipment
PV	Photovoltaic
PVT	Photovoltaic thermal
PVT-PCM	Phase change materials integrated photovoltaic thermal systems
RGB	Red, green and blue
SMA	Shape memory alloy
SnO_2	Stannic Oxide
SPB	Simple payback method
SR	Soiling rate
STC	Standard temperature conditions
STE	Solar thermal collector enhancer
STS	Solar thermal system
TES	Thermal energy storage
TiO_2	Titanium dioxide
UAV	Unmanned aerial vehicle
UV	Ultraviolet
V	Voltage
Voc	Open circuit voltage
Yinput	Cost of input during PV installation
Y_{loss}	Annual yield loss
Youtput	Annual revenue generated by the sale of electricity
Y_{spe}	Specific annual yield
Zn	Zinc

Symbols

B	income
C	cost
Cs	Inflation rate
D	Diffusivity of minority carrier
d	Discount rate
F	Future sum of money
i	Discount ratio
n	Interest rate
n_i	Concentration of intrinsic carrier
p	Period
q	Electric charge constant
U	Annual cleaning cost
u	Cleaning cost per square meter

1. Introduction

The world is experiencing a swift rise in energy demand driven by population growth, technological advancements and industrialization. The use of traditional fossil fuels contributes significantly to the release of harmful greenhouse gases, posing a considerable threat to the environment [1]. In contrast, energy derived from renewable systems (wind, solar, tidal, geothermal, hydro, etc.) presents a viable solution to the ongoing global energy challenges. This source has the potential to reduce greenhouse gas (GHG) emissions by generating clean energy that is naturally replenished [2,3]. Among all stand-out renewable energy sources, solar energy is poised to make significant contributions globally due to its easy accessibility, cost-effectiveness, sustainability, and environmental friendliness [4,5]. The solar photovoltaic (PV) market has experienced substantial expansion in recent years. The cumulative installed capacity is 1177 GW by 2022. The global new installed PV capacity reached approximately 237 gigawatts (GW) in 2022 [6]. Moreover, there was a 25.2% increase in energy production compared to the previous year, indicating substantial annual growth in installing photovoltaic (PV) systems. The recently implemented solar photovoltaic capacity achieved the highest level in the Asia Pacific region during that particular year. Fig. 1 depicts the cumulative installed PV capacity from 2000 to 2022.

However, the PV panels suffer from the accumulation of dust particles, which adversely impact the performance of the system. Dust refers to a broad category encompassing various substances and particles found in the atmosphere, each with a diameter of less than 500 μm [7]. This encompasses a variety of substances, including, but is not limited to, inorganic and organic particles such as soil particles, smoke (including emissions from factories, vehicles, and burning firewood), volcanic vapor, bacteria, fungi, eroded limestones, and microfibers [8]. The presence of airborne dust, especially in dry and semi-arid countries like northern Africa and the Arabian Peninsula, poses a significant difficulty in maintaining the cleanliness of the PV surface. Fig. 2(a) displays a notable instance of soiling on the photovoltaic surface. Soiling, which acts as a barrier between solar radiation and PV unit, can decrease the amount of solar energy that passes through the covers of PV [9–11]. This leads to a significant decline in the effectiveness of PV units, as shown in Fig. 2(b). In addition to this, conventional PV systems convert a small portion of solar energy converted into direct electricity through electronic processes, while the remaining energy is transmitted or transformed into heat [12,13]. Consequently, a substantial amount of solar energy is lost as heat, leading to an increase in the temperature of PV units. According to the literature, 1 °C increase in temperature, the PV module electrical energy decreases by nearly 0.25%, 0.45% and 0.45% for amorphous silicon, monocrystalline and poly crystalline silicon PV systems [14,15]. Although PV panels are optimized for performance under standard test conditions, including solar radiation 1000 W/m^2, cell temperature of 25 °C and airmass 1.5, when exposed to the environment, the temperature beyond 25 °C reduces the electrical performance.

To address this heating issue, researchers recommended implementing cooling systems such as water and phase change material (PCM) based cooling to lower the panel temperature. Photovoltaic thermal systems (PVT) are designed to harvest electrical and thermal energy simultaneously. In addition, PCMs are latent heat storage (LHS) materials that can absorb, store and release heat energy, making them promising for cooling the PV panels and thermal energy storage applications. However, integrating PCMs into PVT systems for building integrated applications can cause serious problems as the roof top may sustain damage if the system is put into place without taking the weight and loading into account [16].

Overall, dust accumulation on solar panels, elevated temperature and the added weight of PVT systems significantly impact electricity production. Prior research has examined the literature pertaining to the accumulation of soiling on solar panels, higher temperatures, weight of PV panel and design concentration on PV systems. For instance, Hung et al. [19] conducted an analysis of the chemical composition of actual dust particles from five common scenarios involving PV panel applications. They assessed the adhesion strength of dust to PV panels under different organic content conditions in the presence of condensation and also analyzed the physical structure of the interface where the dust adheres the panel. It has been found that increasing the organic content or the number of condensation cycles resulted in stronger adhesion. The results showed organic materials build up at the adhesion interface, forming organic films that enhanced the contact surface area.

Kennedy et al. [20]observed that dust deposition on PV panels leads to a decline in the electrical output of the PV unit. Researchers established a model to predict the power output of PV systems, considering cleaning variables such as humidity, wind and temperature. The results indicated a positive correlation between wind and PV power output. Azouzoute et al. [21] reported that the accumulation of dust on the panel declined the optical transmittance by over 28% after one month of investigation, resulting in a decrease in electrical energy by 4.4%. Ghodki [22], designed and implemented a self-automated robot-based dust cleaning system to clean the PV panels. The reported outcomes indicated an 11.9% increase in produced energy, a PV efficiency of 13.02% with an inspiring average performance ratio of 81.35% after 2.4 months of operation. Murkute and Kulkani [23] suggested that a hybrid system provides a cost-effective and easily manageable technique to enhance the efficiency of the PV system, encouraging widespread operation. The effectiveness of the proposed system has been validated by testing it under various partial shading conditions and compared with series-parallel and total cross-tied interconnected arrays. Ahmed et al. [24] examine the impact of temperature, irradiance, wind velocity, water cooling and soiling effect on PV panels based on Bangladesh climate. It was found that PV cooling using water at 0.27 m^3/s enhanced the panel power output, exergy efficiency and energy efficiency by 20.47%, 37.5%, and 12%, respectively. Hariri [25] developed an innovative dust mitigation technology with a shape memory alloy (SMA)-based solar-driven PV self-cleaning mechanism. The result demonstrates the capability of the advanced cleaning system. For self-operation. Shenouda et al. [26] designed a mechanical vibrator, fixed rear side of the PV, and an antistatic coating was applied to prevent dust from adhering to the panel. It has been revealed that electrical efficiency improved by 27% and 41% after 2 min and 4 min of operation. Yilbas et al. [27] indicated that rolling droplets effectively reduce dust on the PV surfaces of hydrophobic mesh-laid PV cells without leaving any fluid on the surfaces. Through the dust removal process, the fluid comes into contact with the dust through infusion, resulting in a modest decrease in speed at which the droplet moves. The results show a significant improvement in electrical efficiency. Eisa [28] developed a new technique to mitigate the dust particle from the PV unit, incorporating light spots and that is adding a windshield to the PV system. The application of anti-coating, coupled with 1D shielding and panel vibration, was reported to maintain efficiency, resulting an increase in panel efficiency.

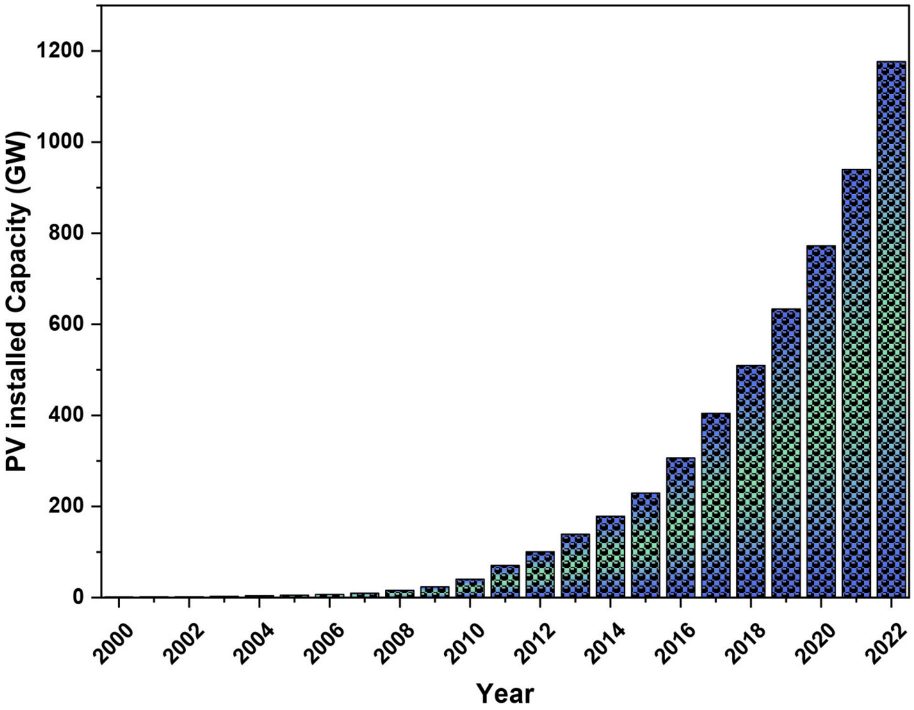

Fig. 1. Cumulative installed solar PV capacity world-wide from 2000 to 2022 [6].

1.1. Novelty of the present review article

PV systems have been more popular than other renewable energy systems. However, the performance of PV panels has been hindered by higher panel temperatures and dust accumulation. Over the past few decades, numerous efforts have been made to reduce panel temperatures and mitigate dust particles in order to enhance panel efficiency and lifespan. Majeed et al. [29] experimentally analyzed a cost-effective method to clean the dust from the PV module. Hossain et al. [30] analyzed the self-cleaning of PCM-integrated PVT system to decrease the panel temperature and enhance the performance of the system.

Numerous review articles have previously been published on different soiling mitigation techniques and PCM integration techniques for thermal management in PVT systems. Vedulla et al. [6] extensively reviewed the techniques to mitigate dust deposition on the PV panels. Aljaghoub et al. [31] underlined the various PV cleaning techniques and related sustainable development goals, and aligned contributions were discussed. Recently, Khalid et al. [32] surveyed the causes of dust accumulation on the panel, the impact of dust on mechanisms used to remove the dust particles, and the mathematical modelling of dust accumulated in PV units were extensively discussed. In addition, the possible sustainable solution to cleaning techniques were proposed. Song et al. [9] systematically summarized and compared the soiling mitigation techniques and discussed the perspectives for improving PV performance from pollution and soiling problems. Salamah et al. [33] reviewed the effect of dust particles and the mitigating techniques at different climate conditions. In addition, the soil mitigating accordance with the life cycle was analyzed. Chanchangi et al. [8] comprehensively evaluated the impacts of dust accumulation and mitigation methods in Nigeria discussed. Another researcher, Derakhshandeh et al. [34] analyzed the automatic cleaning system for removing dust particle from the PV unit and suggested that electrostatic cleaning is the best technique for water scarce region. Heliotex cleaning is also recommended as a cost-effective technique to remove dust particles from the PV system. Goel et al. [35] extensively reviewed PCM-assisted PV cooling, thermal energy storage and associated problems. From the above literature, it is found that the most of the previous review papers, the dust mitigation using natural cleaning, mechanical cleaning and automatic cleaning techniques and there was a limitation on Emerging techniques to cleaning panels Also, very few research on seasonal dust accumulation, increase in Overall Weight of the system, it hindering PVT tracking, advanced technology in dust mitigation system and technologies. To the author's best knowledge, it is most important to mention that there is no article written with the detailed assessment of recent advancements in soil mitigating techniques, seasonal dust accumulation mitigating techniques, how overall weight of system affect the PVT system, To focus on this gap, the study activities engaging the overheat, soiling, design and economic issues with PV/PVT are explored. The research papers printed in high-impact journals in research area of PV/PVT and PCM integrated PVT system will be identified in the subsequent phase. In addition to this, the technical challenges and the limitations of the dust mitigation technologies were extensively discussed. The technical review paper is primarily intended for scientists, researchers, and commercial manufacturers dedicated to improving the efficiency of photovoltaic systems. The dust mitigating techniques and PCM-integrated PVT system exhibit optimal performance within their designated temperature range, thereby enhancing their performance. The dust mitigation techniques of PV systems can significantly contribute to the overarching development goal of affordable and clean energy, ultimately reducing reliance on fossil fuel-based power production.

1.2. Review methodology and structure

The review concentrates on the technological developments of PCM-integrated PVT systems and allied Problems and their mitigation strategies, employing a thorough analysis of the literature. The selected literature items underwent rigorous filtering and were meticulously chosen from reputable and relevant periodicals within the investigation field. In this review paper, the cited findings derived from various research tools like Scopus, Google Scholar, Science Direct, Taylor and Francis, Wiley and Springer are working for the review literature published in latest years. The selection of pertinent publications for this proposed review was guided by the inclusion of relevant keywords like "photovoltaic thermal system, mitigation methods of PV system and PCM integrated PVT system." Subsequently, literature was gathered from books and technical magazines, with a specific focus on the techno-economic benefits of PCM-integrated PVT systems, which are explored in the corresponding sections. The diverse articles and research findings are thoroughly analyzed and presented in the subsequent framework.

Fig. 3 depicts the present research review framework of the soiling effect and temperature issue of PV/PVT/PCM integrated PVT system and mitigation technologies. The article is organized as the global energy issues, and the problems in the PV systems were discussed in the introduction Section 1. The different thermal issues, soiling, PCM

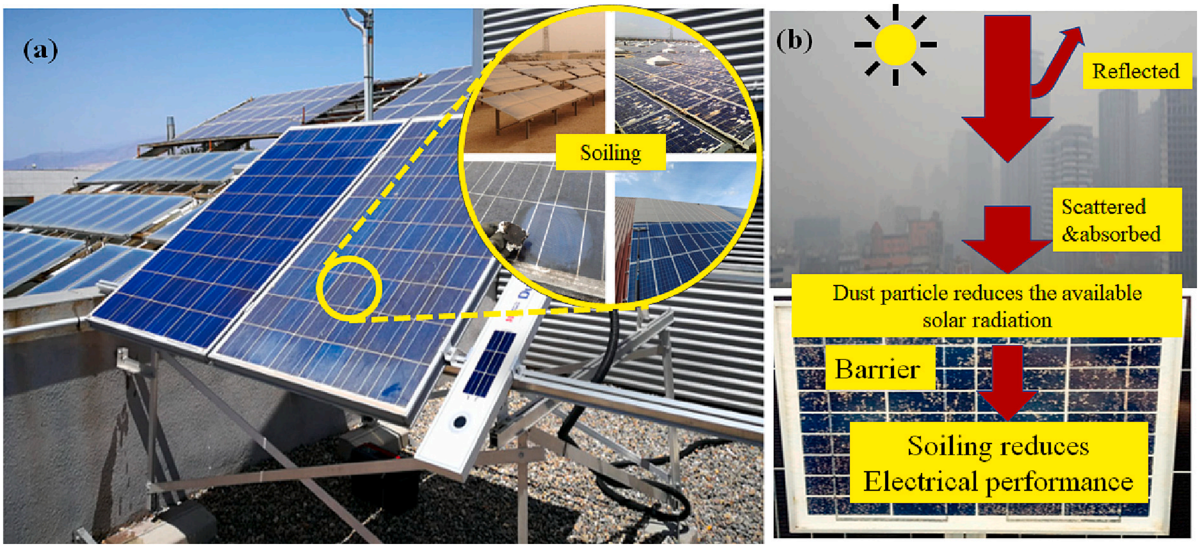

Fig. 2. (a) Soiling effect on PV panel [17,18] (b) Air pollution and soiling effect leads to decreased irradiation reaching the PV panel [6] [Reused/reproduced with permission from the publisher].

volumetric concerns and PV tracking are stated in section 2, and various techniques of thermophysical properties enhancement, PCM integration techniques, and maximizing the solar radiation are discussed in Section 3. The various emerging cleaning techniques and economic assessment of PV and PCM-integrated PVT systems are extensively discussed in Sections 4 and 5. Furthermore, the technical challenges and limitations were discussed in Section 6. Finally, Section 7, concludes the key findings of the present review article and future recommendations to enhance the power output of the PV systems.

2. PCM integrated PVT system: current technologies and allied problems

The efficiency with which solar cells and solar photovoltaic panels convert solar radiation into electrical power is less effective and is currently lacking significantly. Most of the incoming solar radiation striking the solar PV panel is dissipated into the ambient, and it heats the surface of the photovoltaic panel, leading to a drop in the performance of the photovoltaic panels. To improve energy efficiency, a lot of work has been done on researching and developing hybrid systems that combine thermal and photovoltaic collector technology.

Solar radiation is harnessed using solar thermal systems (STS) to utilize thermal energy, likewise, photovoltaic panels are utilized to generate electrical energy. Over the past decades, the common practice is installing two separate solar collectors for thermal and electrical energy. But, an excessive amount of space is needed overall to meet the growing need for both thermal and electrical energy. As a result, it makes sense to utilize solar energy simultaneously for heating and electrical energy generation. Solar photovoltaic/thermal panels (PVT) system is a combination of PV panel and solar thermal systems to generate both electric power and heat energy, which also enhanced the overall performance of the system [36]. Significant advantages of PVT systems are as below.

- Effective utilization of space with improved efficiency to generate maximum electrical and heat energy.
- Low installation cost, as two systems can be installed at a cost of one.
- Ease of design for integration in building roofs.
- Maximum overall efficiency of the system compared to individual systems.

With advanced research, the development of PVT systems has progressed considerably, with in lot recent development which includes a) flat plate PVT system [37]; b) Concentrator type PVT systems [38] and c) Novel PVT systems [39]. As well the working fluid within the thermal system was varied with a) air; b) liquid; and c) Bi-fluid. Subsequently, over the year to further enhance the performance heat storage facility with PCM was designed and developed. PCMs were integrated in two ways a) within the PVT system (beneath the PV panel) and b) external storage tank where the heat energy extracted from thermic fluid is stored for later usage during intermitted period of solar power [40]. PCM technology combined with PVT is one of the renewable energy application's incentive research topics that is receiving more and more attention in the worldwide market to combat climate change. PCM has the ability to absorb or release heat energy during solid-liquid and liquid-solid phase transition; the process is said to occur at a constant temperature [41]. Fig. 4 presents the broad classification of PVT systems with respect to design, type of working fluid and the advancement in technology. Here, it is acknowledged as the most efficient cooling medium for limiting the temperature of the PV unit [42] in order to improve the PVT system's heat collection efficiency [43]. The concept of integrating PCM with the PVT system was first attempted by Malvi et al. [44], where the investigation ensured that by placing PCM beneath the PV device of the copper loop to lower the temperature of the PV panel increased the PV panel generated electricity by almost 9% on comparison to the existing system. In continuation, Preet et al. [45] developed and compared the performance of a) conventional PV panel, b) PVT system with water as working fluid and c) PVT system integrated with PCM. Results ensured that PCM helps to increase the PVT system's energy efficiency. Subsequently, Yang et al. [46] conducted an experimental comparison of the overall energy efficiency of PVT with and with PCM. Results ensured, PVT-PCM system's primary energy-saving efficiency increased by 14%, as the heat loss to the ambient from the PV panel was reduced considerably. In another research work Yao et al. [46] reported that the overall energy efficiency of PVT unit integrated with PCM increased by 17.3 to 28.9% on experimenting the system for an extended period.

However, the PCM possesses low thermal conductivity, which results in high heat transfer resistance [47]. To increase the PCM's thermal conductivity, metal [48], metal oxide [49], and carbon nanoparticle [50] materials have been used often. More precisely, nanoparticles have an extremely high ratio of surface to volume that can offer unique features to improve the thermophysical properties. For example, the heat conductivity of conventional organic PCM, such as paraffin, is about 0.2 W/m·K, while the thermal conductivities of carbon nanoparticles of unique dimensions like multi-walled carbon nanotubes (MWCNTs) (1-Dimensional) and graphene (2-Dimensional) are as high as 5300 W/m·K and 3000 W/m·K, respectively [51]. Therefore, by incorporating materials in the form of nanoparticles into the PCM, the thermal physical characteristics of the PCM may be improved, which helps to increase the efficiency of heat transfer and energy storage. Nonetheless, the uniform dispersion of the nanomaterials with the PCM matrix, during repeated

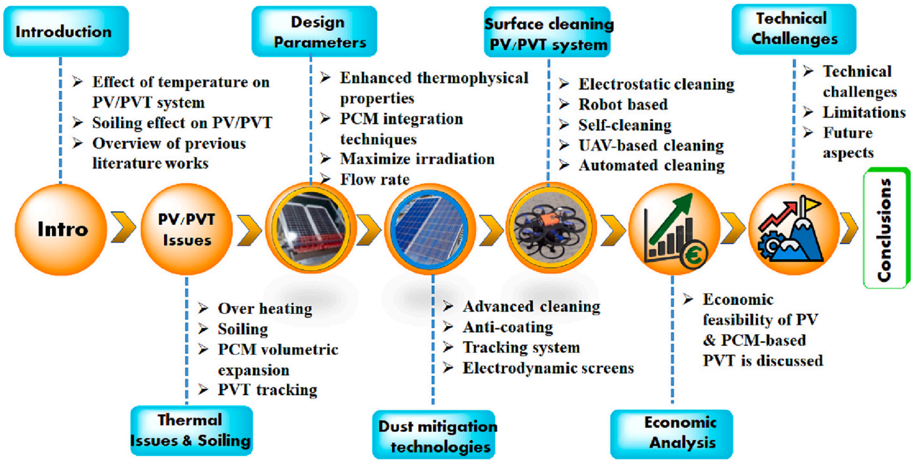

Fig. 3. Review framework.

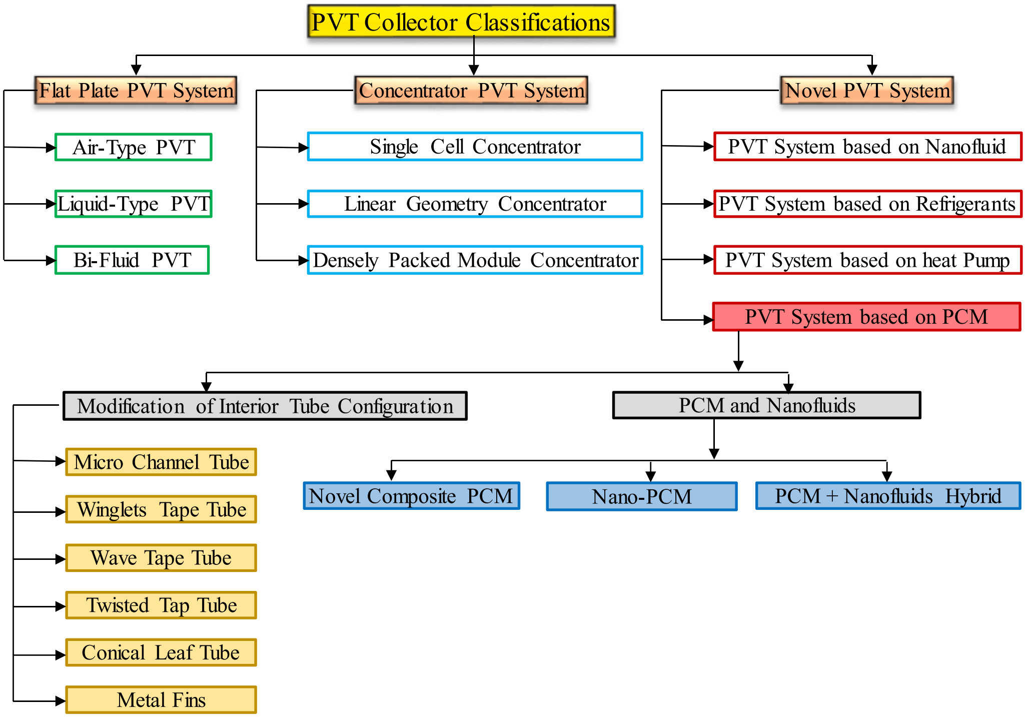

Fig. 4. Classification of PVT collectors.

phase transition process are of utmost concern. Furthermore, PVT with various internal pipe designs is a visually appealing method for real-world use. However, several cutting-edge technologies have been incorporated into the PVT system with PCM module in order to further boost the rate of heat transfer. To boost heating capacity and decrease thermal resistance, different inner tubes, such as conical-leaf, wave-tape, winglets tape, and micro-channel tubes, have been tested and explored. Since PCM has a large latent heat capacity and low conductivity, it is usually positioned as an additional layer beneath the PVT system to absorb heat from the PV unit. Depending on the amount of PCM used, and its thermal physical properties, the temperature of the working liquid may increase once the PCM undergoes proper phase transition process.

Though integrating the PVT system with interior collector tubes, nanofluid, and composite PCM is often the most efficient way to improve system energy performance. As well, this is a cutting-edge and promising approach, the following perspectives and concerns regarding the PVT system with PCM module are raised in order to build the foundation for the future research interests:

- The innovative solutions provided should be feasible enough to accelerate the practical implementation.
- Effects of fin-mounted PVT system with PCM should be optimized
- Low thermal conductivity of organic PCMs.
- Absence of long-term evaluation of the developed novel systems.
- Stability of the developed nanoparticle-based PCMs over repeated usage.
- Lack of theoretical mechanism elaborating the increment of thermophysical behavior of the developed nanocomposite PCMs.

However, in addition to the above mentioned problem, major problems aligned with PV, PVT and PVT-PCM are critically analyzed for the interest of researchers. PV panels tend to function effectively for 25 years under operating conditions; nevertheless, during the aforementioned period, the performance of PV module drops significantly, which is termed as degradation and it causes failure. It is essential to comprehend degradation phenomena and failure types in order to minimize module failure and degradation. Henceforth the upcoming section discusses on the predominant issues occurring in photovoltaic modules and the integrated thermal system.

2.1. Issue of PV surface overheating

Direct solar radiation is reliably converted into electrical power using photovoltaic panels, as they are an efficient technology for harnessing solar power [52]. Solar PV panels account for about 60% of global renewable energy generation and is expected to rise significantly by 2026. On a note, the majority of the commercial PV technologies currently in use have energy conversion rates that fall between 5 and 20%. Regrettably, the PV panel's continuous exposure to an extremely high ambient temperature causes this rate to drop, the unavoidable rise in surface temperature has a negative impact. However, overheating from excessive solar radiation and high ambient temperatures is one of the biggest challenges facing PV panel operation, particularly for crystalline silicon panels in Sunbelt countries. Based on the existing research, the drop in efficiency drop of PV panels is in the range of 0.25% to 0.5% [53] for per °C rise in temperature, based on the PV technology used. Furthermore, overheating of PV panel, with respect to locations, results in serious consequences in regard to the life span of PV panel, which subsequently leads to economic loss. Fig. 5(a) displays the performance comparison between PV panel operating at extreme and normal temperatures.

The amount of electric power generated by PV systems will constantly change dependent on the climatic conditions of the location. The electricity generated by the panel is impacted by variations in surface temperature, shadow effect, soiling, wind speed, and incidence solar radiation. Throughout the energy conversion process, the photovoltaic panel's operating temperature is crucial. PV panel overheating is caused by high ambient temperature and excessive surface operating temperatures, which lengthens the system's payback period and drastically reduces its lifespan and efficiency. For Middle East Asian countries, the ambient temperature is in the range of 40–45 °C, this ambient condition significantly reduces the overall performance of PV panels. Various cooling techniques are used to limit the panel to its nominal

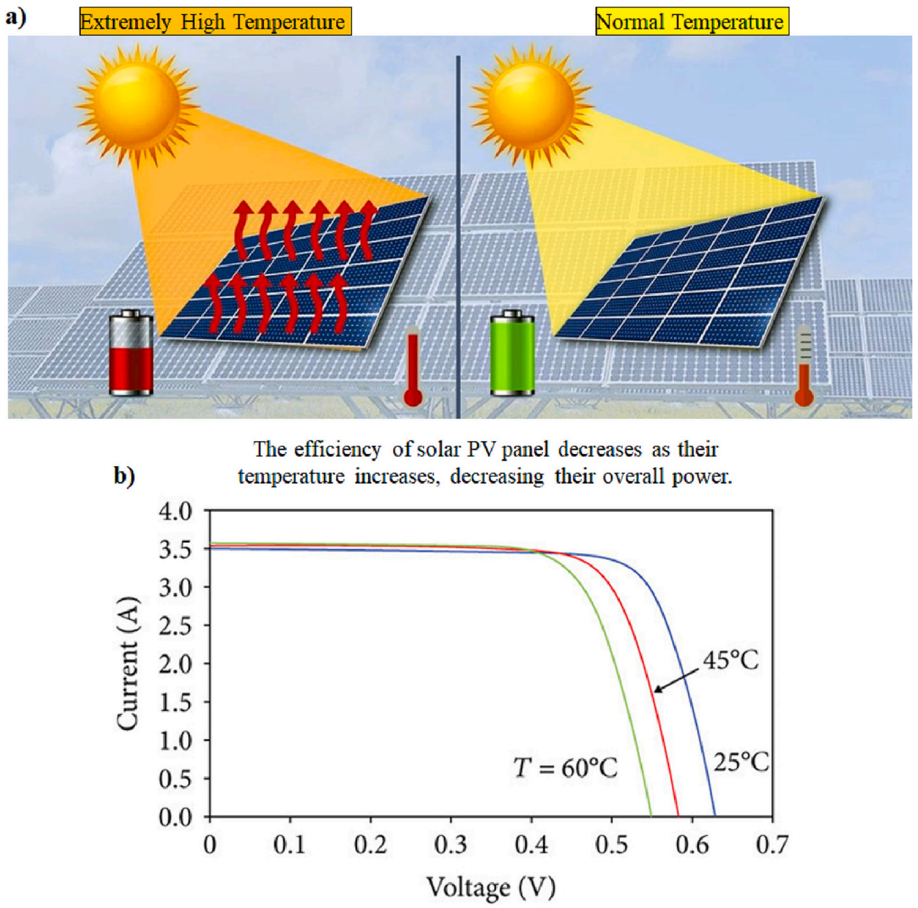

Fig. 5. a) Performance of PV panel under extreme and normal temperature; b) IV characteristics of PV panel with variation in operating temperature [54], [Reused/reproduced with permission from the publisher].
Source: https://www.solarsmiths.com/news/solar-energy-fact-myth/

working temperature to overcome the issues. Subsequently, middle east Asian countries also suffer due to lack of water, which is commonly the preferred thermic fluid for PV panel cooling. Whereas, for European nations, the effect of winter season has a predominant effect on the performance of PV panels, as snow and mist fills the PV panels, and disrupts the operation of PV panel from incident solar power.

The impact of temperature sensitivity on solar cells mirrors its effect on other semiconductor devices. Elevated temperatures disrupt various material properties in semiconductors by reducing the bandgap. One can conceptualize this reduction in the semiconductor's bandgap with increasing temperature as a rise in electron energy within the material. Consequently, less energy is needed to break the connection. This reduction in bond energy, as per the bond model of a semiconductor bandgap, leads to a decrease in the bandgap. The bandgap is thereby decreased by raising the temperature. The open-circuit voltage (V_{OC}) in a solar cell is the parameter that is most impacted by temperature rise. Dark saturation current's (I_0) temperature dependence causes the V_{OC} to drop with temperature. Eq. (1) for I_0 from one side of a p-n junction:

$$I_0 = qA\frac{Dn_i^2}{LN_D} \tag{1}$$

Where,
q is electronic charge constant 1.602×10^{-19} coulomb,
A is the area of cell,
D is the diffusivity of minority carrier (silicon),
L is the diffusion length of minority carrier,
N_D is doping,
n_i is the concentration of intrinsic carrier (silicon),

Variation in the operating temperature of the PV module with V_{OC} as a function of cell is depicted for mono-crystalline and multi-crystalline PV panels. This plot varies with respect to manufacture's, as well it can be inferred that prediction from n_i theory is close to the average values. In general, as per the manufacturer claims the PV panels are tested under Standard Test Condition (STC), as the operating ambient condition of PV panel is location dependent, and this varies from location to location. There are three standard conditions considered for the evaluation of the PV panel manufactured a) Solar radiation of 1000 W/m^2; b) Cell temperature maintained at 25 °C and c) Air mass of 1.5. Fig. 5 (b) presents the drop in V_{OC} of the PV panel, with an increase in cell temperature. As the V_{OC} drops, the overall output of the PV device decreases and reduces the performance. In order to capture more energy, the PV panel is exposed to the environment, and they are all variables that cannot be controlled. In essence, cooling techniques are used to increase a panel's efficiency by reducing temperature rise, which calls for extremely effective, trustworthy, and affordable cooling solutions for commercial use.

Phase change material-based cooling approaches are efficient in removing excess heat from photovoltaic that aren't converted to electricity and retained in the surface of PV panel. With the energy storage enthalpy of PCM, PV temperature can be lowered to around 25 °C and maintained their throughout the solar hours. Because of the increased conduction heat transfer rate within PCM, the inclusion of fins on the PCM side lowers the PV panel operating temperature [55]. This improves PV panel performance by increasing excess heat transfer from the PV panel to the PCM. PV temperature homogeneity is achieved through temperature control during peak hours [56]. In addition to carefully choosing a particular cooling method, a number of other factors, such as the overall working environment, size of the PV panel, PV technology, mounting, and operational configuration, will all substantially impact the cooling performance. Cooling strategy performance varies with respect to the mode of fluid flow, either passive or active. When compared to active cooling, passive cooling ensure a lesser performance improvement. In most circumstances, performance improvement of passive cooling system enable PVT is between 5% and 20%. Meanwhile, performance improvements in active cooling systems surpass 10% and often reach 30%. Certain active cooling techniques, such as jet impingement or spectrum filter cooling systems, have the potential to provide even greater performance improvements than those previously mentioned, which is above 30%.

Most PVT systems are constructed with a cooling fluid operating in an open or closed loop, while some unique system employing a hybrid cooling system that mixes air and water. Air cooling devices are a simple and cost-effective way to cool PV panels. Either natural or forced air circulation can be produced (using a fan). Although forced circulation enhances thermal energy regulation and has a larger heat transfer capacity, the system's net electricity output is decreased by the fan's power consumption [57]. Conversely, in PVT systems, there are certain cases where overheating of the PV panel arises due to the integrated thermal system. In PVT systems, the excess heat generated is dissipated by the thermic fluid flowing with the thermal system, nonetheless during the stagnation period of thermic fluid flow within the thermal system owing to a) sudden power cut; b) pump failure and c) at cases need for very less head demand [58]. During the aforementioned cases, the temperature of the thermal system through which thermic fluid flow rises to a considerably high level. Negligence to integrate protection against overheating of PVT system, will result in generation of steam at certain situation and damages the components of PVT system. Water and propylene glycol are commonly combined and used as a conventional thermic fluid. During overheating, glycol breaks down, making the solution of propylene glycol and water acidic. Copper corrosion, premature component degradation, and scaling are all brought on by the aforementioned process [59].

2.2. How shading leads to overheating?

Shadows falls over the photovoltaic panels owing to buildings, trees, passing clouds and opaque object exhibit a predominant effect on the a) input energy to the cell; b) losses in energy from the shaded cells and c) occurrence of reverse bias due to low input radiation. The performance and amount of electric power generation from PV modules are a function of the installation location, bypass diode used, and shading pattern. On the incidence of solar radiation PV cells gets illuminated and the electrons get excited (forward bias) and moves causing electricity generation, whereas when the incidence solar radiation is interrupted or blocked, the excitation of electrons from PV cell is disturbed leading to reverse bias. Hot-spot is a phenomenon that typically arises from shadowing or shade and causes a solar cell or group of cells to be driven into reverse bias, which requires them to dissipate power and can cause unusually high cell temperatures [60]. Partial or complete shading of solar cell cause reverse bias and significantly reduces I_{SC} compared to other series of cell; this effect subsequently cause excessive heat generation and increases the cell's surface temperature, leading to hot-spot. However, it is not predictable to assess the exact faulty condition, leading to the generation of hot-spot; henceforth PV systems are subjected to be tested at adverse testing criteria. Generally, PV cells are a class of photodiode; where load across the PV cell is shunt resistance (R_{SH}); and the internal resistance is termed as series resistance (R_s). The ideal condition for a PV cell is a) $R_{SH} = \infty$ with resistance to flow of current in any alternate path, and b) $R_s = 0$ with no drop in voltage [61]. R_{SH} of a photovoltaic cell determines its reverse bias properties. When it comes to reverse bias, PV cells can have low R_{SH} when it comes to current limitation or high R_{SH} when it comes to voltage limitation. Hot-spot concerns can affect any of the above-discussed PV cell types, but they do so differently. Basically, shaded cell generates very less current compared to other cells; subsequently owing to Kirchoff's law of voltage and current, the shaded cells tends to operate at maximum current (I_{mp}) point with negative voltage (-V). The amount of power dissipated from shaded cell can be determined by $V^* I_{mp}$. Most severe shadowing situations happen when a substantial part of the cell, or the cell as a whole, is shaded [62]. This results in a confined hot spot where a high temperature is produced by a huge quantity of current flowing through a tiny area. Cells with R_{SH} heat up because they restrict the device's ability to conduct reverse current when a small portion of the cell is shaded. It may take a while for the cell to heat up because the heating is constant throughout the entire surface. Circumference of the hotspot and ratio of current leaking over the confined region of hotspot dictates the rise in temperature.

Generally, PV modules are fitted with bypass diodes to overcome issue of hotspots. By bass diodes, conducts when any series string of the module is reverse biased, thereby reduces the amount of heat dissipated in the shaded cells [63]. Nevertheless, there are mismatches in the characteristics of the diode and the module, so hot spots are not always prevented. Furthermore, it is interesting to note that, the intensity of hot-spot causing heat generation is influenced by the a) material properties of the semiconductor used in the PV module; b) V_{OC} of the PV cell and c) ratio of PV cell connected in a series to the number of faulty cell [64]. With advanced research, with desire to utilize the available space effectively, building-integrated photovoltaic panels and building-integrated photovoltaic thermal panels are installed widely. At this junction, the safety concern is of utmost importance, which gives numerous consideration for reliable solution towards effective thermal management of the PVT surface. Rooftop solar panels at separate houses, solar farms, and smart cities with dispersed solar generation systems could all be designed more efficiently by considering shade into account. Few real-time field image of hot spot occurrence in and its fire hazardous with PV panels are depicted in Fig. 6.

2.3. Dust accumulation soiling problem associated with PV and PVT system

2.3.1. Photovoltaic panels

Soiling losses is a consequence of snow, dirt, dust, and various other particles covering the PV module's surface. The dust layer that cover the PV module's surface is made up of tiny particles that are usually smaller than 10 mm in size, though this varies depending on the location and environment of PV panel installation [67]. Numerous factors contribute to the generation of dust, including wind-blown particles, volcanic eruptions, and automobile motions. As time passes, the deposited dust intensifies the effect of soiling. In actuality, the total energy generated by the PV unit on an everyday, monthly, seasonal, and yearly basis is influenced by the quantity of dust that accumulates on its surface. Even if the energy efficiency of PV systems has grown due to several advances, the operation of these systems might still be inefficient due to both environmental and natural variables such soil, brine, droppings from birds, snow, and other debris that accumulate on the PV module surfaces [11]. Therefore, a thorough analysis to assess the impact of solar panels on dust is required to achieve optimal efficiency and maximum energy generation. Fig. 7(a) presents the energy input and output circuit considering the effect of dust of PV module. Two interrelated factors influence the characterization of soiling accumulation on solar systems, namely the surrounding environment and the property of dust. Dust properties include components, weight, size, and shape [68]. For instance, in Malaysia, the dust is corrosive and is expected to erode the surface of PV panel's. Besides, the surface of PV panel is a predominant factor to be considered in soiling issues. If the surface of PV panel is rough, sticky and fury then the intensity of soil and dust to accumulate over the surface of PV is higher, whereas smooth surface are generally preferred. Additionally, direction of wind and solar radiation of the PV

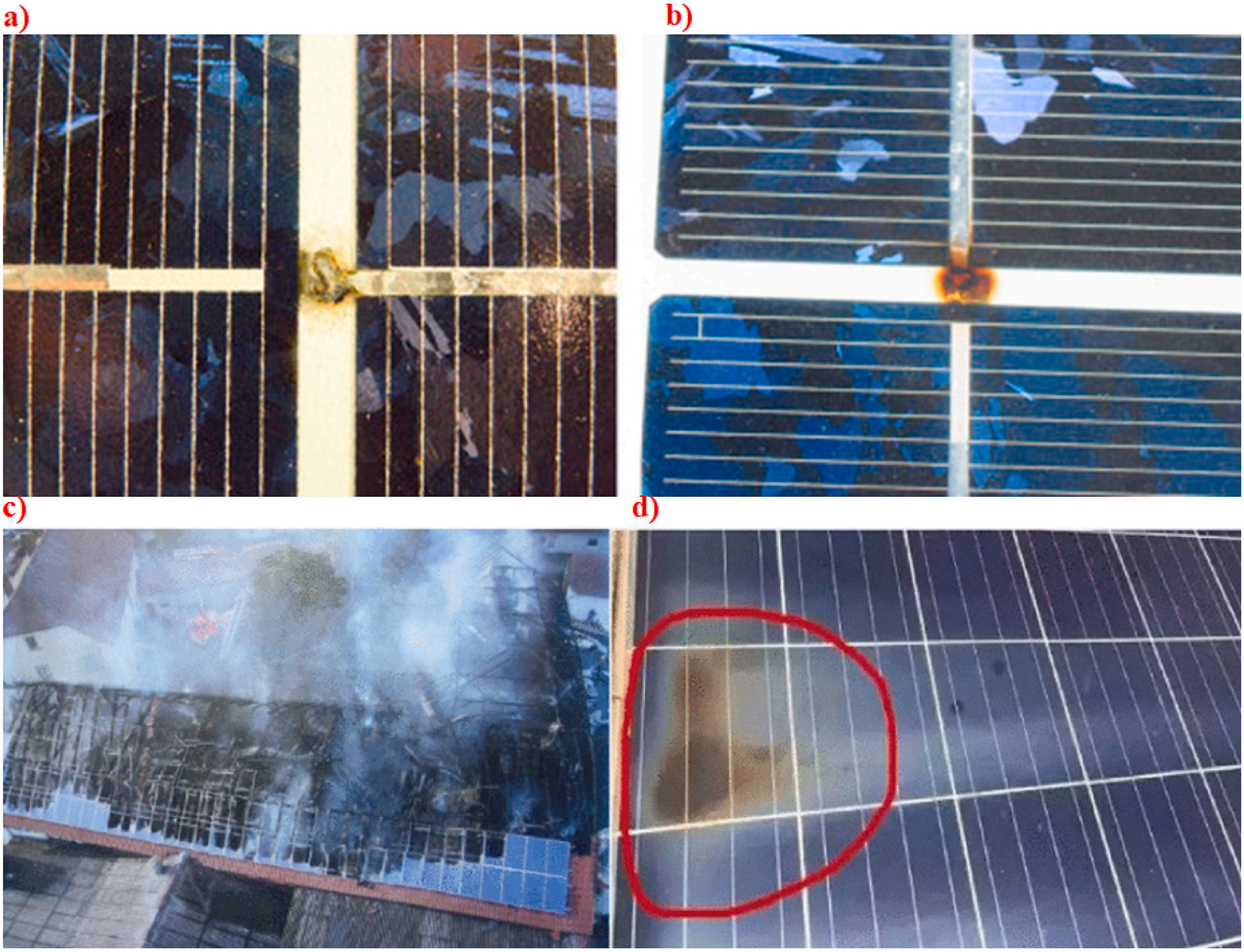

Fig. 6. Actual field image of a) Broken interconnecting cell ribbons due to hots-spot; b) Degraded soldering bond; c) Hot-spot with fire accidents and d) PV cell damage due to hot spot observed on a crystalline-silicon module [65,66]

panel installed location is crucial. Dust accumulate is expected to be more intense for PV panel installed horizontally, depending on the location which is fixed so with the desire to harness solar power throughout the year. Likewise, although powerful winds might clean the panel surface, calm breezes can sometimes lead to accumulation. Nevertheless, wind-induced airflow can affect the deposition of dust or cause it to dissipate in specific areas of the solar panel [69]. As well pressure and wind speed over the surface of PV panel are not constant. When there is a wind, the air pressure drops and the air speed increases. This can lead to reduced dirt build-up and casualties. Technically, soiling and dust shrinks the output power generated by PV panel in different locations globally varying from 2% to 50%. The majority of dust in Asian lands is made up of soil and sand, and in African nations, dust is derived from arid areas that accumulate on the surface. Extensive testing and documentation are crucial in comprehending the influence of sand and dust accumulation on the functionality of solar power producing apparatus. PV modules were subjected for a period of five months in Qatar and Sharjah, United Arab Emirates, and witnessed a 30% and 12.7% decrease in electrical performance, correspondingly [70]. Sandstorms and severe rains in Cyprus caused PV module efficiency to drop by 13% in just a single year [71]. Subsequently, another experiment conducted for a duration of six-month exposure to the outdoor climatic conditions of Egypt showed a reduction in power output of about 60% [72].

There are two primary types of soil shading: hard shading and soft shading, that are commonly observed on PV modules. When substances, like smog, covers the PV surface soft shading happens, while hard shading happens when a solid particle such as gathered dust, covers the surface of PV and interrupts the incoming incidence solar radiation. On close observation, during soft shading of PV panel, there is a variation in current while maintaining the same voltage. Subsequently, with hard shading the PV module's performance varies according to number of cells that are shaded. If certain cells are shaded, then as long as the un shadowed cells receive some isolated radiation, the PV module's voltage will drop. In some scenario, it is advised to increase the efficiency of PV panels by cleaning on a weekly basis during dry seasons and every day when there is heavy dust accumulation, however this lead to extra maintenance of the installed PV system.

2.3.2. *Photovoltaic/thermal panels*

As it is evident that PVT module is a class of co-generation system, used to generate both electricity and heat at a higher efficiency on comparison to their individual system as separate. Few handpicked number of research highlights the decline in overall power generation of PVT system owing to soiling and dust accumulation specifically in regions with semi-arid and arid climate. A number of variables, such as a) temperature; b) tilt angle of PVT system; c) relative humidity of the location; d) the presence of extreme weather (such sandstorms), and e) mounting field characteristics, are significant in affecting the intense of dust on the PVT module surface. Similar to photovoltaic system, the issue of dust deposition affects photovoltaic thermal (PVT) systems,

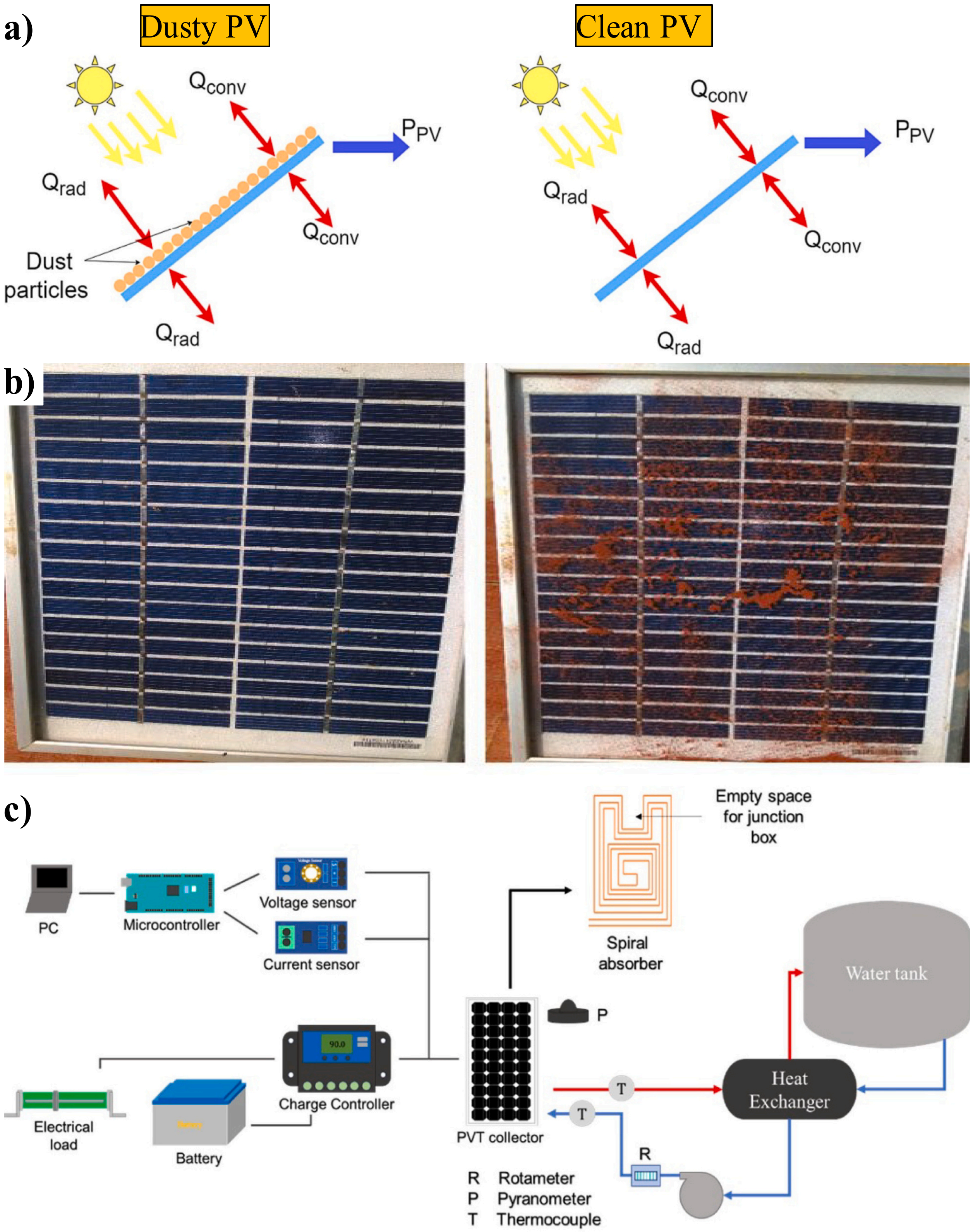

Fig. 7. a) Energy input and output for PV with and without dust accumulation [77]; b) Field image of PVT system with and without dust accumulation [78]; and c) PVT system with spiral absorber plate [76] [Reused/reproduced with permission from the publisher].

which harvest heat and electrical power. The amount of input solar energy that reaches the surface of PV panel is directly decreased by dust formation, as well reduces the heat absorption which lowers the PVT system's ability to collect heat. When the incident solar energy (packets of light: photon) are less to excite the electron-hole pairs for electric power generation using PV module, the incident rays convert into heat energy. Sudden heat generation, transfer only a limited heat source to thermic fluid circulated in the thermal system, as the majority of the heat is dissipated to the environment. Due to the intricacy of the relationship, only the reduction in electric power and the decrease of heat is studied quantitatively with respect to the impact of dust on the PVT system. Several researchers examined the extent of soiling induced by small particulate matter as a function of humidity and wind speed in order to understand the impact of weather conditions on dust accumulation. Fig. 7(b) displays the field image of PVT module with and without dust accumulation or usage for a longer term.

Owing to the fluctuation in weather conditions and solar radiation, Salari et al. [73]. performed a numerical simulation to illustrate the effect of dust on the effectiveness of the PVT system. The simulation study adopts the layer of a monocrystalline silicon-based PV module. Additionally, the influence of different system parameters like a) intensity of solar radiation; b) thermal fluid inlet temperature; c) flow rate of thermic fluid and d) ambient temperature on the PVT system and clean and dusty PV module performance is investigated. According to their findings, both PV and PVT systems have an approximate 26% decrease in electrical efficiency when the dust deposition density rises from 0 to 8 g/m^2. Furthermore, there is a 16.11% decrease in the PVT system's thermal efficiency. In the context, Vaishak et al. [74]. experimentally explored the effect of dust accumulation on the performance of PVT based solar assisted heat pump. The research was conducted for the climatic condition of Surat, India using refrigerant as a working fluid instead of air and water (the commonly preferred thermic fluid for solar PVT). The system's coefficient of performance (COP) and electrical efficiency dropped by 8.53%, and 44.14%, respectively with accumulation of dust over a duration of 8 weeks. Likewise, Yan et al. [75] performed an experimental evaluation of a concentrated PVT system, where artificial dust particles were deposited over the surface of the Fresnel lens and the thermal-electrical performance of the device was evaluated. The study demonstrated that the thermal and electrical efficiency of the concentrated PVT system to drop by 2.65% and 1.29%, respectively, for every 1 g/m^2 increase in dust density. Subsequently, Kazem et al. [76] investigated the impact of dust accumulation over a PVT system for different flow pattern of thermal fluid. The thermal collector was modified with unique spiral shaped absorber as presented in Fig. 7(c). Extending the duration of being exposed to external factors led to a rise in the rate of collected dust, which in turn diminished the power output of both traditional PV and polluted PVT. The PVT system's losses were minimized and the majority of its performance was recovered through routine cleaning. On evaluation for four and eight weeks, decline in performance for the conventional PV system were 19% and 9%, the clean PVT system was 2.5% and 3.3%, and the polluted PVT system was 7.5% and 17.7%, respectively. In addition to raising the surface temperature of solar panels, dust reduces the power that they can generate. By employing PVT systems, the impact of overheating on PV modules can be mitigated. Dust, still continues to be a contributing factor to lower output. Certain research emphasizes on the anti-soiling coatings over the glazing surface. Water being a commonly used thermic fluid it is either "repelled" or "attracted" owing to the hydrophobic or hydrophilic phenomena, which form the basic mechanism for the anti-soiling action [79]. Hydrophobic coatings that are "repellent" to water possess a low surface energy and a contact angle with water that exceeds 120°, making them super-hydrophobic and ideal for effective cleaning.

2.4. Phase change material and its concerns with PVT system

One of the significant applications of PCMs is in the thermal regulation of PVT systems. PCMs are used in PVT systems to control and store thermal energy to obtain the maximum electrical power generation and effectively regulate the excess heat generation over the surface of PV panel. However, there are significant concerns on integrating PCM with PVT system. Predominant issues are discussed in details

2.4.1. Thermophysical property

As PCMs, are integrated with PVT systems, to effective regulate the heat energy generation in PVT systems, the thermophysical properties of PCM (thermal conductivity; phase transition enthalpy; congruent melting [80]; thermal stability over repeated thermal cycles and phase transition temperature) are of utmost importance. Meanwhile, organic PCM (the commonly preferred PCM for PVT systems) hinders due to low thermal conductivity, less melting enthalpy and are flammable in nature). In case of any fire hazard owing to hotspot as discussed above will lead to serious accident [81]. To overcome the low heat conductivity of PCM, research suggest the solution of insertion of fins and dispersion of nanomaterials of unique dimensions [82]. Dispersion of nanomaterials within the PCM matrix, tends to increase the overall cost of the system, which is a problem to be sorted in future.

2.4.2. Toxic and corrosive nature of PCM with PVT system

Inorganic salt hydrate PCMs are corrosive in nature, additionally nanoparticle dispersed PCMs are toxic. PCMs are integrated with PVT system via two methods, a) external storage tank with thermal fluid flowing through the pipes fixed beneath the PV panel as in Fig. 8(a); and b) PCM placed beneath the PV panel as in Fig. 8(b) supported with nanofluid for transferring the heat from PCM module to external system. Subsequently, the ability of the PCM materials to react with the container and the thermal pipes carrying thermic fluid will increase the overall cost of the device, and erosion of containers will cause leak and further economically issue. Furthermore, in certain cases direct contact of PCM with the PV unit surface, cause rupture and disturbs the performance of PV panel [83]. Henceforth utmost care is to be given for PCM integrated PVT system. Increase in a number of mechanical components for heat transfer will considerably affect the overall efficiency of the system.

2.4.3. Volume expansion

On a broad-spectrum, PCMs opted for thermal regulation of PVT system undergoes solid↔liquid phase transition, on the contrary it is evident that solid↔liquid phase transition is accompanied by change in volumetric expansion. Fig. 8(c) depicts the PCM filled PVT system, where PCM in enclosed with the confined space, however with phase transition their occurs a change in confined space of PCM owing to the change in volume. Though phase change materials doesn't have significant differences in volumetric change, over repeated thermal cycle there exist a void in the confined space due to leakage, which considerably drops the energy efficiency. Based on current research, most popular solution for the above problem is the development of shape-stabilized or form stable PCM, in which the PCM are encapsulated within polymer supporting material and overcomes the issue of leakage as well as volumetric expansion. Subsequently, inclusion of supporting materials predominantly reduces the energy storage ability of the developed shape stabilized nanocomposite PCM; and the potential of energy storage ability is proportion to the amount of PCM in the developed nanocomposite [84]. The characteristics of NePCMs may be impacted by the shell's thermal conductivity [85]. An upsurge in melting temperature can be caused by the shell slowing down heat transmission via PCMs if its thermal conductivity decreases compared to that of the respective PCMs. Furthermore, in certain instances, the temperature increased and the coefficient of thermal conductivity decreased. Microencapsulated PCM have a smooth, thick shell that can withstand repeated temperature cycling without losing its core integrity and stopping liquid core leakage. Nevertheless, liquid leakage for the core/shell structure may result from encapsulated PCM owing to faulty morphologies. Two potential defects occurring over the surface of encapsulated PCMs are the shell flaking on the PCM surface and the big cracks on the shell surface, which are typically caused by thermal stress brought on by the core's volumetric change and/or by heating and cooling [86].

2.4.4. Thermal stability of nano particle dispersed PCM

PCMs are energy storage materials, that undergoes repeated phase transition from solid to liquid state and vice versa, and it is important to ensure the uniform dispersion of nanoparticles with the PCM during

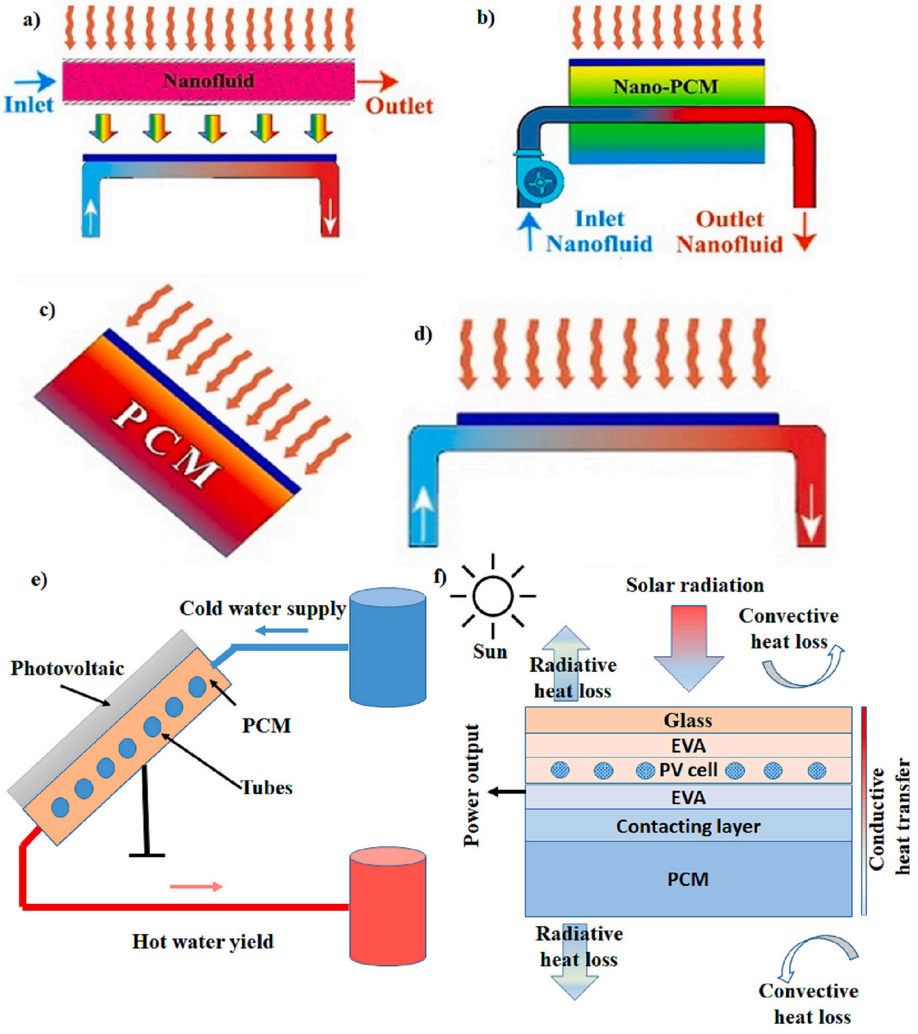

Fig. 8. a) PVT system operating with nanofluid; b) PCM integrated PVT system with nanofluids; c) PCM integrated beneath PV panel (PVT-system); d) PV cooling with thermic fluid [93]; e) Cut section view of PVT-PCM system and f) PVT-PCM system with external storage tank for thermic fluid. [Reused/reproduced with permission from the publisher].

both the state; whereas as far as nanofluids are concerned the thermal regulation if possible with single phase as in Fig. 8(d). The phase shift that occurred throughout the charging and discharging operation had an impact on PCM's thermal stability. An upsurge in leakage caused by the variation in density between the solid and liquid states is expected to have an impact on thermal stability. Leakage may cause PCM stability to decline. Few techniques to ensures stability of nano-enhanced PCM are a) modification of synthesis process involving the dispersion of nanomaterial with PCM; b) inclusion of porous nanomaterial [87], which offers adsorption of PCM in liquid state owing to the capillarity action c) addition of stabilizer like surfactant to the nanoparticles [88]; and d) functionalizing the nanomaterials with different functional group assisting the PCM matrix [89]. In regard to the synthesis process, mechanical stirring of the nanocomposite sample tends to modify the pore structure of nanoparticle [90], likewise some intense sonication boosts thermal stability as agglomerated nanoparticles break into tiny flakes [91]. As well usage of N-Methyl-2 Pyrrolidone as a nanoparticle stabilizer tends to overcome the issue of agglomeration with graphite nanomaterials (commonly used nanoparticles owing to economically cheaper). During freezing process (phase transition from liquid to solid), eliminating agglomeration of nanoparticle aids in the development of the proper crystalline structure in solid state [92]. Furthermore, the vast difference in nanomaterials' density and the PCM opted causes agglomeration and settling of the nanomaterial. Likewise, the optimum concentration of nanomaterial is to be dispersed with the PCM matrix, as higher concentration of nanomaterials results in maximum gravitational push thereby suppressing the buoyant force supporting uniform dispersion.

2.5. Increase in overall weight of the system, hindering PVT tracking

As per the global research trends in regard to photovoltaic panels performance is completely depended on their type and nature of semiconductor used, and as on today it is 15–20%. Consequently, several changes has been made to the PV system installation in order to boost its efficiency, such as the use of sun trackers and maximum power point tracking controllers. Based on tracking PV systems fall into two categories: fixed-tilt PV and tracking system PV. Fixed-tilt frames are a less expensive but less efficient option for solar PV systems.

Alternatively, solar tracking devices can be employed to allow PV modules to capture the most sunlight possible during the day and throughout the year. In order to utilize maximum possible energy from the sun during a given day, solar panel tracking systems typically consist of a mechanical tracking device which employs mechanical elements (sensors, drives, motor and motor controller, tracker mounting, and tracker solving algorithm) [16]. Fig. 8(e) displays a cut section of PVT system integrated with PCM, it is quite evident that the system developed has multiple component attached to PV panels, which drastically increases the overall weight of the system. Increase in weight is owing to a) quantity of PCM used; b) thermal configuration setup; c) piping's connecting thermal system with external storage; d) thermic fluid flowing; e) auxiliary mechanical elements. Installation of the PVT-PCM system for BIPVT applications can cause serious problems as the roof top may sustain damage if the system is put into place without taking the weight and loading into account. This tends to complicate the installation process of the system, as it required skilled labours from the use of semi-skilled labours for installing PV system.

On the contrary, PVT system are assisted with multiple rigid connections in terms of pipelines of thermic fluid and cooling system. This circuit suppress the possibility of tracking the PVT system to harness maximum solar power throughout the day. Fig. 8(f) indicates the connection of PVT-PCM system with external thermic fluid storage tank, the connection are rigid and restricts the flexibility of PV system to track both in terms of active and passive technology. Few research work insist the use of flexible rubber hose for circulation of thermic fluids, nonetheless the problem associated in this case is the overall weight of the system, which leads to more power for motor and other electronic devices to regulate the system [94]. As the thermic fluid flows continuously within the system, the fluid flow causes imbalance of the system during tracking. Any sustainable solution offered in advanced technology should be effective enough, that they do not lay foundation of new problems that will considerably reduce the performance of the system. On integration of many mechanical and thermal system with existing PV system should ensure to justify the economic feasibility [95] as well as the ease to manufacture the system for effective commercialization.

2.6. Seal proof thermal insulation

PVT-PCM system assists thermal regulation of PV panel and increases the overall efficiency of the system by offering possibility to effective harness thermal energy and also provided thermal energy storage for later use [96]. PCMs are thermal batteries that operated with temperature difference. PCM absorbs energy, when the ambient temperature rise above the melting point of PCM opted, and release the stored heat energy when the ambient temperature drops below the freezing temperature of PCM. As PCM are used as thermal energy storage units, they are tend to offer the reliability to store maximum energy, without dissipation, poor insulation system will cause ease of heat energy dissipation thereby fails to meet the need for the integration of PCM. Henceforth, PVT system assisted with PCM should be assured for effective thermal insulation. Subsequently, PCM deals with low-grade energy and this are common problems which are researched and addressed over the decade. In comparison with electrical batteries, thermal batteries are inferior in terms of operating with low grade energy, lack of desired thermal switch to decide the energy charging and discharging process.

All the aforementioned problems aligned with PV, PVT, and PVT-PCM systems are of utmost importance and should be addressed and considered while designing any PV-based thermal system for effective operations. Considerably, the upcoming section discusses more of the design parameters influencing the effectiveness of PCM-integrated PVT systems and mitigation technologies.

3. Design parameter influencing the effectiveness of PCM-integrated PVT systems

The impact of design parameters geometry extends beyond the microscale when it comes to PV cell cooling efficiency applications. Energy derived from the sun (solar energy) is the most plentiful, economical, and efficient sustainable renewable energy source utilized for electricity generation, lighting, and heating [97,98]. Due to its ease of usage and instantaneous application, solar energy is widely used. The PVs are the most efficient type of solar cell generation available; they may operate using diffuse radiation. This is accomplished by directly turning solar radiation into thermal energy. The PV loses some of their power efficiency as they heat up when exposed to sunlight. The PV cooling improves electrical performance, resulting in more cost-effective units. Owing to these financial benefits, other PVT system applications have been carefully considered. The PVT system was initially introduced during the mid-1970s as a solution to the issue of reduced solar efficiency caused by elevated solar cell temperatures. When the utilization of over 80% of renewable energy occurs, heat is generated. To prevent damage to PV cells, it is necessary to ensure that heat is effectively preserved within a thermal collector. The PVT utilizes active cooling technologies to enhance the reliability and performance of PV solar cells and generate thermal energy concurrently [99]. However, the thermal energy generated by the photovoltaic system is used immediately otherwise it may waste [100].

Numerous studies on PVT design parameters have been effectively categorized [101–103]. The usage of additional parameters supports the research discussion. More articles are discussed about collector design than any other parameter. Several authors have worked with different design consideration geometry to cool the PV surface temperature by utilizing different back absorbers to the rear side of PV panel. In Fig. 9, it was seen that the flowrate of 0.01 kg/s spiral flow design was found the most effective. This design possess the best electrical and thermal efficiencies, with 11.98% and 50.12%, respectively, making it the most effective pattern. Flat photovoltaic (PV) modules came in three different varieties: Type A, Type B, and Type C. TheType- A had PV cells covered by a transparent film; Type B contained PV cells covered by glass; and Type C was an unglazed PVT module with PV cells covered by glass [104]. An experimental evaluation of their total performance was conducted. Lab experimental results suggests, Type-A, B and C PVT modules had maximum overall efficiencies of 71.110%, 68.11% and 61.10%, respectively. The Type-A and Type-B modules with glazing have higher thermal efficiency than Type-C PVT modules without glazing because glazing reduces heat losses brought on by the greenhouse effect. Thirteen PVT modules (Type B) put in the home generated 4430.1 kWh of electricity and 8187.1 kWh of heat over the course of a year-long field test. During the course of the investigation, it was found that the thermal efficiency was 17.7%, while electrical efficiency was 9.7%. The decrease in the electrical anad thermal efficiency have been found due to shading. The electricity performance analysis showed a monthly average performance ratio of 55.4% to 63.2%, which was lower than conventional BIPV, because of factors like lower transmittance from glazing, higher temperatures of the PV panels due to glazing and high temperatures of the working fluid, and low incoming solar irradiation from shading. The PVT-PCM systems was examined in an experimental study to compare the energy efficiency of a hybrid photovoltaic module with a conventional PV [105]. The hybrid module's average overall hybrid efficiency is 31.35%. The integration of PCM with PVT system outperforms traditional photovoltaic systems by as much as 20.45% at its peak efficiency of 34.98%. The optimal collector design with respect to electrical and thermal efficiency output is reviewed [106]. This study was evaluated using a qualifying standard that has been established in advance. The dual oscillation collector design is more efficient than other types. The overall performance results in thermal efficiency as 59.6% and electrical efficency as 11.71%. Recently Pathak et al. [107] reported use of PEG6000 PCM in U-tube evacuated tube solar collecter thermal performance was enhanced and it was recommended to work in on demand operation.

This innovative CW reheating application aims to study the feasibility of using corrugated pipes with different combinations of rib height and pitch length to collect and store GW waste heat into PCM [108]. In all three categories, it was discovered that the corrugated pipe with the dimensions of case 9 (e4.5p30 mm) produced the best results. The best result is achieved when the flow is slightly turbulent and highly helical, and the fluid is guided easily through the corrugations. The best heat transfer enhancement and the least amount of pressure drop are achieved by this combo. Also, both sides of the pipe wall are better at keeping heat in with corrugated pipes. Compared to a flat pipe, the

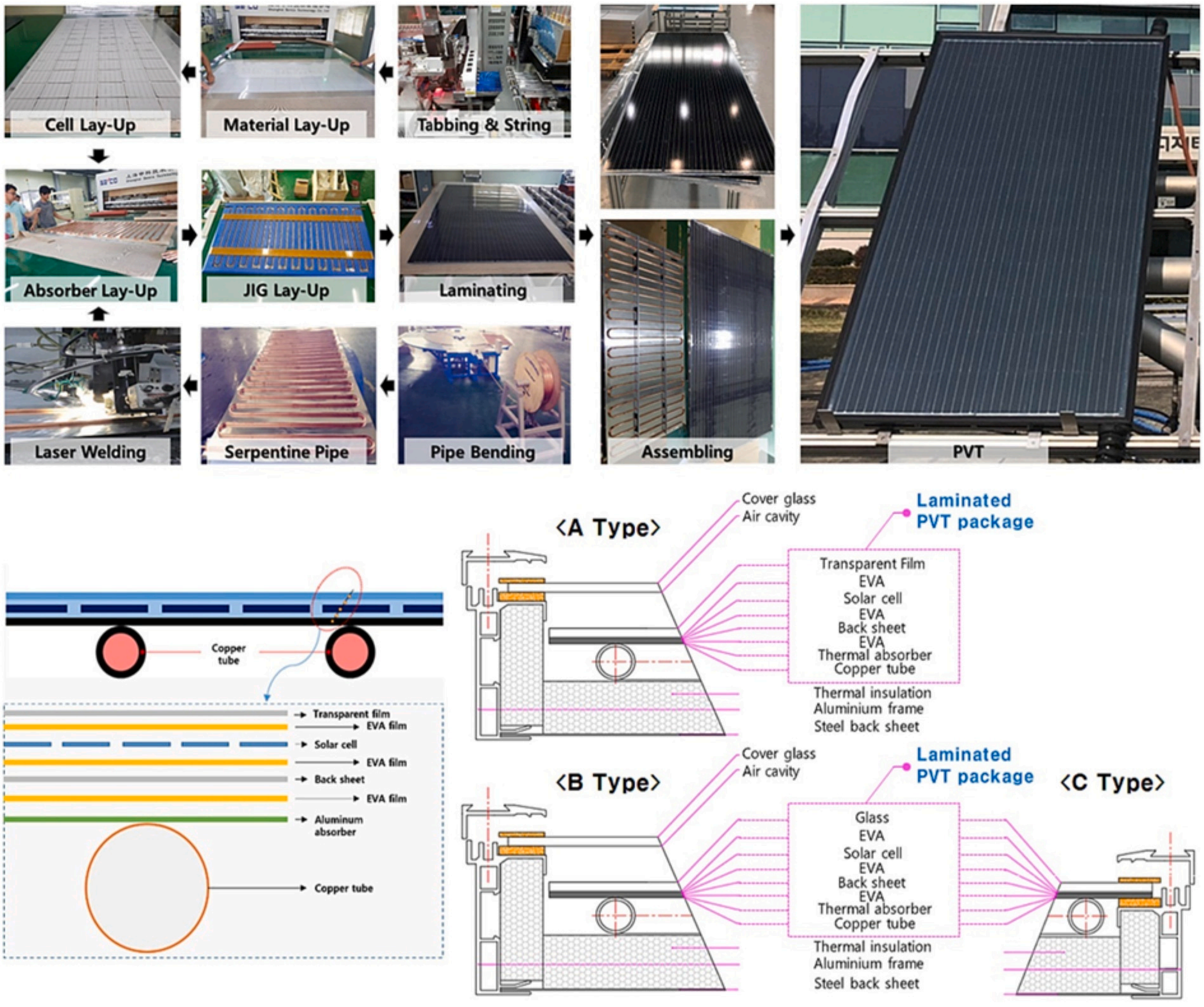

Fig. 9. Design consideration of PVT modules [104] [Reused/reproduced with permission from the publisher].

phase-changed PCM mass goes up by about 1.5 to 4.5 times. Within the same amount of time, freezing a PCM is 60–70% slower than melting it. In the same way, the improvement caused by the corrugated lines works less well when it's freezing outside. An innovative hybrid solar system is introduced to improve the electrical energy produced by PV systems through temperature regulation and the conversion of absorbed heat into hot water [109]. An increase of 54.5% in electrical power output is achieved in the morning compared to PV without PCM. The electrical efficiency has grown by around 34% and can reach 42.5% with two PCMs. After optimizing the interface of contact, the absorbed heat can improve thermal energy production by 52% compared to a PV system without PCM, and by 63% with the suggested system PV with two PCM. Table 1 displays the outcomes and key points from the many experimental studies that examined the efficacy of the systems using different absorbers and PV modules.

3.1. *Enhanced thermophysical characteristics of PCM with controlled weight*

PCMs are highly capable of storing energy. When PCMs undergo phase transitions, their high storage potential becomes active. As stated differently, these materials lack the unique capacity to retain energy compared to other materials if they do not experience a phase change. The enormous energy storage potential of PCMs is its principal advantage. The impressive energy storage capabilities of PCM is shown in Fig. 10. Compared to a straightforward heat transfer process (T_f), the amount of energy retained in the PCM is substantially larger at a phase change.

In recent years, various types of PCMs are available in the market. Choosing PCM for PVT systems involves considering several factors, including thermal properties, compatibility with system components, cost-effectiveness, and ease of preparation. Generally, Organic PCMs have higher latent heat, low cost, wide range of available materials and biodegradable options, and some drawbacks limited thermal conductivity and compatibility with high temperatures [112]. Inorganic PCMs hold higher thermal conductivity than organic PCMs but have a limited range of latent heat, corrosion effect, supercooling effect, hygroscopic nature, and low chemical stability. In the case of eutectic PCMs have customized phase change temperatures, compatibility with system components and enhanced thermal properties [113]. In general, Paraffin is a PCM stands out as the most preferred solid-to-liquid phase transition material among the PCMs. Key properties such as melting point, thermal conductivity, and latent heat play crucial roles in determining the suitability of a PCM for various applications. In solid-state, the material absorbs heat energy and transitions into a liquid state, releasing heat upon phase transition back to solid state. Solid-to-liquid phase PCMs find extensive application across diverse fields, including Solar Thermal Systems [107,114], photovoltaic thermal systems [115] building heating and cooling [116], Battery Thermal Management Systems [117], and food industries [118].

Although the PVT module's solar thermal and power capabilities were significantly improved with the inclusion of the PCM layer, the

Table 1
Summary of different studies on different absorbers at various flow rates.

Reference	Year	Study Type	PV Module	Absorber Type	Remarks
[152]	2023	Experimental	Polycrystalline	Parallel tube collector	The electrical efficiency was 14.64% at a flow rate of 90 kg/h and a concentration of 0.10%, the thermal efficiency was 34.94%, the overall energy efficiency was 49.28% at 88 kg/h and 0.10% concentration, and the overall energy efficiency was 16.45% at 60 kg/h and 0.50% concentration. All of these figures were obtained according to the flow rate and concentration.
[153]	2022	Experimental	Polycrystalline	T-shape finned type collector	The average surface temperature of systems that do not have fins is 13.31%, while the surface temperature of systems that have six fins is 309.6869 K, however, a T-shaped fin lowers the latter by 5.03%. The container with 10 fins has a liquid fraction of 46.83%, up 4.05% and 10.60% from PVT/PCM systems with 6 and no fins.
[154]	2021		Monocrystalline	Parallel flow absorber	The PVT-NePCM system achieved an overall energy efficiency of 85% while increasing the water output temperature by more than 46.0 °C.
[15]	2020	Experimental	Polycrystalline	Serpentine flow absorber	The energy losses of glazed water-based PVT/water, PVT/EG 50%, and PVT/EG 100% systems are reduced by 9.28%, 23.33%, and 48.58%, respectively, as compared to the energy losses of unglazed systems.
[155]	2020	Experimental	Polycrystalline	Spiral flow collector	The overall efficiency of typical photovoltaic (PV) systems was around 7.8%, whereas the efficiencies of web, direct, and spiral PVT types were approximately 18.5%, 28.0%, and 35.0%, respectively.
[156]	2020	Experimental	Polycrystalline 250 W	Serpentine flow absorber	The PV/T system's efficiency was found to be 76.58% at 2 lpm. A 9.89% electrical efficiency for PV and a 10.46% electrical efficiency for PV/T-only were shown by the results. Max exergy efficiency for a PV/T system was 12.98% at 0.5 lpm, compared to 7.16% for PV alone.
[157]	2019		Polycrystalline 250 W, 60 cell	Serpentine flow absorber	The PVT-PCM system reached a high thermal efficiency of 87.72% at flow rate 2 lpm. At a flow rate of 4 lpm, PV systems realised an electrical efficiency of 9.88%, while PV/T-PCM systems reached an efficiency of 11.08%.
[158]	2019		Polycrystalline	Spiral flow absorber	The channels with 100% water have the lowest module temperature, the highest electrical, thermal, and overall efficiency, and the maximum electrical output power gain compared to pure PCM.
[159]	2019	Numerical	3D	–	The comparison showed that the mathematical model could match experimental data. The mathematical model and measurements show thermal efficiencies of 71.3% and electrical efficiencies of 13.7%. In contrast, glass, PV cells, PW PCM, and nanofluid reach 41.2, 39.92, 38.8, and 36.5°, respectively.

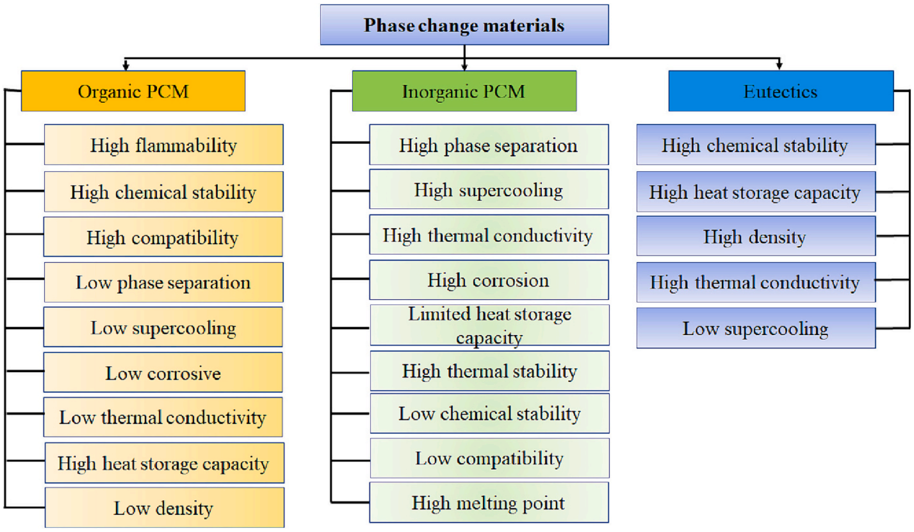

Fig. 10. Energy storage capability in PCMs, Classification of PCMs [110,111].

backplane temperature was successfully regulated by the PCM layer. While PVT technology has improved overall efficiency, its implementation has been slowed by a number of issues, such as inefficient heat removal, PCM weight increases, PCM leakage, and so on. The incorporation of PCM results in an enhancement in the number of hours that the greenhouse dryer is operational; nonetheless, the primary issue with PCM is that it has a low thermal conductivity. The thermal performance of the material is improved by the incorporation of nanometal and carbon fiber, which together make about 3 % of the mass of the PCM. The efficacy will decrease as the concentration of nanometal and carbon fiber increases. Together, the incorporation of PCM and the establishment of the packing factor contribute to an improvement in the performance of the PVT. The packing factor is capped at 50 %, and any additional decrease in packing factor will increase the area PVT per unit. A hybrid photovoltaic (PV) system has the potential to address the challenges that relate to greenhouse dryers, such as low operation hours and sustainability in the absence of sun. Since it offers a greater packing factor and more power per unit area, a bifacial PVT has been recognised as having the potential to become the PVT of the future.

A PVT-PCM panel with a serpentine flow channel on both sides was used to measure heat removal efficiency with water as the working fluid [119]. Several tests were done with different amounts of fluid water flow on sunny, clear days in Malaysia to make sure that the collector panel got the right amount of energy. By analyzing the heat transfer results, we may determine which panel characteristics are most suitable for the given collector design configuration. To determine the optimal operating parameters for the manufactured panel in both laminar and turbulent fluid flows utilizing water as the working fluid, it was subjected to a number of transient operating scenarios. The equivalent panel layout's effectiveness ratio was 0.033 kg/s, and the optimum water flow rate enhanced heat transfer efficacy. In a similar study, NePCM-integrated PVT collector systems was examined, which showed enhanced electrical and thermal characteristics [120]. The optimal conditions display 6.497 kg of melted PCM, a coolant exit temperature of 37.72 °C, and an electrical efficiency of 13.92%. By using Nano-PCM layers as cooling media, electrical efficiency can be improved compared to conventional systems.

PCM-integrated PVT systems offer several advantages but also some limitations to using PCM in PVT systems. The heat transfer rate between PV and PCM is limited due to low thermal conductivity and surface area contact between the two materials. These results slow down the cooling rates, especially in large-scale PVT systems. Further, PCM materials have a finite number of thermal cycles they can undergo before experiencing degradation or reduced performance. Repeated heating and cooling cycles can lead to changes in PCM properties, such as decreased latent heat and phase change temperature range. In addition, space and weight considerations are a big issue. Integrating PCM into the PVT system adds additional weight to the PVT system. This can be a limitation, especially in applications where space and weight constraints are critical. Also, PCM-based cooling systems need periodic maintenance to achieve optimum performance, such as replacing degraded PCM and monitoring leakage or damage to containment systems. This adds to the operational complexity and cost of maintaining the PVT system.

3.2. PCM integration technique towards enhanced heat transfer

Numerous uses for latent heat-based energy have been previously detailed, including but not limited to air purification, space and building heating, waste heat recovery, cooling clothes, battery thermal management and home hot water applications. PCMs are used in LHTES systems to describe materials that undergo phase shifts through the storage and release of latent heat. Several methods have been investigated in the past to enhance heat transfer within PCM, such as dispersing nanoparticles, using fins, encapsulating PCM, etc. There are, however, some problems with installing and using these options. Most favorable thermal energy storage system shape can greatly impact heat transfer, which in turn improves heat transfer overall [121–123]. Improved energy efficiency can be achieved by employing PCM, which is highly efficacious in absorbing surplus heat from the solar panels' reverse side.

The analyses study the efficiency of a PVT system that uses the proposed PCM-based multilayer structural heat exchanger [124]. An increase in the PVT system's average electrical efficiency is possible by utilizing a heat exchanger in conjunction with PCMs. However, because of the extended working period, the thermal efficiency increases. A composite PCM with 15% expanded graphite may result in a 25.2% increase in overall efficiency. The thermal performance of a slab-finned cross-flow PCM heat exchanger is currently being explored, with a particular focus on the impact of PCM type, fin density, and distribution [125]. A longer heating time was achieved for greater set point temperatures when a PCM with a higher melting temperature was used. In contrast, at lower set point temperatures, lowering the melting point yielded better performance. The highest average latent heat discharge power of 0.46 kW was observed, suggesting that the thermal energy of PCMs is released more rapidly at higher PCM melting temperatures. According to the results, improving PCM qualities to get heating and discharge characteristics is crucial.

Evaluating the efficacy of two PVT-PCM integrated systems for thermodynamic analysis, which includes examining energy and exergy [126]. Sunny days in August are used for the outside experimental testing. The findings demonstrate that even with increased thermal energy efficiency. Furthermore, adding EG as an impurity to the clean water lowers the PVT-PCM system's overall energy and energy efficiency. In comparison to the unglazed systems, the glazed examples of water-based PVT/water, PVT/EG (50%), and PVT/EG (100%) show a decrease in the percentage of energy losses of 9.28%, 23.33%, and 48.58%, respectively. The study [127] investigated the effects of a number of active and passive cooling methods on photovoltaic cells in order to ascertain the ways in which these cooling methods influenced the thermal and electrical performance of PVT integrated systems. The studies are carried out in a solar simulator with solar radiation power ranging from 800 to 1700 W/m^2, which is a broad range of regular-concentrated solar radiation. PCM is infiltrated with a specialized heat-conductive foam (PS-CNT foam) in order to compensate for its low thermal conductivity and prevent it from malfunctioning. This is done in order to make PCM a passive cooling system. A drop in PV-cell temperature of 6.8% and an increase in electrical efficiency of 14% were both observed as a result of the utilization of PCM-composite. Using a flow rate that ranges from 0.3 to 1 litre per minute (lpm), the effects of active cooling are investigated independently by passing water through a cooling block that is positioned beneath the PVT system. System performance is significantly better in active cooling systems compared to passive PVT systems, with energy efficiencies in active cooling ranging from 66.8 to 82.6%.

The three-dimensional model of computational fluid dynamics (CFD) was designed to carry out a numerical study on heat transmission in various weather conditions [128]. The model was used to investigate the unique PVT collector with an integrated phase change material (PCM). During the course of the investigation, both fresh experimental data for unusual organic PCM and a revolutionary multi-parameter numerical technique were taken into consideration. The crystal phase of PCM commenced melting at 8.3 °C and finished at 45.2 °C, yielding a latent heat of melting of 45.4 J/g. With the exact proportion ranging between the domains that were taken into consideration, the numerical forecast of the operating temperature departed from the experiment by an average of 2.9% to 4.9%. The findings of this study can be exploited for the purpose of improving the designs of PVT-PCM collectors that are now in use. The results of an investigation into the experimental outcomes of a photovoltaic (PV) system that includes a regular PV system, a PV system cooled with PCM, and a PV system cooled with nano-enhanced phase change material for the purpose of cell thermal management were investigated [129]. The PCM utilized was polyethylene glycol (PEG) 1000, which has a melting point ranging from 33 to 39 °C. The insertion materials were nanomaterials of alumina and silica. The results show that the electrical efficiency of the system is increased by 4.82%, by 8.1%, and by 7.17% when a PV-Alumina nano phase change material (ANPCM) cooled system is used, as well as by 5.12%, by 8.4%, and by 7.29% when a PV-Silica nano phase change material (SNPCM) cooled system is used. A 17.15% reduction in panel temperature is achieved as compared to an uncooled PV system. Results suggest that PCM and NPCM regulate PV solar cells' operating temperatures well. The experimental investigation of a PCM-filled PVT system and comparison with the traditional water-based PVT system [130]. Increasing the convection heat transmission, bubbles were injected into the PCM to improve its performance. Researchers found that PCM greatly slowed the rate at which PV panels heated up. In the situation where bubbles were injected into the PV device, the highest temperature rise detected at the back surface of the device was 48% lower than in the case without bubbles. The thermal efficiency could be significantly improved in this way. A decrease in the bubble injection chamber's total temperature occurred due to the faster thermal energy absorption from the PV panel and the subsequent more uniform temperature distribution. There was a significant improvement in solar panel performance when bubble-driven flow was used in the PVT-PCM system.

The literature [131] suggests, a PVT system with a solar thermal collector enhancer (PVT-STE) that contains phase change materials that are capable of simultaneously generating thermal power and electricity as well as thermal energy storage is being considered. The purpose of this analysis is to obtain a result to the problems that are associated with standard photovoltaic thermal systems. These problems include low thermal power, thermal exergy, and the temperature at which heat transfer fluids are released into the atmosphere. The key objectives of this research are to evaluate the proposed system's performance and identify appropriate phase change materials for each component. Under the conditions that are encountered in real-world operations, water is used as the heat transfer fluid. The results suggest that under the current circumstances, the best PCM choice would be to use a lower melting point RT31 for the PVT component and a higher RT42 for the STE component. For the charging process in July, the system can store 3234 kJ/m^2 of thermal energy, and for each component, it can store 1802 kJ/m^2 when using the best phase change materials. The suggested system also outperforms a stand-alone solar thermal system using a phase change material in terms of heat energy production per square metre in July (1.8 times) and November (2.0 times). This work conducts experimental investigations into five different asymmetric hybrid solar collectors that use flat plate receivers connected in series [132]. Experiments are conducted with water as the working fluid and in open circuit mode with respect to the collectors' electrical parts in order to assess their performance under different operating conditions in terms of thermal energy and exergy production. To include electrical production in the total performance evaluation of PVT solar collectors, the mathematical model and thermal analysis are further refined. The primary results, the end experimental data, demonstrated that these series-connected solar collectors function effectively all year round, with summer yielding approximately 2.2 kW of usable energy, spring yielding about 2.8 kW, and fall yielding about 2.6 kW.

An innovative solar energy collector that combines thermal and photovoltaic technologies with phase change material (PVT-PCM) has been designed [133]. The thermal system incorporates air- and water-based conditions to provide the building's constant heating requirements throughout the year. The cross-season test findings show that the system's overall efficiency is 39.4% and energy savings efficiency is 64.2%. The system controls the temperature and makes use of heat via its thermal system. The energy-saving potential and economic analysis of the system are investigated in low-latitude regions. The system's additional payback period is 13.1 years based on the numbers. The PVT-PCM system increases the overall rate of solar energy utilization and offers more opportunities for research and development than the conventional PV system. Research [134] demonstrates that PVT collectors with hybrid cooling can reduce panel temperatures by up to 7.5 °C, which greatly improves electrical power conversion. With a maximum efficiency of 15.71% in February, the hybrid panel outperforms the traditional panel by over 22%. At steady air and water flow rates, the maximum thermal recovery efficiency is 84.40% and the highest overall recovery efficiency is 69.25%. Maximum electrical efficiency of 15.2% was recorded in July, which is almost 22% greater than that of a traditional PV system. Overall efficiency reaches 85.7% and thermal efficiency reaches 70.8%. Comparing the proposed hybrid PVT system to the traditional PV system, the economic and environmental analyses reveal shorter payback times and lower carbon emissions.

As per the discussion the addition of nanoparticles dispersed with PCM enhances the thermal conductivity of the PCM as well as alters its other thermal properties. Several techniques were employed to address the charging and discharging stability of the nanoparticle-dispersed PCM,. The careful selection of nanoparticles with suitable properties can enhance the stability of the nano PCM. Nanoparticles with high thermal conductivity, good dispersion stability and compatibility with the PCM matrix can improve heat transfer and prevent nanoparticle agglomeration during charging and discharging [80]. One of the best methods is surface modification of techniques such as functionalization of the surface [89], coating nanoparticles with use of surfactants can enhance the compatibility with the PCM matrix and improve the dispersion stability [88,135]. This method helps to prevent the agglomeration of the nanoparticle after a few heating and cooling cycles. Another method to enhance the dispersion stability of the nano PCM is the addition of stabilizing additives such as dispersants, crosslinkers, and nucleating agents [80]. These additives can enhance particle dispersion, prevent aggregation, and improve compatibility with the PCM matrix, thereby enhancing overall stability during thermal cycling operation. In addition to this, encapsulation or hybridization will help improve stability. Encapsulating nanoparticles within protective shells or incorporating them into hybrid structures can enhance the stability within the PCM matrix [136]. This prevents contact between nanoparticles and the PCM, reducing the risk of particle aggregation and improving long-term stability during charging and discharging. By employing these strategies, researchers and engineers can mitigate the challenges associated with charging and discharging stability in nanoparticle-dispersed PCM systems, leading to more reliable and efficient thermal management and thermal energy storage solutions for various applications.

3.3. Maximize the incidence solar radiation

Traditional solar PV technology can only convert a small percentage of the sun's rays into usable power; the vast majority either gets wasted as heat or is reflected back [137]. According to earlier studies, electrical efficiency might be improved by increasing the energy production per unit area of PV modules by including inexpensive reflectors in PV systems. The major drawbacks of photovoltaic (PV) systems have been addressed, and their performance has been improved by a number of innovations that have been made over the years by manufacturers, research centers, and researchers from all over the world [138,139]. These advancements can be accomplished at the level of the materials, like making PV panels more efficient converters while reducing production costs, or at the overall system level, like making the most of the power PV panels produce. Floating PV systems, cooling systems, cleaning systems, solar tracking systems, and maximum power point tracking (MPPT) controllers are some of the most common methods for improving PV system performance and maximizing the use of solar energy. To optimize solar radiation that reaches the solar panels, one of the key elements of a solar energy system's tilt angle. Because it is dependent on the sun's daily, monthly, and yearly journey, this angle is site-specific. To maximize the system's energy production, the ideal tilt angle for the place of interest must be precisely determined. To get around the biggest problems with PV systems and boost their efficiency, manufacturers, research institutes, and scholars from all over the world have developed a number of advancements. Either the materials level improving PV panel conversion efficiency while lowering manufacturing costs or the system level maximizing or optimizing the electricity extracted from PV panels are the sites of these advancements. The most widely used methods for improving the efficiency of PV systems and obtaining the most energy from solar radiation are floating PV systems, cooling systems, cleaning systems, solar tracking systems, and MPPT controllers.

The low conversion efficiency of the PV modules in weak sunlight circumstances is the reason for these losses. The efficiency of the PV module is often stated by the manufacturer under STC circumstances, which is 1000 W/m^2 of solar radiation at 25 °C cell temperature and an air mass 1.5 (AM 1.5) spectra. Because of patristic resistance, efficiency decreases as the intensity of solar radiation decreases in low-light settings. Low efficiency in low-light settings is caused by shunt resistance, series resistance, and diode quality. Depending on the study, these losses can be anywhere from 1.5% to 5% maximum. For the sake of this estimate, this loss is assumed to be 3% [140,141]. The impact of solar radiation on the electrical and thermal output of PVT and PVT-PCM systems was investigated [142]. The findings exhibit that PCM addition greatly lowers solar cell temperature and boosts electrical efficiency in PVT systems. Results showed that a PVT system including PCM could achieve a maximum electrical efficiency of 14%, compared to 13.75% in the absence of PCM. A rise in solar radiation from 500 W/m2 to 1000 W/m^2 causes a drop in electrical efficiency of 13.75–11.1% for the PVT setup and a drop of 14–12% for the PVT-PCM configuration. The results show that PVT systems' cooling and energy output were greatly improved with PCM integration. Solar radiation levels ranging from 800 to 1700 W/m^2 were studied using the three passive PVT systems: PV-PCM, PV-standard PV panel, and PV-standard PV PCM [127]. Additionally, using mass flow rate 0.3, 0.6, and 1 lpm flow rate were investigated in the active cooling studies. While active cooling would boost electrical efficiency while simultaneously producing thermal energy, passive cooling would increase overall electrical efficiency. In fact, active PVT performs better overall than passive PVT. The energy efficiency of active cooling is 66.8–82.6%, while that of passive cooling is 13.–14.2%.

3.4. Desirable fluid flow rate within integrated thermal system

The performance of a PVT system is determined by the electrical and thermal efficiency of the system simultaneously [143]. In addition, various elements, including fluid kinds, mass flow rates and volumes, collection structures, setting angles, and environmental conditions, all impact efficiency. The mass flow rate of fluid circulation was an even more relevant aspect that played a role in determining the performance of a PVT system [144]. With an increase in mass flow rate, the PVT collector's temperature drops while its output power rises. Remarkably, when the mass flow rate is increased, both vary oppositely. Additionally, the PVT system's electrical efficiency and temperature differential are rarely impacted by the volume of water. The flowing fluid in a PVT air collector increases thermal conduction between the absorber and tubes, improving the collector's performance [145]. Integrating PCM with the PVT system can result in better temperature distribution in the solar cells, and the thermal energy saved during the melting process can be recovered after sunset.

To assess the design and efficiency enhancement of PVT systems, extensive research has been published in the literature. Based on various design configurations, a notable improvement in PVT systems has been achieved lately. The suggested modelling study aims to evaluate the thermo-electrical efficiency of hybrid PVT systems [146]. Using hybrid PVT collectors cooled by pure water, copper (Cu)/water, and aluminium-oxide (Al_2O_3)/water nanofluids, a mathematical model is built. It has been examined and shown how the mass flow rate and volume percentage (vol%) of the nanofluids affect the PVT results. In comparison to pure water and Al2O3/water nanofluid, the study shows that Cu/water nanofluid exhibits superior PVT performance. Copper nanoparticles, which have a volume concentration of only 2%, have been shown to improve the average electrical efficiency by 4.98% and the thermal efficiency by 5.23%. Adding Cu/water nanofluid to PVT at a mass flow rate of 0.03 kg/s increases the thermo-electrical efficiency by 4.40% and 2.9%, respectively. A mathematical model is constructed by employing hybrid PVT collectors that are cooled by pure water, Cu/water, and Al_2O_3/water nanofluids. It has been examined and shown how the mass flow rate (m) and volume percentage (vol%) of the nanofluids affect the PVT results. In comparison to pure water and Al_2O_3/water nanofluid, the study shows that Cu/water nanofluid exhibits superior PVT performance. The average electrical and thermal efficiency are improved by 4.98% and 5.23%, respectively, with just 2% volume concentration of Cu nanoparticles. The thermo-electrical efficiency of the PVT with Cu/water nanofluid increases by 4.45% and 2.9%, respectively, at a mass flow rate of 0.03 kg/s. Abdallah et al. [147] examined the performance analysis of hybrid PVT integrated nano fluid system at low concentration MWCNT. Compared to PV modules without cooling systems, the average temperature of the former was lowered by cooling systems, which may use either pure water or water mixed with Nanofluid. MWCNTs, a water-based nanofluid at 0.075% V produced the highest system efficiency. An overall system efficiency of 83.26% was achieved at this concentration when the PV panel's temperature was reduced by 12 °C at maximum incident radiation. Furthermore, an overall efficiency of 61.23% was attained during the daytime with an average temperature drop of 10.3 °C. The results and main takeaways from the numerous numerical and experimental investigations on the performance of PVT systems with varying absorbers and flow rates are presented in Table 1.

3.5. The negative influence of PCM, NePCM and nanofluid on PVT system

The integration of PCM/NePCM and nanofluid significantly enhances PVT systems in terms of electrical and thermal energy. However, it is important to note that integrating PCM and nanofluid in PVT has some significant limitations that must be addressed in future research. In general, compatibility issues may arise between PCMs, NePCMs, nanofluids, and system components such as heat exchangers within Photovoltaic-Thermal (PVT) systems. These compatibility concerns can manifest as material degradation, corrosion, and clogging over time, potentially compromising the reliability and longevity of the PVT system [148]. Furthermore, integrating PCM/NePCM and nanofluids into PVT systems often necessitates intricate system designs and additional components, such as PCM containment structures and circulation systems. Consequently, incorporating these components may elevate both the installation and maintenance costs and augment the risk of system failure [149].

A significant challenge associated with PCM-integrated PVT systems lies in ensuring the proper containment of PCM materials. Leakage or seepage of PCM can occur due to various factors, including material degradation, mechanical damage, or inadequate sealing of containment structures. Such instances of PCM or nanofluid leakage not only compromise system performance but also pose environmental and safety risks [150,151]. Moreover, PCM or nanofluid leakage can precipitate system malfunctions, loss of heat transfer fluid, and damage to critical system components such as pumps, heat exchangers, and pipes. Consequently, these reliability issues may culminate in system downtime, escalated maintenance expenditures, and a diminished overall system lifespan.

3.6. Summary

The structural design of the PVT, which had previously been the most prominent aspect of the field, became less important as the PVT evolved into a more polished hybrid system. It would be a bold move to optimize PVT collectors to deliver thermal energy at higher temperatures with simpler, cheaper designs while reducing electrical and thermal losses and ensuring the collectors last a long time and are reliable. This would increase the technology's potential applications and market adoption. It is possible to improve the energy efficiency of the PVT system by increasing the packing factor. When the collector length, the number of pipes, and the ideal pipe diameter are all raised in a PVT system, the exergy efficiency of the system is maximized.

All of the PVT collectors discussed here are compatible with solar technologies, allowing them to produce thermal energy, electrical energy and thermal management. Considerations like as application, location (solar irradiance and ambient temperatures), and technology all play a role in determining the best PV-T collector and solar thermal storage system. PCMs are very good at saving potential energy. Their great storage potential becomes activated when PCMs undergo phase changes. If these materials don't undergo a phase change, they won't have the same special ability to store energy as other materials. Stability under cycling, latent heat, the temperature range needed, and the availability of a heat source are the main factors that decide whether a typical PCM is suitable for a given application. A good example is the requirement that PCMs used in passive solar buildings have tolerable temperature ranges for humans. In an attempt to improve the system's performance, researchers have examined and changed common PVT-PCM components. We may classify the current best designs for PVT-PCM systems into three broad categories: first, the addition of fins or other enlarged surfaces; second, the use of multilayer PCM; and third, the modification of the collector shape. In comparison to purchasing PV panels and solar thermal collectors independently, the price of PV-T collectors is still somewhat high. Substituting Si or other non-crystalline PV materials for Si polycrystalline PV cells is one way to cut costs. To add to that, economies of scale should cause the price of PV-T collectors to go down as the number of PV-T systems installed grows. The discrepancy between theoretical studies and the system's actual industrial development is undeniably significant. Industries can benefit from the work's principles and essentials, which can be used to promote this system. Finally, the most pressing issues originate from the fact that there is no universally accepted method for monitoring or analyzing the efficiency of PV/T systems; this is because experts in the field continue to hold divergent opinions, which could slow down or even halt the advancement of relevant technologies. That is why it is critical to prioritize the establishment of an international standard.

4. Mitigation technologies & techniques to improve performance of PCM integrated PVT system

Solar power plants are typically designed with a projected operational lifespan of from 25 to 30 years. Nevertheless, the accumulation and consolidation of dust particles and their various forms might diminish the efficiency of power generation to its maximum potential [32]. According to Al-Badra et al. [160], Elamin et al. [161] Kazem et al. [162], the presence of collected dust and soiled on solar panels has been found to lead to a yearly reduction in energy output of up to 7.0% in specific regions of North America, Latin America, and the Caribbean. Energy losses of up to 50.0% have been documented in the Middle East. [163]. Fig. 11 shows the various types of cleaning methods used to clean the PV system. There are two categories of cleaning and mitigating strategies. Both organic and synthetic cleaning agents are used. Wind, rain, snow, gravitational forces, and dew all play a role in the natural cleaning process. Various methods of mechanical cleaning, such as manual, automatic, semi-automatic, as well as electrodynamic screen cleaning and surface heating. Also, preventive measures encompass the implementation of several strategies, such as the establishment of a tracking system, adapting the site, and carefully selecting the location. Additionally, the installation of specialized photovoltaic (PV) modules with anti-soiling coating and optimal design also recommended. In addition, various factors affect s the cleaning the PV panel as depicted in Fig. 12. This section discusses the potential mechanisms that may contribute to effective solar panel cleaning while preserving their power generation capabilities.

4.1. Advanced surface cleaning techniques

4.1.1. Electrostatic cleaning

Electrostatic cleaning is a widely recognised technique for the purpose of cleaning solar panels in environments characterized by high levels of dust accumulation. The concept has been devised utilizing a high alternating current (AC) voltage, which is employed to energize the electrodes positioned on the filthy solar panels, so facilitating the removal of dust particles. This method effectively eliminates dust and other types of debris (except algae) that accumulate on the solar panel. A finite element model was employed to analyze this mechanism, utilizing the ANSYS software. The width of the electrode was set at 0.5 mm and the electrode spacing was set at 1.3 mm [164]. The investigation focused on examining the distribution of the electric field in both the horizontal and vertical directions. The electric field density inside the system exhibits spatial variation across the plate, resulting in the generation of a force acting upon the dust particles, hence causing their displacement away from the plate [165]. The alternative electrode configurations that were investigated are depicted in Fig. 13. Kawamoto et al. [166] reported that when the high voltage is applied, there is an electrostatic force act ion particle near solar panel parallel screen electrodes. As a result of the alternating electrostatic field, particles move through the apertures in the upper screen electrode and descend down the slanted panel under the influence of gravitational force. The dust removal efficiency was increased due to minimal-frequency high-voltage, panel inclination, and minimal initial dust loading maximize cleaning efficacy. Repeated cleaning reduces dust accumulation.

Furthermore, an experiment conducted under sunlight shown that the selection of electrodes had a negligible influence on the generation efficiency of the PV unit [168]. Kawamoto and Shibata, reported the use of electrostatic cleaning > 90% of the adhering sand is removed from the slightly tilted PV panel [169]. The power usage of the system is negligible. The anticipated to considerably improve the performance of big solar power stations built in deserts.

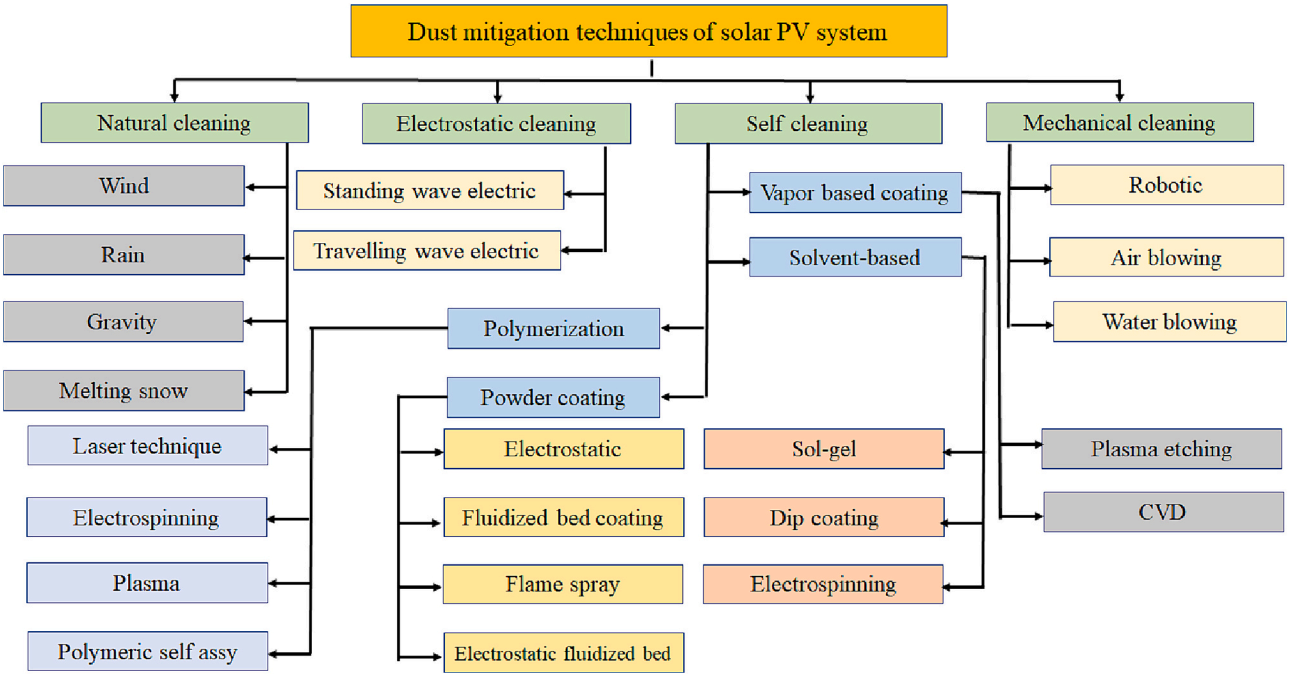

Fig. 11. Dust mitigation techniques adopted for solar PV system.

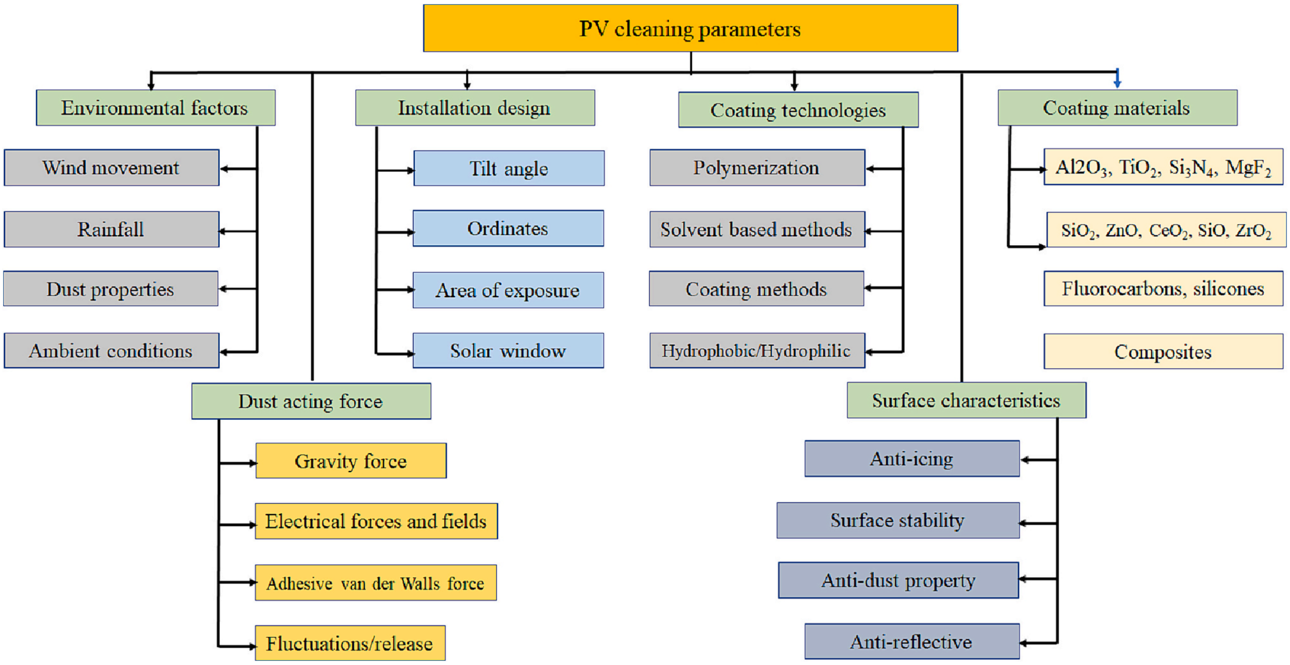

Fig. 12. Parameter affects the cleaning of PV system.

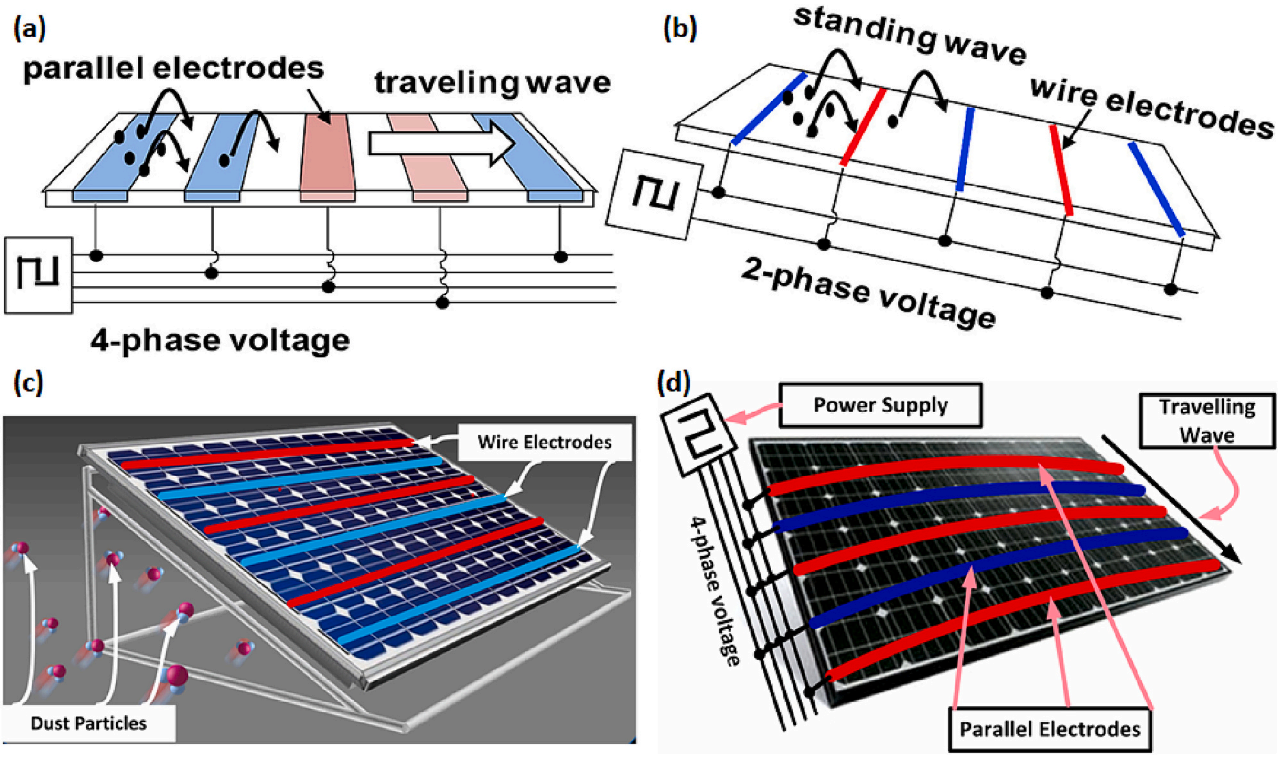

Fig. 13. Electrostatic PV panel cleaning methods (a) Parallel electrodes with travelling wave, (b) Standing wave with wire electrodes, (c) Wire electrode (d) Parallel electrode cleaning method [32,167] [Reused/reproduced with permission from the publisher].

4.1.2. Robot-based cleaning

Robot-based cleaning is a contemporary approach employed to effectively remove dust from contaminated photovoltaic (PV) panels. Typically, this approach involves the utilization of a robotic arm or a robotic cleaning gear in conjunction with a mobile carrier. The majority of systems are equipped with either a wiper or brush, moving either horizontally or vertically depending on dirt detection. Furthermore, certain systems are designed as robotic cleaners [170]. The activation of the system can be achieved through manual means, as well as through the utilization of electrical or electronic control devices, or a combination thereof. Typically, they are affixed to the photovoltaic panels as an ancillary component intended for the purpose of cleaning [171]. Parrott et al. [172]designed an automated robot for cleaning a solar system using a silicon rubber brush. The research revealed that using a silicone rubber foam brush in the robotic system led to a notable decrease in the detrimental impact of dust accumulation on the power output of solar panels. Consequently, this led to a notable rise in power output than the control group, which underwent weekly cleaning.

The different types of robot cleaning techniques such as suction-type of robot cleaning, water-free cleaning robot, wiper type robot, and silicon rubber brush type are displayed in Fig. 14 (a)-(d). Recently Fan et al. [173] developed a robot for cleaning PV panel for water scarce areas like high elevation areas. A novel dust removal device, which incorporates a rolling brush and negative pressure, has been designed to effectively mitigate the issue of dust dispersion during the cleaning process and the experiments conducted on a 2-kW distributed PV system installed on the roof of a Northeast China university. The findings indicate that the waterless cleaning robot is capable of efficiently eliminating dust particles from the panels. The mean dust cleaning rate is recorded at 92.46%, while the range of improvement in photovoltaic efficiency spans from 11.1% to 49.5%.. Cai et al. [174] optimized the height width and neck radius robot to achieve the optimum cleaning of PV system. An orthogonal technique was used to optimize the parameters by computational fluid dynamics (CFD) using ANSYS fluent. The optimal results of fluid inlet width, outlet width, inlet height, outlet height and neck radius were 650, 175, 6, 100 and 350 mm, respectively. Ghodki et al. [22] developed a revolutionary silicon rubber-based infrared sensor technique that enables multitasking capabilities like shadow-free cleaning, seamless transition from day to night cleaning, monitoring the movement and overheating of the robotic arm. The experimental study conducted on a 30 WP system yielded an average energy increase of 11.88%, a PV module efficiency of 13.02%, and a performance ratio of 81.35% after a cleaning period of 2.4 months. The system demonstrates a higher cleaning rate of 1.86 m^2/s while consuming a reduced amount of water at 0.31 L/m^2. Additionally, it offers a cost-effective solution with a price of 1.84 dollars per kilowatt for each cleaning cycle. Mousavi and Farahani newly developed suction robot called MFv01 has better cleaning performance than other systems like Antonelli and Ecoppia T4 devices. The interesting is this system operates without guides, rails and fins its spatial position by ultrasonic sensors [175]. One notable benefit of utilizing robot-based cleaning methods is the enhanced accessibility it provides for cleaning panels from diverse horizontal and vertical angles, hence resulting in improved overall cleaning efficiency. Additionally, it has the ability to endure severe fluctuations in climate.

4.1.3. *Self-cleaning*

The development of self-cleaning methods aims to address the challenges posed by labour costs and the inaccessibility of certain areas that cannot be effectively cleaned by labour. By implementing the automation auxiliary system for cleaning as an additional feature to the existing system, the need for manual labour can be substituted or minimized. Numerous self-cleaning techniques have been devised to address the issue of dust and soiling mitigation. The self-cleaning approach is employed to remove the dust, whereby various coating materials such as hydrophilic, hydrophobic, surfactants, and others are utilized. This will enable the development of a hydrophobic surface that facilitates the rolling off of water droplets, effectively removing dust from PV panels. Hariri et al. [25] investigated a novel technique to remove dust from the PV system by SMA based cleaning system. It was reported that the rejected panel heat has used to run the SMA-based cleaning system. The novel system significantly improves the performance of the PV device and no additional power is required to actuate the mechanism. One of the primary benefits of self-cleaning methods is their ability to sustain optimal power efficiency for extended durations, due to their advanced repellent surface technology.

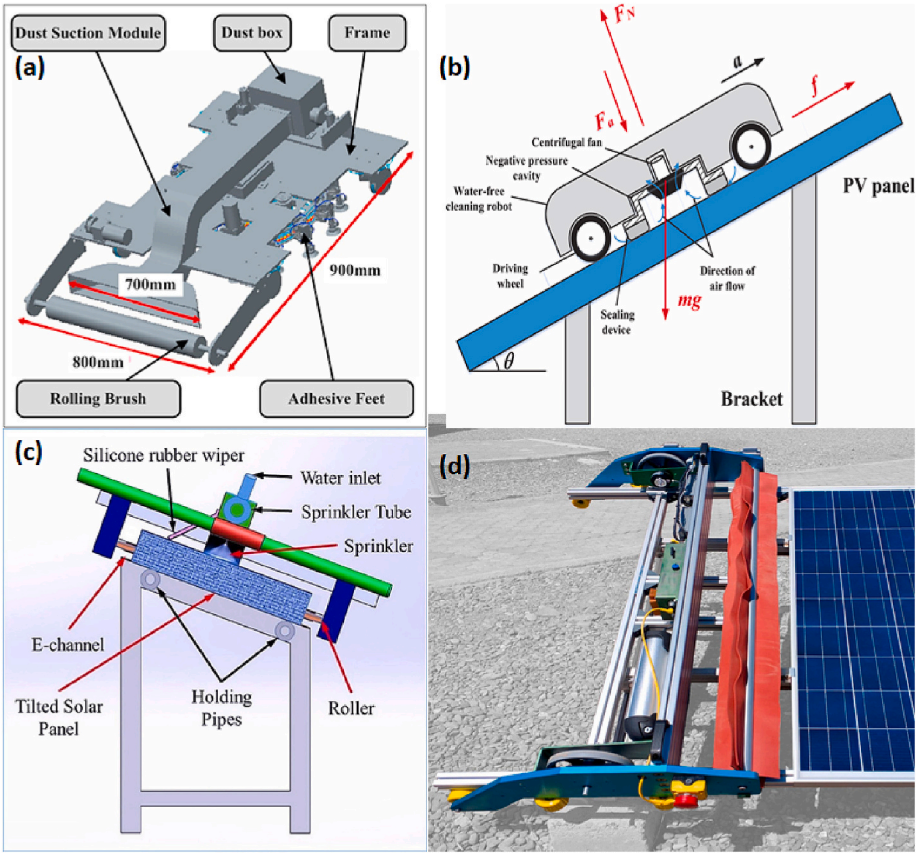

Fig. 14. Various robot cleaning of PV panels (a) Roling brush robot [174], (b) Water free robot cleaning [173], (c) Arrangement of silicon rubber viper and sprinkler [22] and (d) Dry cleaning robot [172]. [Reused/reproduced with permission from the publisher]

4.1.4. *UAV based cleaning*

Unmanned aerial vehicles (UAVs) are an innovative method for the purpose of maintaining and cleaning solar panels. The technology has the capability to transport cleaning fluids and pneumatic pressure in order to effectively clean PV panels. It also utilizes active sensors equipped with illumination sources and mapping cameras to ensure optimal location during the cleaning process. The incorporation of autonomous elements enables these systems to engage in uninterrupted operations. Al-Housani et al. [176] studied and compared the different types of drone retrofitting to enhance the performance, minimize the cost, time saving, and reduce environmental degradation. It has been found that when employing drones to clean PV panels, the most appropriate options are brushes and wipers with microfiber-based cloths due to their lightweight, compact size, and user-friendly nature. Tommaso et al. [177] investigated the PV panel defects using an automatic multistage model on the images captured by YOLOv3 network and computer vision technique, as shown in Fig. 15(c). The model assesses hotspot area severity by leveraging estimated temperature gradients and calculates soiling coverage using visual images. Finally, the impact of varying YOLOv3 output scales on detection performance is examined. Mohendes et al. [178] investigated PV panel duct cleaning using a drone technique. The effort aims to decrease the soiling effect on the panels by flying the drone above the panes in certain height and time intervals. The downward thrust is a cruise at a certain height to remove the dust. It has been described that the horizontal movement of drone efficiently cleans the panel, consistently achieving the highest efficiency. Recently, Sarkis et al. [179] designed a novel drone, as shown in Fig. 15(a) for the removal of dust from a small type of PV power plants, PV-based street lights, solar-powered water pumps, etc., The approach relies on a hybrid drone capable of rolling across the entire surface of a PV for cleaning and flying between different units. The results confirmed the prototype efficiency in cleaning distributed small PV panels. Nonetheless, additional improvements are necessary to realize a fully autonomous cleaning system.

Fig. 15(d) explores a technique for monitoring energy production site applications through the use of UAVs and examines the potential impact of this concept on energy management procedures. Furthermore, on-site investigations have been conducted, and UAVs have been employed for inspections [180]. Javier [181] demonstrated the full automation the inspection and identification of damaged collector tubes in parabolic trough techniques as shown in Fig. 15(b). This was achieved through the creation of airborne detection algorithms rooted in machine learning (ML) techniques. The ML algorithm was trained using aerial UAV digital images obtained from operational facilities. These images underwent pre-processing via machine vision algorithms to enhance the detection of panel failures. The approach involved a blend of thermographic images in identifying detrimental temperature patterns in the parabolic trough collector receiver glass sleeve. Concurrently, visual red, green, and blue (RGB) images were analyzed to assess the receiver's efficiency losses compared to an intact receiver's reference efficiency. Consequently, the researcher inferred that the developed method could predict the presence of broken collector glass with an accuracy of up to 70%.

Grando et al. [182] studied the primarily delves into various commercially available UAV robots designed for cleaning PV panels. The research examines the following cleaning methods; Ecoppia E4, sprinklers by Heliotex, NOMADD system, wash panel and solar brush UAV robot. The predominant cleaning methods typically involve using a motorized brush to mop the panels in various configurations. However, there are less efficient cleaning techniques, such as the dust removal method using a water jet applied to the panel. One significant benefit of utilizing UAV-based cleaning methods is the ability to improve the effectiveness of solar panels through the utilization of thermal detectors or thermography for cleaning prognosis procedures. Additionally, it enhances the accessibility of panel cleaning.

4.1.5. *Automated cleaning*

The implementation of automated cleaning techniques for solar panels has great potential in mitigating the limitations faced by operators. The cleaning system provides autonomous capabilities through the utilization of programmable logic controllers (PLCs) and microcontrollers to effectively automate the cleaning procedure. This process is facilitated by a collection of reservoirs and nozzles containing water and cleaning ingredients, which are utilized to execute wash and rinse cleaning cycles.

Myyas et al. [184] invented an automatic cleaning system to clean the PV panel to boost the effectiveness of the unit. The proposed system cleans the panel and harvests rainwater. The salient feature of the proposed system is (i) harvesting rainwater, (ii) automatic on/off, (iii) recycle the cleaning water, (iv) PV panel always clean, (v) less maintenance due to no moving parts, (vi) less manpower, (vii) system cost is less compared to manual, robotic cleaning, (viii) without maintenance long years will work. Al-Badra et al. [160] explored nanocoating with automatic vibrator to enhance the electrical performance of the PV panel. Notably, electrical efficiency was improved 60.78% while the use of nano coating and automatic vibrators. Jaiganesh et al. [185] discovered the performance of PV using an automatic wiper cleaning system using Arduino. It has been found that the cost of the entire system is significantly lower in comparison to other alternative systems. There was a reduction in the overall level of deterioration, leading to an improvement in the efficiency of the PV panel. Sugiartha et al. [186] developed a water spray and operates in a semiautomatic manner prototype, serving as a cleaning mechanism. The repetitive wiping action, conducted 10, 20, and 30 times, results in performance levels of 57.0%, 79.10%, and 86.71% relative to the initial clean surface condition. Katakam et al. [187] designed and fabricated a semi-automatic mechanism for removing the dust from the PV panel using water and energy. It has been found that use of a semi-automatic mechanism, the efficiency was improved to 1.2–3%.

Automated cleaning offers a notable advantage as it is an environmentally friendly solution that actively supports decarbonization. Furthermore, the implementation of automatic cleaning systems not only minimizes the need for regular maintenance but also contributes to the improvement of power efficiency in solar panels.

4.2. *Emerging anti-coating technologies*

The utilization of anti-soiling coatings on the surface of solar panels represents an additional approach aimed at mitigating the adverse impacts of dust and soil. These coatings enhance their hydrophobic properties, allowing rain or dew to effectively remove dirt particles from their surfaces. Hydrophobic coatings have the capacity to reduce adhesion and enhance cleanability of surfaces. Anti-soiling coatings play a crucial role in preserving the optimal performance of panels by reducing the frequency of necessary human or automated cleaning procedures.

Hydrophobic coating increase the contact angle between the surface of photovoltaic panels and water droplets, allowing the droplets to roll off freely and effectively remove dust. The substitution of group I ions with either groups II or III ions through chemical process can generate solutions resistant to water or imbued with hydrophilic properties. Such hydrophilic solutions are engineered to repel the accumulation of dust, and the sheeting action of water aids in effectively cleansing the surface of PCV systems [189]. Various coating mixtures are currently under exploration, but they face commercial challenges due to prolonged exposure to UV radiation, which can result in permanent damage and reduced durability, especially when subjected to wind and sand erosion. To address this issue, thick coating of oils like natural oils, mineral oils, engine oil or brake oil are applied to exposed PV panel planes. Notably, mineral oil coatings offer 24% higher transmissivity than standard glass coating, making them a viable option for enhancing PV glass with antireflection coating [190]. Fig. 16 depicts the detailed representation of hydrophilic and hydrophobic self-cleaning process.

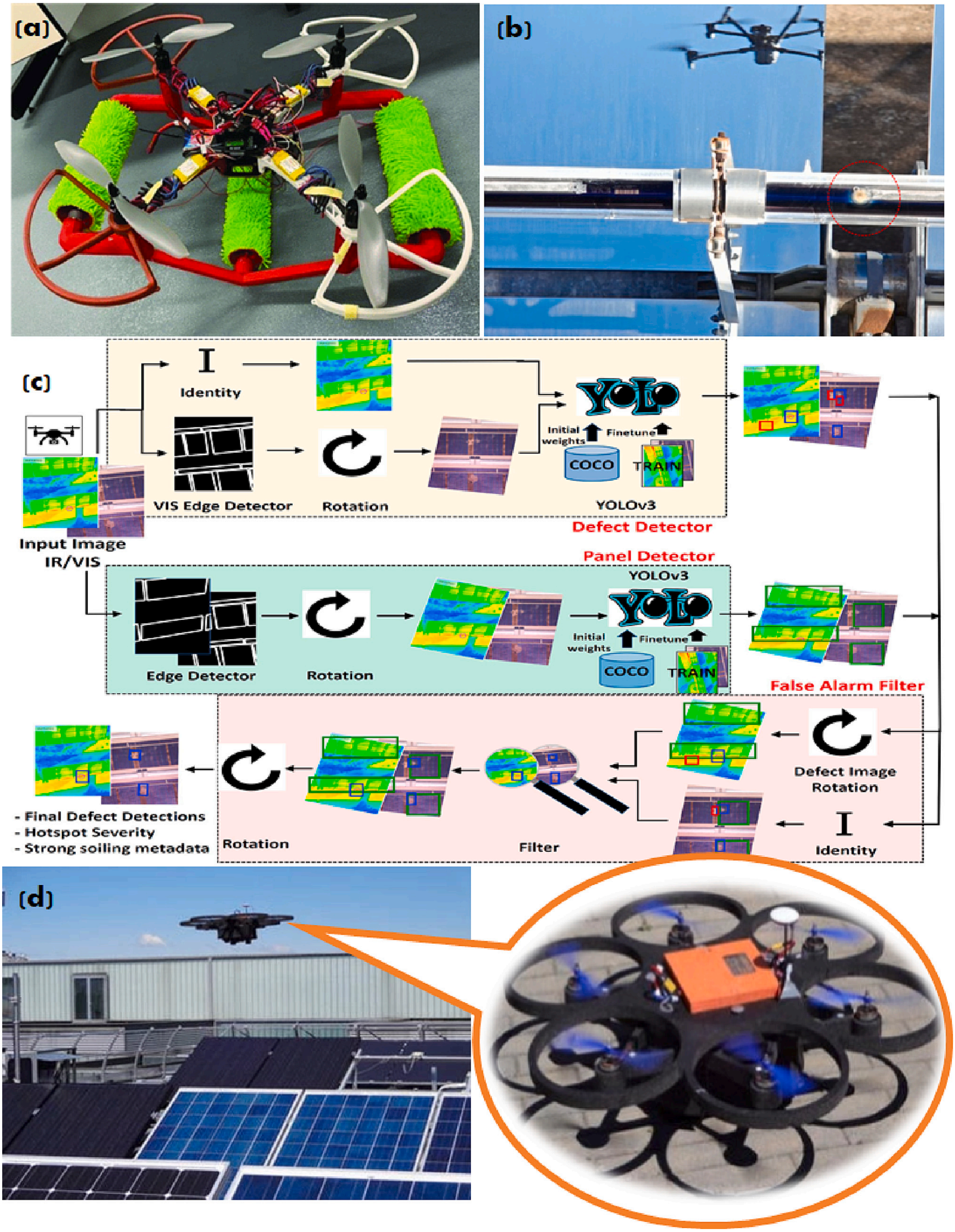

Fig. 15. Unmanned Aerial Vehicles based PV panel cleaning (a)Integrated hybrid drone for PV panel cleaning, [179] (b) Aerial inspection of collector tube damage in a parabolic trough technique [183], (c) the workflow of the proposed model involves taking an input image, whether it's in the infrared or visible spectrum, and passing it through the panel and defect detectors utilizing the YOLOv3 architecture and computer vision technique [177], and (d) Solar tech laboratory Nimbus PPL-610 UAE- PV panel inspection [180] [Reused/reproduced with permission from the publisher]

Tuff Fab is a user-friendly coating that transforms glass surfaces into non-sticky, easy to clean surfaces. It eliminated the need for harsh chemicals and scrubbing when cleaning PV panels. With this method, a simple combination of clean water or a gentle cleanser and a soft towel is all that's required to effectively clean the PV panels [191]. In addition, few researchers [192,193] have executed other stuffs similar to Tuff Fab.

Recently, Lu et al. [194] investigated self-cleaning coating for four different dust removal coating. After the deposition of dust, an analysis was conducted on the micro and macro sizes of particles, deposition density, transmittance, and power output. The superhydrophobic coating significantly mitigates the reduction in transmittance caused by deposited dust on the solar cell. It demonstrates the highest effectiveness against dust C, followed by dust D and dust B. Dust A exhibits the least improvement in transmittance with the super hydrophobic coating. Consequently, the coating proves to be efficient in reducing the degradation of transmittance after dust deposition. Ekinci et al. [195] examined the PV panel power output of various chemical cleaning (2-Propanol, Ethanol and Acetone) techniques and cleaned by robot which is run by 3D printing technology to replace the dust particles from PV panels. It was found that 2-propanol had higher cleaning efficiency than the other 2 chemicals. In a study by Ratnaparkhi et al. [196], the soiling effect on hydrophobic coating was compared with and without dew suppression. The findings revealed that the percentage reduction in soiling was higher for the coated surface under dew suppression compared to the coating without dew suppression. Ye et al. [197] investigated distinctive nanostructure coating, characterized by its remarkably low surface energy and, roughness is formed by incorporating fluorinated cluster core shell structure solar cells in to a self-developed silicon precursor through a template free two step base /acid catalyzed reaction. The findings of this study demonstrate the promising potential of nanocomposite coatings for outdoor applications, namely in the areas of energy harvesting and optical instruments under wet settings. These coatings are prepared to possess smooth surfaces, high refractive indices, and low reflection. Wang et al. [198] explored the anti-soiling performance of PV employing transparent and super-hydrophobic FHA/SiO_2 coating. It was found the coating demonstrates impressive self-cleaning capabilities and it exhibits robust resistance to the impact of both sand and water drops. Zhong et al. [200] examined a super hydrophilic coating (TiO_2/ silane coupling agent composed of 3-triethoxysilypropylamine) for PV systems to increase the properties of anti-dust. The results indicated that the static water contact angle on the surface of the superhydrophobic coating was less than. 5°, indicating an excellent anti-dust property for PV panels. Huang et al. [201] examined the anti-soiling effect of various coatings (Super hydrophilic, hydrophilic, super hydrophobic and hydrophobic coating) with different tilt angles and flow rates. The dust adhesion on super hydrophilic coating is primarily influenced by their inherently greater surface energy, with a roughness of surface playing a lesser role in resisting adhesion. Conversely, for other coatings, reduction in surface energy further does not significantly enhance their dust-prof abilities. To achieve a surface with low surface energy, one of the most commonly employed approaches, as suggested by Arkles [202], involves silane based surface modifications. In Fig. 17(a), a schematic depicts the creation of a super hydrophobic surface achieved through the self-assembly of surface-modified nanoparticles. When water droplets land on this surface, they stay on the top of hierarchical structures, reducing their contact with the solid surface and forming spherical drops. These droplets, resembling beads, easily roll off the surface, effectively picking up and carrying away contaminant and dust particles as they roll.

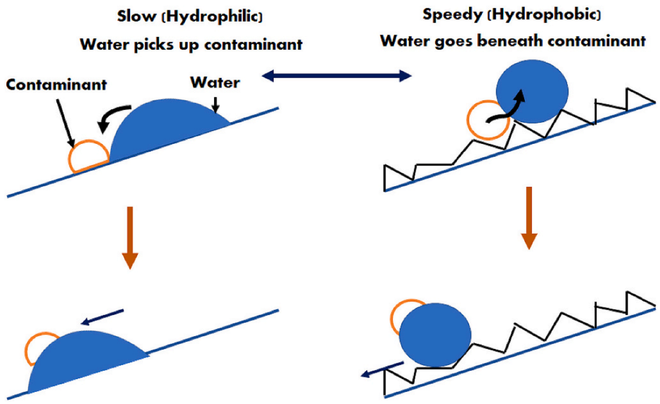

Fig. 16. Hydrophilic and hydrophobic self-cleaning process [188] [Reused/reproduced with permission from the publisher].

Fig. 17(b) illustrates the self-cleaning process of highly wettable hydrophilic surfaces. The emergence of photo-induced super hydrophilicity, particularly in wide band gap photoactive metal oxides like TiO_2, SnO_2 and Zn has spurred the creation of numerous hydrophilic self-cleaning surfaces for commercial use. In this mechanism, the photochemical degradation of organic pollutants occurs when metal oxide semiconductors like TiO_2 absorb photons with energy surpassing the energy band gap (hv > Eg). This activation results in the generation of powerful oxidants through the activation of O_2 molecules and the photolysis of water molecules. Subsequently, the chain reaction initiated by these radicals facilitates the oxidative degradation of organic pollutants, producing nontoxic inorganic compounds like CO_2, H_2O and mineral acids [203].

4.3. Tilt angle and preferable tracking systems

The installation of solar panels at an inclined angle or with a slight tilt can effectively mitigate the accumulation of dust and soil. Rainwater has the capacity to effectively remove dirt from inclined mounting systems, so preventing its accumulation on the panels [204]. Moreover, the inclined orientation of solar panels facilitates the effortless sliding of snow or ice, so substantially reducing the impact of dust and silt on the efficiency of the modules [205]. The optimal tilt angles are contingent upon factors such as climatic and geographical location conditions. Form the previous studies the soiling rate can be significantly reduced by steeper surface tilt angles [206]. Moreover, recent studies reported that, during night-time some selected places soiling is higher than daytime, suggesting that soiling mitigated by the PV panel placed by an inverted position or vertical direction during nighttime [17].

Recently, Alzahrani [207] investigated the impact of sand grains, and soiling deposition on the performance of PV modules in various environmental circumstances. The researcher employed the PV modules of two distinct technologies, Mono-Si and Poly-Si, in their experimental setup. Additionally, two different tilt angles, specifically 10° and 24°, were considered, along with two distinct surface conditions, namely clean and soiled. The monocrystalline silicon panel exhibited superior performance compared to the polycrystalline silicon module, with an average performance advantage of 13.7% observed across soiled and clean panels over the duration of the research. Nevertheless, the average power output losses resulting from the effects of soiling on the poly-Si modules were found to be 11% lower compared to the mono-Si modules. There is a reduction of approximately 40% in average power losses for mono-Si and poly-Si modules when installed at a tilt angle of 24°. Ota et al. [208] assessed the performance of PV unit with two tracker systems system. The PV panel has transition into a standby state facing downwards during nighttime, while the latter assumes a standby state facing upwards. The implementation of the tracker system with a standby state pointing downwards resulted in a constant increase of over 5% in direct transmittance at a wavelength of 500 nm.

The experiments conducted in Doha, Qatar, involved the use of glass coupons to investigate the impact of different storage orientations on dust-related losses. The results show that when the coupons were stowed vertically, there was an average reduction of 41% in dust-related losses. Furthermore, when the panels were inverted during the night, the

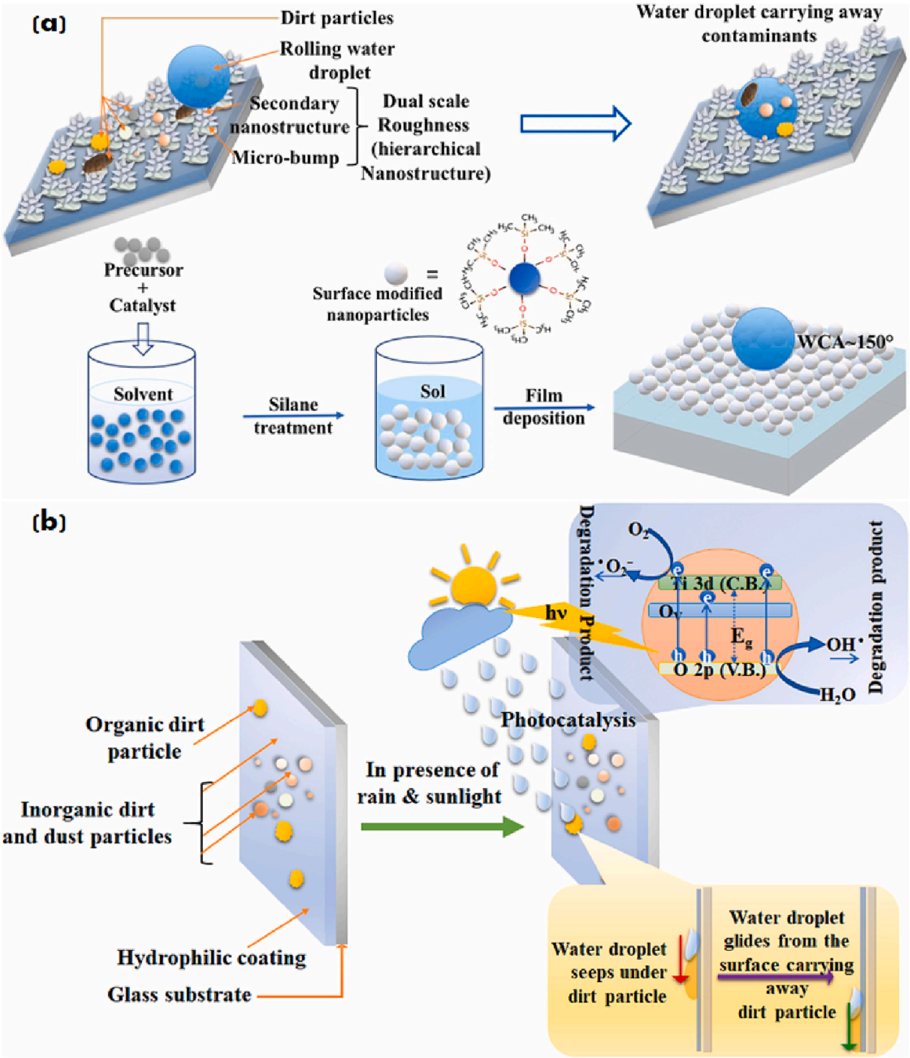

Fig. 17. Self-cleaning action (a) Schematic representation of self-cleaning action of hydrophobic surfaces, inspired by Lotus effect and standard super hydrophobic surface formed through the self-assembly of surface-modified nanoparticles [199], and (b) Schematic representation of photoinduced hydrophilic self-cleaning [199] [Reused/reproduced with permission from the publisher].

reduction in dust-related losses increased to 50%. Likewise, in the context of India, it has been observed that the act of inverting PV modules during periods of limited sunlight has led to a documented decrease of 60% in losses attributed to dust accumulation [209]. Furthermore, for vertically installed bifacial modules that are not equipped with tracking mechanisms, the reduction in losses surpassed 98% [210]. A comprehensive analysis of the leading 13 photovoltaic solar tracking firms revealed that the prevailing tilt angle range for conventional tracker designs is limited to either ±45° or ± 60°, hence rendering the practice of stowing during nighttime impractical [211]. The predicted growth of solar tracker usage in the utility-scale PV plant industry, from around 20% in 2016 to 40% in 2020, presents an opportunity to consider the expansion of the tracker tilt range for night stowing as a potentially cost-effective approach to mitigate dust. In contrast, most concentrated solar power heliostats are designed to include the capability of assuming inverted stow orientations. Specifically, parabolic troughs are commonly stowed at an inclination of −15° with respect to the ground [213]. However, it should be noted that many heliostat designs are not capable of accommodating inverted stow positions. In such cases, the modification of these designs may not be economically viable, as the costs associated with building modifications may outweigh the possible savings in cleaning expenses. Therefore, it is necessary to evaluate the technological feasibility of adapting trackers for night stowing on an individual basis. However, it is noteworthy that previous research found a significant decrease in dust collection of over 30% due to the steep stowing positions adopted by conventional photovoltaic (PV) tracking systems during nighttime [209].

A single sided PV panel with a mechanical tracking system to tilt the panels respect to various climate season was investigated as show in Fig. 18 (a)-(g) [212]. The Fig. 18(a) depicts the normal operation of PV panel. In windy conditions, based on the force Fig. 18(b)&(d), the PV panel is erected, and the dust particles are blown away by the natural wind. Similarly, in rainy season, the PV [panel tilt angle increased based n the force of accumulation dust as shown in Fig. 18(c)&(e). The installation of solar panels during nighttime has been seen to substantially impact reducing the deposition of dust on their surface, as depicted in Fig. 18(f). This study examines the distribution of dust accumulation within the PV plant and its impact on the power output. To mitigate the effects of dust accumulation, manual high-pressure water lances are employed to clean the components located at the borders of the plant. An unmanned field patrol machine is employed to detect and collaborate with the inverter in order to regulate the proportional variation of the power output of the solar panels within the array. Additionally, PV panels that are heavily contaminated by bird droppings are sporadically cleaned using manual means. It is advisable to install photovoltaic (PV) panels that allow for manual cleaning, utilizing instruments such as soft

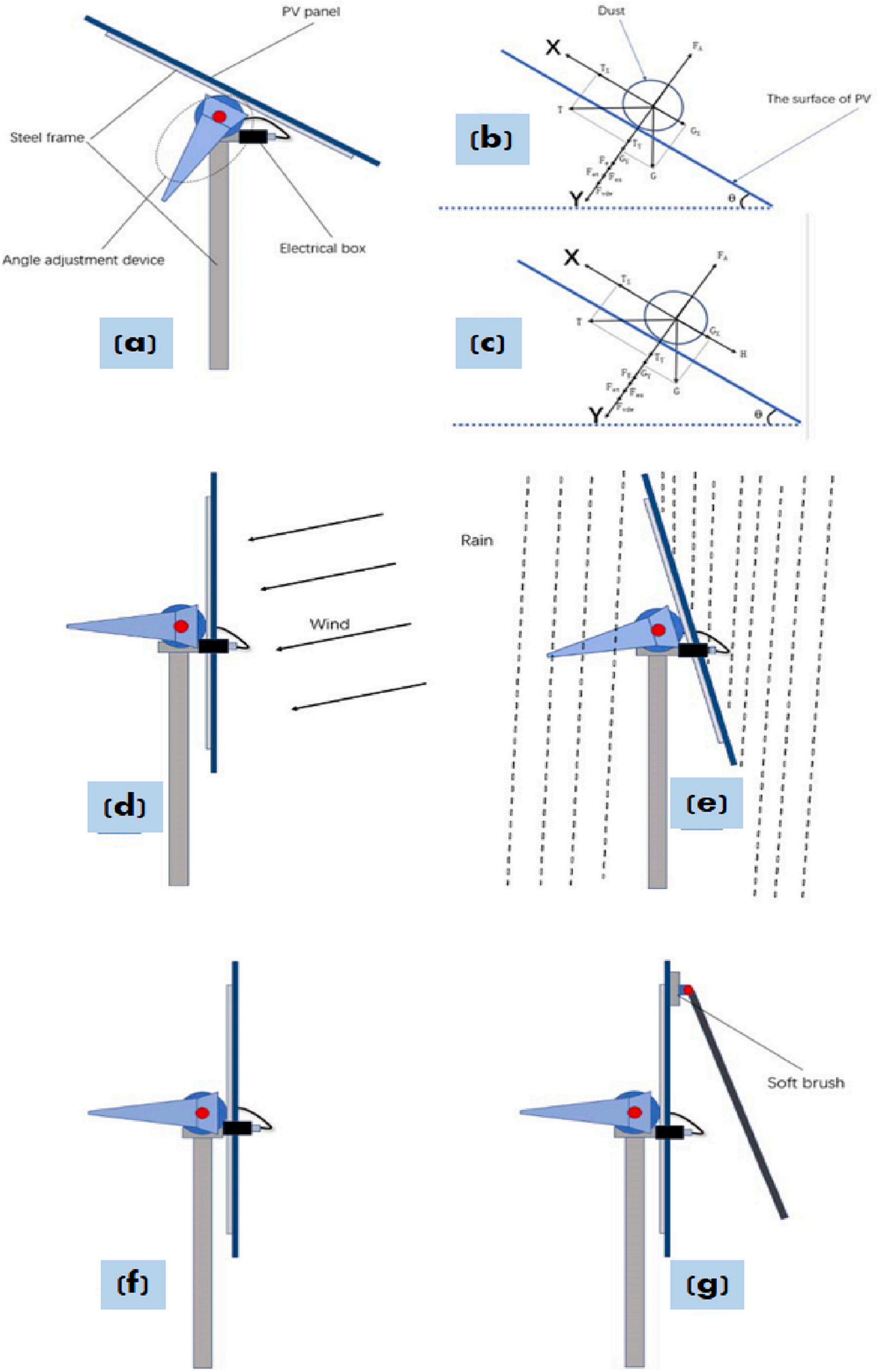

Fig. 18. Dust removal strategy using tracking system (a) normal model, (b)Mechanical system for dust accumulated by wind, (c) mechanical model of dust accumulation when washed by rain water, (d) windy weather conditions, (e) rainy seasons, (f) dust proof at night, and (g)manual cleaning [212] [Reused/reproduced with permission from the publisher].

brushes or mops to prevent any potential damage to the tempered glass surface(g). recently, various tracking systems (horizontal single axis, vertical single axis and fixed tilt system) based techno-economic study was performed [214]. It was found that horizontal and vertical single-axis tilt systems are expensive compared to fixed tilt systems. Hence, a thorough examination of the utilization of each tracker is imperative in order to evaluate whether the energy benefits obtained surpass the tracker's inherent limitations. In addition, Tejwani and Slanki [215] reported that 360° solar tracking system enhance the energy by production by 30%. Recently, Dahlioui et al. [216] reported that use of an automatic tracking system mitigates dust particles and enhances energy efficiency by 11.5% in the arid region. Majeed et al. [29]conveyed that less dust density was measured at tilt angle 60° and lower output power loss for polycrystalline PV system than systems.

4.4. *Electrodynamic screens*

The dust particles can effectively be removed by generating a time-varying electric field across a PV surface called transparent electrodynamic screens (EDSs), also known as electrodynamic dust shields. The electric fields are produced by interdigitated electrodes covered by a protective covering and powered by alternating high voltages are commonly used as displayed in Fig. 19. EDSs have been shown effectively in the lab and are frequently advocated to prevent soiling in PV systems. However, adapting them for use in the field has proven challenging due to factors such as the interference of coarse environmental conditions on electronic systems and the adhesion of dust to the surface caused by moisture [217]. The reported problems include diminished efficiency under higher relative humidity conditions, prolonged particle residence on the top surface, and low surface tilt angle. Saudi Arabia recently introduced a PV panel with a 32% reduction in dust accumulation. However, its large-scale implementation is not preferable due to the high cost of approximately 30 €/m^2. An effort is being made to mass-produce EDS systems in an effort to bring the price down. For widespread commercial use, however, proof of reduced costs as well as performance in a range of climates and durability is required [17]. Therefore, EDSs will probably be used only in situations where large system costs are tolerated in the near future.

Mazumder et al. used transparent parallel electrode to remove the dust particles from the PV panel. When subjected to phased voltage, the electrodes become activated, resulting in the electrostatic charging dust particles present in the film surface. These charged particles are subsequently eliminated by the moving wave produced by the applied electric field. [218]. The advantage is within two seconds, around 90% of the dust particles are removed. The integration of transparent and reflective electrodynamic screens onto the surface of solar mirrors has the potential to uphold a specular reflection efficiency of over 90%. The utilization of gravure offset printing and flexographic printing techniques in the production of EDS films demonstrates the possibility of achieving scale-up and high-volume manufacturing capabilities [219]. In their study, [220] showcased the efficacy of transparent self-cleaning dust shields employing the EDS system technology as a viable dust mitigation solution. Transparent plastic sheets, specifically polyethylene terephthalate (PET) chosen for its UV radiation resistance, are utilized in constructing electrodynamic screens. This screen comprises a set of parallel conducting electrodes crafted from transparent indium tin oxide, this screen is integrated beneath a thin transparent film. Furthermore, it has been documented that to maintain the high optical efficiency of PV units, the operation of the EDS film requires less than 0.2 W/m^2 per cleaning cycle, demonstrating an impressively low level of power consumption for the EDS. A design for PV panels involves applying parallel optically transparent and conductive thin films, such as ITO, AZO and IZO, onto a glass substrate. This substrate is then enclosed within a thin transparent dielectric layer to create a distinctive EDS configuration. By applying high voltage pulses of appropriate frequency to the electrodes, electrostatic forces are utilized to charge and repel dust particles that accumulate on the EDS surface [221]. In addition, Bock et al., [222] the pulsed high voltage signal needed for this dry-cleaning process is directly generated by the solar PV itself. The integrated approach has been devised to eliminate dust from PV panel without need of water, specifically in remote regions where water is limited. The next sub section discussed the other techniques like dew mitigation, model design etc.

4.5. *Other methodologies*

4.5.1. *Dew mitigation*

Research has identified dew as a significant contributing factor to soiling in various locations, affecting both PV and concentrated solar power (CSP) systems. Dew influences this phenomenon by promoting cementation, reducing particle rebound, and creating noticeable soiling patterns. Condensation typically reaches its peak just before sunrise during periods of elevated relative humidity. This is because PV modules tend to be cooler than the surrounding air due to their infrared radiative emission to the sky, a phenomenon known as radiative cooling.

PV modules often exhibit a noticeable temperature decrease below the ambient temperature, leading to the modules reaching the dew point temperature, specifically in clear sky conditions. Moreover, condensation may take place at temperatures exceeding the dew point, influenced by capillary and hygroscopic condensation phenomena. Dew significantly increases soiling rates compared to dew-free days. The different techniques of soil mitigation are clearly represented as Fig. 20(a)-(d). As a result, innovative methods have been proposed to tackle soil contamination, such as active and passive surface heating techniques to prevent condensation. These methods involve generating heat through a controlled current supply to solar cells, modified use of PVT collectors, or the utilization of PCMs, commonly used for cooling PV systems during daylight hours. Furthermore, implementing low-emissive (low-ε) coatings has the potential to reduce radiative cooling and dew occurrence [17].

Active heating at a reasonably high power level, has been proposed as a method that could achieve up to a 65% reduction in soiling. However, there is currently a lack of empirical evidence, theoretical models, and practical conclusions regarding the economic feasibility of employing heating techniques for mitigating soiling. Nonetheless, considering the benefits of cooling PV modules during the day, it is

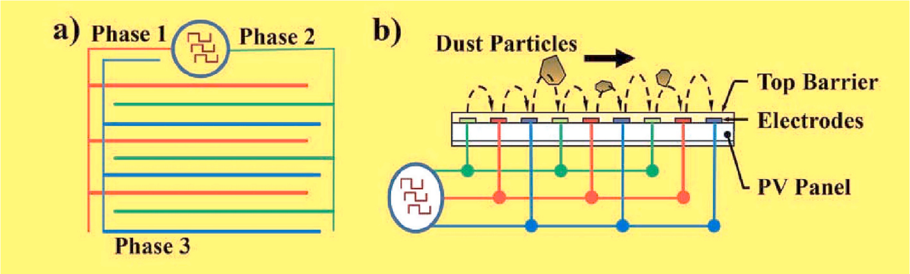

Fig. 19. Working principle of EDS system (a) three phase electrical diagram, (b) Dust removal by EDS Technique.

worth exploring the potential of heating these modules at night to reduce soiling, particularly in scenarios with high maintenance costs. This approach may be particularly relevant in arid areas, remote localities, street lighting systems, and building-integrated PV setups [17].

4.5.2. *Module design*

The design and materials of PV modules can be customized to mitigate the effects of non-uniform soiling patterns. The utilization of half-sized PV cells, the arrangement of cell strings and bypass diodes, and the implementation of frameless modules to prevent the accumulation of dirt along the edges serve as illustrative instances. The presence of partial shadowing on a PV unit, caused by the accumulation of dust in a preferential manner, can result in a more pronounced degradation of power production compared to an equivalent amount of dust that is evenly spread across the module. It is worth noting that shading a single solar cell by 50% has the potential to activate the bypass diode within the string, as depicted in Fig. 20(e)-(f). This activation can result in a reduction of power production by one third in a standard 3-string module. Given that soiling typically tends to develop on the lower frame, it is plausible to suggest that a concentrated layer of dust covering the lower row of cells might potentially result in a total loss of power if the module is positioned in an unfavorable manner. On the other hand, in the case of modules employing PV cells with decreased dimensions, the potential occurrence of this scenario can be mitigated through the implementation of parallel sub-strings of cells. The power output of half-cell modules may exhibit an increase of up to 65% compared to equivalently shaded full-cell modules. However, noteworthy that this enhancement is contingent upon various factors like as the arrangement of cell interconnections, the pattern of shading, and the orientation of the module. Moreover, in situations when shade is present, it is possible for half-cell modules to exhibit lower temperatures as a result of altered heat dissipation in the reverse-biased state. Currently, there exist commercially available PV modules that possess advantageous module designs within the market. Because of diminished electrical losses and enhanced optical benefits, it is anticipated that half-cell modules may exhibit comparable or potentially lower production costs per Watt peak in comparison to full-size modules.

4.6. *Possible sustainable solution*

PV researchers have paid little attention to soiling mitigation through plant site selection and adaptation. However, insights can be gleaned from CSP systems, which experience more significant effects from soiling compared to PV systems. During resource assessment measurement campaigns, it is critical to conduct a detailed investigation of soiling parameters (daily loss rate, dust characteristics, and rain frequency) at each potential site. This involves using full-size PV module soiling measurement equipment at their designated tilt, tracking pattern and orientation. At the moment, reliably predicting soiling based purely on climate data remains difficult, while several research studies have found fundamental principles of soiling dependence on other weather indicators. Furthermore, soiling rates might vary widely, even within the same site. The risk of soiling increases in proximity to dust-generating sources, such as industrial facilities like cement factories, agriculture and livestock farms, or dirt and high-traffic roads. The graphical representation of minimizing the dust particle settling on the PV panel is show in Fig. 21(a). Such sources can be avoided by site selection, but if they are unavoidable, the impact can be managed through solar plant design and architecture that allows cleaning. This covers determining row spacing and length to make the most of cleaning equipment. Preventive measures, such as vegetation, water spray, paved roadways, dust barriers, or higher installation height, can also help to mitigate the impact of fugitive local dust sources. Some PV plants in the United States have successfully used chemical soil stabilizers to drastically reduce dust emissions. Wind and dust barriers, while showing potential in wind tunnel and FEM dust transport simulations, need validation in operational environments, and their effectiveness may need to be tailored to specific sites, considering the potential impact of strong winds on soiling.

Recently, Majeed et al. [29] explored mitigating the soiling effect and cool the PV panel by water-based cleaning system. The generalized proposed system line diagram is shown in Fig. 21(b). This method can potentially address the enormous difficulty of water availability and transportation in rural places and desert-like environments. The proposed approach's water recovery rate is 55%, with a water need of 1.8 l/m^2 for the solar PV panel area. Also, the cleaned wastewater can be used to cool the refrigeration system, and the wastewater from the refrigeration system is used for drinking

4.7. *Summary of various soiling removal techniques*

In summary, the notable reported various solutions for mitigating soiling in PV system have been highlighted and discussed in this section. Table 2 displays the techniques used to mitigate the soiling effect, the methodology, operating conditions, and the important key findings summarized. Natural cleaning occurs due to wind, rain and gravity without needing any additional equipment or controllers, eliminating additional costs. Nevertheless, these techniques are highly contingent on weather conditions and geographical location. T overcome these limitations, one can opt for a manual cleaning technique, which boasts an effectiveness 100%. Despite the merits of manual cleaning approach, it comes with a higher relative cost and demands a significant amount of water, occasionally resulting in scratches on the panels. Water consumption can be reduced by implementing proactive cleaning methods like mechanical or robotic cleaning. Efficient automatic cleaning procedures, such as mechanical cleaning employing wipers, blowers,

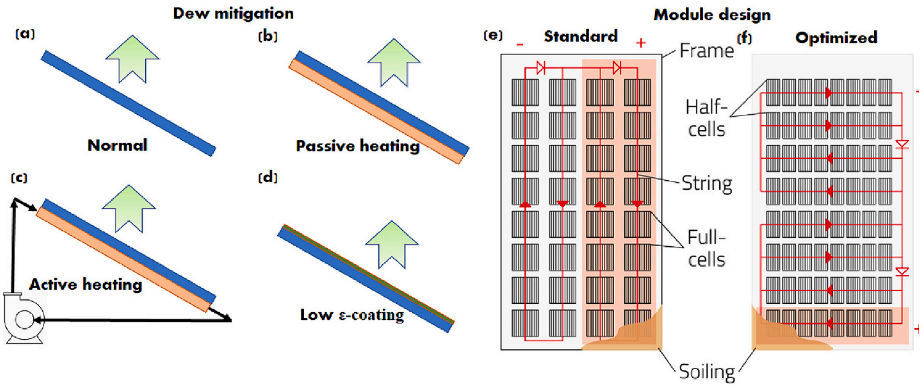

Fig. 20. Dew mitigation techniques and module design (a) normal panel, (b) passive heating, (c) active heating, (d) low emissive coating, (e) standard module design and (f) optimized module design [17] [Reused/reproduced with permission from the publisher]

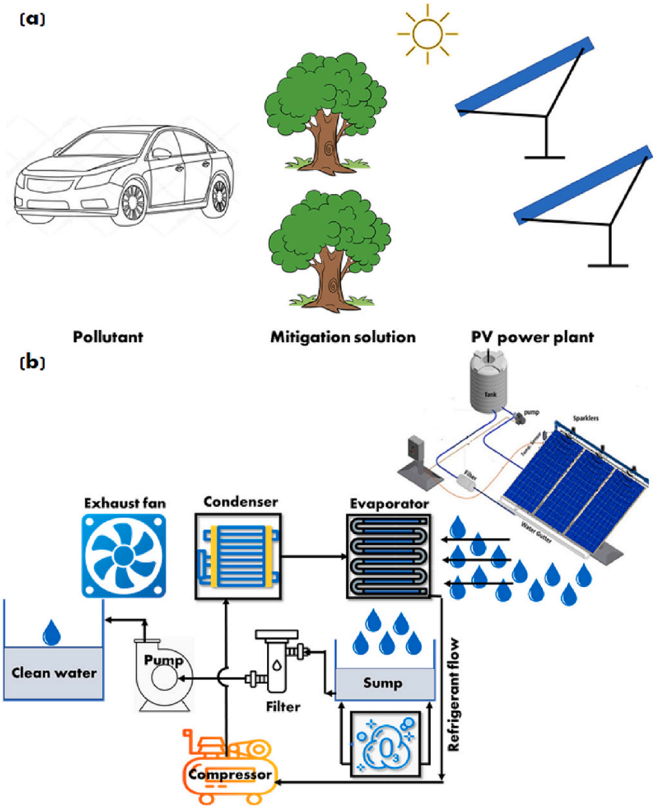

Fig. 21. PV-panel dust mitigation possible sustainable solutions (a) Planting trees near by road side, and (b) PV panel clean by using water- waste water to clean water production and other applications [Reused/reproduced with permission from the publisher].

suction, and brushes, can achieve up to 95% cleaning efficiency. To achieve this level of efficiency, active cleaning methods rely on advanced control systems like PLC and microcontrollers. Although active cleaning techniques offer several benefits, mechanical cleaning approaches necessitate maintenance, a substantial power supply, and significant expenditure. In contrast, robotic cleaning methods require periodic filter replacement and a high initial investment. Alternative cleaning techniques, such as chemical coating, hydrophobic, hydrophilic nanofilm, and electrodynamics screen, can also be utilized. Hydrophobic, hydrophilic, and chemical coating cleaning methods can achieve an efficiency of 71.80% without using any substances or water. These cleaning procedures can be created by producing nanofilms and nanospray films. Using a passive cleaning approach can diminish the optical efficiency of PV unit and is associated with a restricted lifespan. By implementing the EDS approach, which incorporates PLC, screen sensors, and microcontrollers to harness high voltages, the effectiveness of passive cleaning techniques can be enhanced to reach a 90% efficiency in cleaning PV panels. The deployment of the EDS cleaning approach offers the benefit of efficient automatic cleaning without the need for water or mechanical components, resulting in reduced power usage. The drawbacks associated with using the electrodynamic screen approach include substantial financial commitment, reliance on relative humidity, limited effectiveness against minute dust particles, and the inherent low durability of the screen.

Various cleaning methods may be appropriate for distinct climates and geographical areas. An in-depth analysis of the dust characteristics at the location is necessary to choose the most suitable cleaning method for deployment. Therefore, it is advisable to adopt cleaning methods that are efficient in removing larger dust particles, such as an electrodynamic screen. In addition, there are several possible ways to minimize the dust deposition on the PV panel. The power plant should be located far away from roadsides and industries and more trees should be planted surrounding by the power plant. Additionally, in a water-based cleaning system, the water can be reused and the additional water-cleaned wastewater can be used to cool the refrigeration system. The wastewater from the refrigeration system is used to be utilized for drinking purpose after several times filtration. Furthermore, a novel approach involves integrating PCM with the PV system to mitigate soil contamination by preventing of condensation. An instance of reducing the radiative cooling of the cover glass of photovoltaic (PV) modules, such as by implementing low-emissivity coatings, may result in elevated surface temperatures during night time. In addition, the utilization of PCMs, which have been previously examined for actively cooling modules during daylight hours, could also be employed for heating modules at night time. The exploration of alternative module designs, inspired by the utilization of PVT collectors featuring a water cooling system at the module's rear, presents the potential for implementing active heating capabilities during night time periods. The aforementioned considerations also extend to the potential presence of an active heated layer on the glass surface or the implementation of reverse current supply in the PV modules.

5. Economic analysis of PVT systems

For PVT technology to get a substantial share in the energy industry, it must exhibit a diminished investment payback period compared to rival PV and solar thermal technologies. This section aims to evaluate the potential impact of the performance enhancements discussed in the preceding section on the payback period of PVT systems. The primary objective is to determine the target costs at which PVT systems should be marketed and installed in order to effectively compete with PV technologies. Additionally, the aim is to examine how these prices may diminish as the PVT technology progresses in accordance with the established roadmap. In order to accomplish this, it is essential to assess the relative annual energy outputs of various collector types and conduct a quantitative analysis comparing the economic and environmental benefits of electrical and thermal energy.

The possibility of deploying different materials for TES systems was analyzed, and total efficiency was found to be maximum for zeolite (40%). The payback period of the zeolite-incorporated system PVT was comparatively less (8 years) than that of other systems [238]. This section contains the evaluation of present index (Net present value (NPV method)), novel index (Cost payback time (CPBT), cost of energy (COE), etc.), specific index (Investment Payback time (IPBT)) and general index (Payback time (PBT)).

5.1. Present index

NPV method was employed to perform the economic analysis of the proposed system. It stands out as the most commonly favored approach, providing insights into the repayment period and cash flow. Eq. (2) below estimates the Net Present Value (NPV).

$$NPV = \sum\nolimits_{i}^{n} (B - C) i a_i \tag{2}$$

$$a = \frac{1}{(1 + i)^{p}} \tag{3}$$

Where, B is the income, C is the cost, p is the period, i is the discount ratio, and a (Eq. 3) is the NPV factor.

5.2. Novel index

The economic analysis of a novel PVT with nanofluid [239] was done with three key indicators, CPBT, IRR and COE. The cost payback time is estimated using Eq. (4), and it is estimated to be two years.

Table 2
Key findings of various techniques of soiling mitigation in PV system.

Advanced PV cleaning techniques	Location	PCM used	Duration	Technology	Methodology	Operational conditions	Key findings	Ref.
Electrostatic cleaning	United Kingdom	–	105 days	Chemical coating	Commercial coating self-cleaning	Sensor operated	Commercial coatings had a negligible effect on the overall power generation when compared to the control panel.	[223]
	Doha, Qatar	–	–	Electrostatic force	Higher voltage applied to parallel electrodes	Need less power and no need for water	To enhance the overall efficiency of large-scale solar power plant in desert regions	[169]
	China	–	–	Plasma technology	Generates plasma in wet condition	Work with even wet condition	The electrode has a minimal impact on the regular operation of PV panel, suggesting its potential for practical applications.	[168]
	Qatar	–	17 days	Electrostatic force	High AC voltage supplied in parallel electrodes	Less power consumption	Better cleaning performance was achieved at low-frequency high voltage, and panel inclination 20°	[166]
Robot based cleaning	India	–	2.4 months	Silicon rubber-based wiping mechanism	Infrared sensor, Temperature monitoring embedded controller	Wet cleaning	A 30 WP PV system produced module efficiency by 13.02% and a performance ratio 0.8135, after 2.4 month cleaning.	[22]
	Turkey	–	–	3D printer technology	Test is conducted in natural dust and dirt dust conditions	Chemical solutions and performance analysis	Use of water with 2 proposal (5% v/v) enhances the energy performance by 15% and Ethanol (5% *v*/v) improves the energy performance b 14%.	[195]
	Malaysia	–	3 h	Arduino based technology	Rechargeable battery type robot	Water or water less cleaning	A 50% improvement in electrical power generation after cleaning	[224]
	Thailand	–	–	Fall detection technique using photoelectric sensor	An activated water source	Water, spiral brush, rubber sweeper	Electrical power generation has improved after cleaning. Clean up to 4 m distance.	[225]
	Brazil	–	–	Solar panel cleaning robot	Comparison of various technologies	Solar brush, UAV robot Ecoppia F4 wash panel NOMADD system	Analyzed with various types of PV cleaning technologies available in the marker	[182]
	Lebanon	–	15 days	Water based robotic	Arduino Uno board, 3-L298N H-Bridge boards, 3-24v DC motors equipped with Gearboxes, and 2-12v Lithium rechargeable batteries	Wet cleaning	Effectively minimize the dust particle on the PV and improved the panel efficiency by 32.27%	[226]
	Lebonan	–	15 days	Robot cleaning	Optimization using Orthogonal experiment	CFD simulation	The optimal design values were inlet width 650 mm, outlet width 175 mm, inlet height 6 mm, the necking radius 350 mm and outlet height 100 mm were observed to achieve excellent cleaning	[226]
Self-cleaning	Saudi Arabia	–	40 min	Self-cleaning	Automatic or machine-driven cleaning method	SMA wire actuator	The solar to electrical energy significantly increased	[25]
	Malaysia	Lauric acid	6 h	Self-cleaning	Self-cleaning assisted PV-TES technique	Micro controller	The average electrical efficiency was enhanced due to self-cleaning by 2.02%	[30]
	India	–	5 months	Self-cleaning	Sliding system	Less power	The outcome shows the electrical efficiency enhanced by 18.35, 6.4% and 13.35 respectively, in summer, past monsoon and winter seasons compared to conventional PV system.	[227]
	India	–	One year	Self-cleaning	Water based self-cleaning	Wireless data acquisition system	Cleaning the PV panel as well as protects it from hailstorms.	[228]
	Malaysia		–	Mechanical vibration	harmonic excitation force	No need power supply	The designed system removes 3.5 g out of 5 g dust from the panel with a vibration technology. The system effectively proven wind energy converted in to vibration force and used to remove the dust frm PV panel.	[229]

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Table 2 (*continued*)

Advanced PV cleaning techniques	Location	PCM used	Duration	Technology	Methodology	Operational conditions	Key findings	Ref.
	–	–	–	Mechanical vibration	The solar panels are stimulated by utilizing an external source of vibration, causing them to resonate at their fundamental frequencies and self-clean.	Vibration detection	Newly developed technique is capable of being retrofitted and has the potential to reduce costs, conserve energy, and streamline the process of cleaning solar arrays, thereby offering a viable alternative to existing methods.	[230]
	Turkey	–	–	Surface acoustic wave	Electronically controlled and sensitive self-cleaning techniques	Requires gravity for potential operation	The utilization of Surface Acoustic Waves is a highly efficient technique for eliminating large particles from the surfaces of panels.	[231]
	Malaysia	Lauric acid	–	Self-cleaning	microcontroller programmable integrated circuit	Requires microfiber and water flow	The electrical efficiency increases from 9.89% to 11.91%	[30]
UAV based cleaning	UAE	–	–	Hybrid drone system	Automated brush cleaning method	Small solar power units	Remove the dust	[179]
	Italy	–	–	UAV-based cleaning system	Monitoring and planning by UAV technique	Analysis and inspection of cites	Monitoring the application of power production	[180]
	–	–	–	Drone aerodynamic	–	–	Downward thrust	[183]
	Qatar	–	One month	Experimental investigation in desert climates	Drone technique	Compare the drone retrofitting methods	Microfiber-based cloth wipers are the most suitable choices due to light weight, compact size and user-friendly nature.	[176]
	Italy	–	–	Automatic multistage model to detect PV panel defects	YOLOv3 network and computer vision technique	Thermographic or visible images	The model assesses hotspot area severity by leveraging estimated temperature gradients and calculates soiling coverage using visual images.	[177]
	Saudi Arabia		–	Drone aerodynamic		Downward thrust	The horizontal movement of the drone achieves the highest efficiency	[178]
Automated cleaning	Jordan		365 days	Cleaning and detection of dust particles	Solar and temperature control mechanism	Rainwater harvesting	The novel intelligent cleaning system cleans the panel and harvest the rainwater for domestic applications	[184]
	Egypt		6 weeks	Intelligent fuzzy logic-based system	Noncoating with vibrator	Automated vibration	Using coatings for dust mitigation has shown to be a highly effective strategy in cleaning solar panels. The effectiveness of this technique can be further enhanced with the implementation of a vibration system.	[160]
	India		–	Water wiper	Automatic wiper cleaning using Arduino	Roof top structure	The performance was improved the PV panel by 15–20% with proper interval	[185]
	Indonesia		3 h	Semi-automatic	Water spray type cleaning	Rotational range of wiper	The findings indicate that the repeated sweeping of the wiper for 30, 20 and 10 cycles yield performance levels of 86.7%, 79.1%, and 57.0%, accordingly, in comparison to the original clean surface state.	[186]
	India		7 days	Automated Nozzle	Self-cleaning mechanism	Module system	The electrical performance was enhanced by 1.2–3%	[187]
Anti-coating	China	–	–	Chemical cleaning	Super-hydrophobic	Coating	The maximum cleaning efficiency was observed at 24.35%	[194]
	Turkey	–	–	Chemical cleaning	Cleaning by robot	PLC controlled by 3D printing technique	2-Propanol increased the output power by 15%	[195]
	India	–	70 days	Hydrophobic coating with dew suppression	Self-cleaning		Effectively preventing dew formation on the surface has a substantial impact n the percentage of soiling reduction observed	[196]
	Egypt	–	–	Oil coating	Self-cleaning	–	Labovac oil coating enhanced the PV performance by 20%	[190]

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Table 2 (*continued*)

Advanced PV cleaning techniques	Location	PCM used	Duration	Technology	Methodology	Operational conditions	Key findings	Ref.
	China	–	–	Nano coating	Template-free two-step acid/base catalyzed technique	Artificially simulated cleaning	High weathering resistance and outstanding anti-reflective properties as a result of the amalgamation of sol particles with different refractive indices	[197]
	China	–	30 days	Nanoparticle coating	Hydrophobic and Super hydrophobic coating		When exposed to minimal precipitation or light rain, the super hydrophobic coating demonstrates impressive self-cleaning capabilities.	[198]
	China	–	–	Self-cleaning coating	Autoclaved technique	–	Contact angle on the surface of super hydrophobic coating lower than 5° indicating an excellent property	[200]
	China	–	–	Wettability of transparent coating	Super hydrophilic, hydrophilic, super hydrophobic and hydrophobic coating		Increased airflow velocity is advantageous for preventing dust adhesion in all coatings. However, considering various tilt angles, it's worth nothing that a larger flow velocity has a limited impact on enhancing the anti-soiling properties of the super hydrophilic coating.	[201]
Tilt angle and tracking system	Saudi Arabia	–	2 years	Tilt angle	Varying tilt angle and different type of panels	Two different tilt angles (10° and 24°) and two surfaces (cleaned and soiled)	The modules inclined at an angle of 10° exhibited a higher power output compared to the modules inclined at 24°	[207]
	Japan	–	20 months	Tilting the panels	Tracker system	Automatic system	Implementation of the tracker system with a standby state pointing downwards resulted in a constant increase of over 5% in direct transmittance at a wavelength of 500 nm	[208]
	India	–	365 days	Inverting panel during sunshine hours	Automatic tracking system	No water	Soiling loss from fixed panel 0.45% per day and for inverted module by −0.17% per day	[209]
	Pakistan	–	2 months	Tilting the panels	Automatic tracking	Self-cleaning	The dust density was lower at a tracking angle at 60°. Poly crystalline silicon PV cell has a higher output than mono-crystalline silicon solar cell.	[29]
	UAE	–	2 weeks	Tilting the panel 25° and 45°	–	Self-cleaning	Dust removal increases with an increase in tilt angle due to gravity.	[70]
	Egypt	–	10 months	Tilt angles 15,20,30,45	–	Self-cleaning	During winter, the optimum tilt angle is 30°, and it is 15° for summer and autumn.	[232]
	Iran		70 days		–	Self-cleaning	6.1 g/m^2 dust accumulated on the surface, reducing the power output by 21.47%.	[233]
	Iran		8 months	Tilt angles 15,30, 45	–	Self-cleaning	Dust storms have reduced the daily energy generated of PV by 58.2%, 27.8%, 21.7%, and 20.7% at 0°, 15°, 30°, and 45° tilt angles.	[234]
	Australia	–						[235]
Electrodynamic Screens	–	–	2 min	Transparent EDS	Electrodynamic removal mechanism	No water or mechanical movement	Within 20 min> 90% of the dust has been removed.	[218]
	–	–	3 months	Self-cleaning	Electrodynamic	No water and no robot	High optical efficiency with low energy requirements	[219]
	USA	–	–	Self-cleaning	Electrodynamic	No water no robot	The dust removal efficiency is higher than 80% with 1.27 mm electrode spacing.	[220]
	India	–	–	Self-cleaning	electrodynamic	waterless	The single-phase EDS with higher pulse voltage gives a better yield compared to the complex three-phase EDS system	[221]
	Switzerland	–	458 days	Self-cleaning	Pulsed electric fields	Water free	It has been found that a remarkable cleaning efficiency reaches up to 98%.	[236]

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Table 2 (*continued*)

Advanced PV cleaning techniques	Location	PCM used	Duration	Technology	Methodology	Operational conditions	Key findings	Ref.
	Qatar	–	24 h	Self-cleaning	Electrodynamic	Outdoor soiling microscopy	Initiating the EDS at more frequent intervals is expected to lead to a greater overall dust removal efficiency.	[237]

$$CPBT = \frac{IC}{EC_{sav\ per\ year} * COE_i} \tag{4}$$

IC corresponds to investment cost, COE_i corresponds to the cost of input energy (Eq. 6)

$$ALCC = LCC*CRF \tag{5}$$

$$COE = \frac{ALCC}{EC_L} \tag{6}$$

ALCC denotes annualized life cycle cost of the system (Eq. 4), LCC denotes life cycle cost, CRF represents capital recovery factor, EC_L denotes electrical energy savings by the PVT unit.

From the estimated calculation, the cost of energy generated by PVT is 0.002367 per kW/h which is 82% less than the domestic electric price. Moreover, the PBT for a water-based PVT-PCM system installed at Kottayam, India is six years, which is 11.26% faster than a conventional PV panel [240].

5.3. Specific index

Crystalline Silicon Heterojunction PVT was designed, and the payback estimations were done for the system. The cost of these systems was found to be less than that of conventional PV systems. The Investment Payback Time *(IPBT)* is calculated using Eq. (7).

$$IPBT = \frac{Y_{input}}{Y_{output}} \tag{7}$$

Y_{input} refers to the cost inputs during PV installation and Y_{output} corresponds to annual revenue generated by the sale of electricity. The PBT of the proposed system was estimated to be less than three years which is lesser in comparison with PV systems [241]. The Annualized Life-Cycle savings (ALCS) of a PVT-SAH installed is estimated by the following Eq. (8).

$$ALCS = \frac{LCS}{PWF(N_L 0, D)} \tag{8}$$

LCS is the life cycle cost savings for operating the PVT- solar air heater system, $PWF(N_L 0, D)$ is the present worth factor.

5.4. General index

The PBT is defined as the ratio of time required for cumulative fuel cost savings in the present worth to the capital investment cost of the PVT-SAH system are as per Eqs. (9) and (10). The system was able to deliver a competitive payback period between 5.7 years and 16.8 years and an annualized energy savings ranging between 925 AUD and 4606 AUD [242].

$$PBT = \frac{ln\left[\frac{C_{ca}(e-d)}{S_{fuel,1}} + 1\right]}{ln\frac{(1+e)}{(1+d)}} \tag{9}$$

$$LCS = \sum_{j=0}^{j=N} P^{W-S_{Total,j}} \tag{10}$$

The PBT of a combined solar cooling, heating, and power system (S-CCHP) is estimated by the following Eq. (11) and is found to be around 16.7 years.

$$PBT = \frac{ln\left[\frac{C_0(i_F-d)}{CS_{S-CCHP}} + 1\right]}{ln\left[\frac{1+i_F}{1+d}\right]} \tag{11}$$

d is the discount rate i_F is the fuel inflation rate CS_{S-CCHP} is the annual cost savings and was computed using the following Eq. (12). The payback period is higher (2.7 times) when compared with an equivalent PV system (6.1 years) [243].

$$CS_{S-CCHP} = E_{COV}.c_e + \frac{Q_{COV}}{\eta_{boiler}}.c_{ng} + E_{grid}.FIT - C_{O\&M} \tag{12}$$

The performance analysis of four solar trigeneration systems for subtropical climates was done using the simple payback method (SPB) and internal rate of return (IRR), according to Eq. (13).

$$SPB = \frac{CI}{ECS - MC} \tag{13}$$

CI denotes the capital investment, and MC denotes the maintenance cost. ECS was determined from electricity savings,

The payback period falls shortest for PV_{ugl} $ABCH_{HE}$ layout and is approximately 12.7 years. However, when considering a 50% rise in electricity prices or a 35% reduction in PVT collector prices, PVT_{gl} $ABCH_{HE}$ layout's payback shortens from 14.7 years to 10 years [244].

A comprehensive 3E analysis was performed on PVT systems as well as conventional solar systems. The economic analysis of the proposed system is shown by Eq. (14).

$$LCS = \frac{C_S}{d - i_F}\left[1 - \left(\frac{1 + i_F}{1 + d}\right)^n\right] - C_0 \tag{14}$$

d denotes the discount rate, C_S corresponds to the inflation rate for yearly fuel savings associated with investment costs (Eq. 15)

$$C_S = E_{COV}.c_{el} + E_{exc}.S_{el} + \frac{Q_{COV}}{\eta_{boil}}C_{ng} - C_{O\&M} \tag{15}$$

The LCS of the PVT S-CHP system was reported to be 0.77 M€, and that of the PV system is 0. 76 M€. The LCS is highest for combined PV-ETC (75%) S-CHP (25%) with 0.80 M€ for a life cycle of 25 years. The PBT of the PVT S-CHP system was estimated to be 13.7 years. The PBT of the ICE-CHP system is 6.2 years, which is primarily due to the low investment cost associated with the system. Among solar-based systems, the PBT of PV systems was 9.4 years [245]. A 15% reduction in investment cost and 30% reduction in roof space was noted with the novel PVT collector system compared to PV systems with an equivalent capacity [246].

The following Eq. (16) estimates the LCC of the novel proposed PVT system with nanofluids.

$$LCC = C_{capital} + \sum_{1}^{n} C_{O\&M}.R_{PW} + \sum_{1}^{n} C_{replacement}.R_{PW} - C_{salvage}.R_{PW} \tag{16}$$

$C_{capital}$ is the total capital, $C_{O\&M}$ annual operating& maintenance cost and R_{PW} denotes the current value of each factor and was computed using

$$R_{PW} = \frac{F}{(1+i)^n} \tag{17}$$

F denotes the future sum of money, n denotes the interest rates.

The recovery period of the proposed system was estimated to be (4.4–5.3) years, the LCC of the system was 1288.37 USD, and the energy cost was found to be 0.112 USD/kWh [247].

5.5. *Potential cost range for cleaning and soil mitigation technique*

On the other hand, the annual cleaning cost can be calculated by

$$U = u \times C \times \frac{1}{A} \times \frac{365}{n} \tag{18}$$

Where, n = average number of days between cleaning, u = cleaning cost per square meter €/m^2, C = installed capacity, and A = module area in m^2 [248].

The total soiling-related cost can be calculated by

$$T = F_{loss} + U \tag{19}$$

$$Floss = \mathrm{Y}_{\mathrm{loss}} \times \mathrm{l} \tag{20}$$

$$Y_{loss} = C \times Y_{spe} \times S_{loss} \times cy = 365\ C \times Y_{spe} \times SR \times \frac{n+1}{2} \tag{21}$$

$$n = \frac{365}{cy} \tag{22}$$

Where, Floss = financial loss due to reduced energy output, $\mathrm{Y}_{\mathrm{loss}}$ = annual yield loss, C = installed capacity, $\mathrm{Y}_{\mathrm{spe}}$ = specific annual yield, SR = soiling rate, it can be found from below Fig. *22*, l = Solar power generation and deliver to the grid typically rewarded with incentives, as expressed by feed-in tariffs or bid prices (€/kWh) [17,249].

The optimized cleaning cycle can be calculated by eq. (23) [250].

$$Cy_{opt} = \frac{365}{n_{opt}} = 365\sqrt{\frac{Y_{spe} \times SR \times A \times l}{2u}} \tag{23}$$

The maximum and minimum number of cleaning cycles were estimated for maximum and minimum utility-scale plant cleaning costs utilized for the estimation of financial loss for each country. The soiling loss was measured from the equation-24 [250].

$$\frac{\sum_{i=1}^{22} Y_{loss,i}\ \left(n_{opt,i}\right)}{\sum_{i=1}^{22} C_i\ Y_{spe,i}} \tag{24}$$

The soiling cost can be calculated by Eq. (25)

$$\sum\nolimits_{i=1}^{22} T_i \tag{25}$$

The calculated results of each country's financial loss were used to determine a possible achievable cost range for technology that can reduce soiling, assuming certain reductions in soiling rates. In order to address this, the soiling rate in eq. 21 was modified to account for the lower soiling rate, $\mathrm{SR}_{\mathrm{mit}}$. The recalculated country-specific maximum number of cleaning cycles are utilized to determine the modified overall costs associated with soiling mitigation, as indicated in Eq. (19). The possible yearly cost savings of soiling mitigation per square meter of $\mathrm{CS}_{\mathrm{mit}}$ were determined by calculating the deviation between the total expenses for non-mitigated and mitigated soiling and then dividing it by the capacity-related area [17].

$$CS_{mit} = T_i - T_{mit,i} \tag{26}$$

The maximum permissible technological investment costs, Vmax, are determined by based on maximum and minimum cleaning costs. The calculations were made to ensure that a positive NPV is attained with a 10-year PBT and a rate of discount of 5% [17].

$$V_{max,i} = \sum_{l=0}^{9} \frac{CS_{mit,i}}{(1+l)^l} \approx CS_{mit,i} \times 8.11 \tag{27}$$

Bank lenders typically require a repayment term of approximately 15 years for financing PV facilities in regions with moderate weather conditions. However, when it comes to soil degradation, particularly in desert areas, the issue becomes significant, and there is currently a lack of credible evidence regarding the long-term effectiveness of mitigation strategies [251]. Therefore, a duration of 10 years was selected, aligning with the customary guarantee period for PV units. The rate of discount calculations has been documented to generally fall within the range of 4% to 9%, with variations seen based on the specific country in consideration [252].

6. Technical challenges and limitations

The present review investigates the current technologies, allied problems, and design parameters that influence PVT and PCM-integrated PVT systems in terms of developments and challenges. The present review also provided an exhaustive look at the overheating issue of PV, soiling problem, increasing weight of unit hindering PVT tracking, PCM integration technique with enhanced heat transfer, maximizing the incident solar radiation, various mitigation technologies

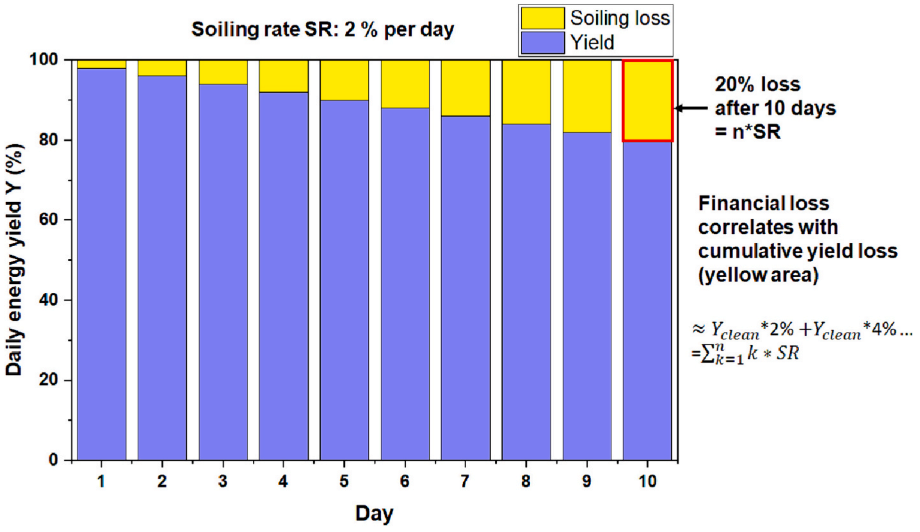

Fig. 22. Evaluation of global soiling impact [17] [Reused/reproduced with permission from the publisher].

and techniques have been examined and discussed over the past few decades. Various techniques, including manual, automatic, self-cleaning, and electrostatics, with and without water to mitigate dust have been employed to enhance PV energy production. However, integrating PCM into the PVT system, dust removal technologies poses certain limitations and challenges. The numerous important issues off PV and PVT systems dust removal technologies are discussed in Table *3*. Addressing these issues faced by the PV system proposing potential solutions, presenting the ongoing research and offering future recommendations to improve the performance of PV units are comprehensively discussed in Fig. 23.

In addition to this, Table 4 presents a comparative analysis of the four primary approaches. The focus is on factors such as operational expenses, carbon dioxide emissions, labor expenses, water waste, air pollution, fuel usage, human safety, as well as the pros and cons associated with each technique. The table provides a comprehensive overview of various features related to PV cleaning methods, technologies, and approaches. However, additional inquiry is necessary to identify precise indicators that effectively characterize these techniques and evaluate them in a cost-efficient manner. Therefore, it is the responsibility of the researcher to thoroughly investigate each element indicated in Table 4. The most optimal, efficient, and cost-effective solution should be chosen based on the design of the PV device, the type and quality of the dust, and the ambient conditions of the plant. Moreover, these considerations delineate the obstacles faced by researchers in enhancing cleaning techniques in both technical and economic dimensions.

The use of PCMs in hybrid PVT systems is hindered by their substantial cost. The synthesis of nanoparticles, creation of nanocomposite PCMs, and ensuring nanoparticle stability within PCMs for applications like thermal management in PV systems are both time-consuming and expensive. A significant challenge that optimization models must address is the elevated costs associated with hybrid PVT systems compared to those employing pure PCMs. Although PCM-based PVT systems offer a somewhat passive cooling approach, they are comparatively simpler to construct, more compact, and easier to operate than active PVT systems. However, an active cooling system is essential to either solidify the PCM or extend its lifespan. Achieving optimal cooling often requires a combination of PCMs with liquid cooling, air cooling, fins, nanoparticles, and heat pipes. Nevertheless, implementing both active and passive thermal management necessitates additional components such as pumps, blowers, flow meters, fins, heat pipes, valves, and other expensive elements, all of which consume extra power to maintain the battery at the desired temperature.

Furthermore, it is essential to acknowledge the potential health risks associated with nanomaterials. These materials can enter the human body through various means such as inhalation, ingestion, injection, or skin penetration [260], with studies indicating potential consequences including inflammation, liver and kidney damage, and DNA damage [261]. Due to their unique thermophysical properties, nanoparticles can undergo physical, chemical, and biological modifications to enhance their interaction with biological tissues, potentially resulting in oxidative stress, pulmonary inflammation, and effects on distant organs [262]. Working with nanomaterials demands stringent safety measures, and the use of personal protective equipment (PPE), including respiratory protection with Filtering Facepiece Respirators (FFRs), is crucial to guard against nanoparticle exposure [263]. The US National Institute for Occupational Safety and Health (NIOSH) establishes respirator performance requirements [264], while the European Union regulates them through European Norms. Numerous studies have examined respirators with P100 and FFP3 filters, demonstrating their effective performance [265].

Despite significant advancements in the frameworks and technology employed in cleaning mechanisms, the full-scale implementation of the current cleaning infrastructure may encounter numerous challenges. Another obstacle lies in devising a precise technique for measuring the

Table 3
Advantages and disadvantages of soil mitigation techniques.

Soiling mitigation techniques	Advantages	Disadvantages	References
Anti-soiling coating	No need for external labor and other sources Passive soiling mitigation technique Highly durable Better anti soiling effect with nanostructure	Reducing PV efficiency Dependent on dew or rainfall Short lifespan The collection of soiling is exacerbated when the coating is undergoing deterioration. Due to UV exposure, the durability is uncertain	[17,162]
Automatic cleaning	Soiling removal efficiency up to 95%. Low or no labor cost Surface temperature low. Automatic activation of cleaning panels with electromechanical controller	High Initial cost Surface damage High maintenance cost	[34]
EDS	Fast clean action Dry conditions, the dust removal efficiency is 90%. The removal of dust particles can be achieved efficiently and effectively without the requirement of any moving elements.	Less effective at high relative humidity. High initial cost Need high electrical current. The process of cementation and the presence of wet dust particles might lead to inefficiency.	[162]
Electrostatic cleaning	No need of natural sources like air or water. Manual cleaning is absent.	Need three-phase voltage High initial cost Need additional cost for power	[220]
Robotic cleaning	Easy to control Light weight Efficient	Need high maintenance Brush may damage the surface of the panel. Consumes energy. Need human intervention	[34],
Tracking system Single-axis tracking system	More reliable and cheaper Longer life span than dual axis tracking system It is mostly suitable for companies with low budgets or in cloudy areas These solar trackers are designed to track the movement of the Sun from East to West, ensuring a continuous power output throughout the day.	Energy output is lower than the duel axis tracking system. Limited technological development	[253–255]
Dual axis tracking	Capable of continuously tracking the movement of the sun, ensuring a consistent power output throughout the day. Require less space and offer the potential to	Dual-axis trackers are more complicated to make, which makes them more likely to have bugs. These trackers also less lifespan and are	[253]

(*continued on next page*)

Table 3 (*continued*)

Soiling mitigation techniques	Advantages	Disadvantages	References
	utilize the surrounding area for supplementary functions, such as automobile parking and gardening, among others	less reliable. Poor results when it's cloudy or rainy conditions	
Natural cleaning	No cost	Depending on weather conditions and geographical environment Not suitable for small dust particles	[256]
Manual cleaning	Low capital cost Soiling removal efficiency is 100%	Surface may damage It is not suitable for water-shortage regions High labour cost	[8,17,257,258]
Mechanical cleaning	Reducing the surface temperature Low or low labor cost Soiling removal efficiency is up to 95% Controlled by an automatic electromechanical controller	Initial cost is high Maintenance and operation cost is higher Initial cost is high	[170,259]

extent of soiling and dust accumulation and their adhesive characteristics. Utilize research and development in nanotechnology to discover a novel cleaning substance and protective coating that can effectively prevent the accumulation of various types of dust in both dry and humid weather conditions. Nevertheless, the new cleaning substance is expected to possess the following characteristics: non-toxicity, ease of application for various PV technologies, high transparency to solar irradiation, and affordability. Also, researchers should employ a more efficient approach to water utilization. Furthermore, the processes of water recycling and filtration hold significant importance. Additionally, it is necessary to limit the energy consumption required for pumping water. Table 3 and Table 4 visually depict the pros, cons and the comparison of basic cleaning techniques information. These challenges stem from integrating electrostatic and robotics techniques, potentially leading to limitations in data transfer and power management. Electrostatic cleaning technologies face primary obstacles related to material selection, production processes, external resilience, and pricing considerations. Dust cleaning robots encounter a multitude of issues, including challenges in robot handling such as sliding, weight distribution, control, material selection, power management, stability, energy harvesting, online monitoring, security concerns, data transfer, cleaning methods, and cleaning substances. Operationally, obstacles encompass skilled worker availability, operational matters, commissioning, and troubleshooting.

7. Conclusion and future perspectives

7.1. *Conclusion*

The efficiency of the PV system is influenced by various factors, and understanding these elements is essential for optimizing the solar power generation. This review study presents a different technique to cleaning the PV panel and economic considerations are summarized as follows.

Efficient energy production and maximizing solar installation efficiency depend on mitigating the adverse effects of dust and soil on the behavior of solar panels. The efficiency of PV unit is strongly influenced by environmental factors such as outdoor temperature, wind speed, humidity, the deposition of dust, and other factors, PCM volumetric expansion concerns, increase in overall weight of the system, hindering PVT tracking shading, panel orientation and tilt, system design and installation and other particulate matter on their surface. The deposition of particulate matter from the surrounding atmosphere onto the surfaces of PV panels reduces the incident solar radiation reaching the PV surface. Additionally, the adherence of dust particles to the surfaces of the panels may result in the formation of scratches and corrosion, hence diminishing the overall longevity of the panels. This review discusses

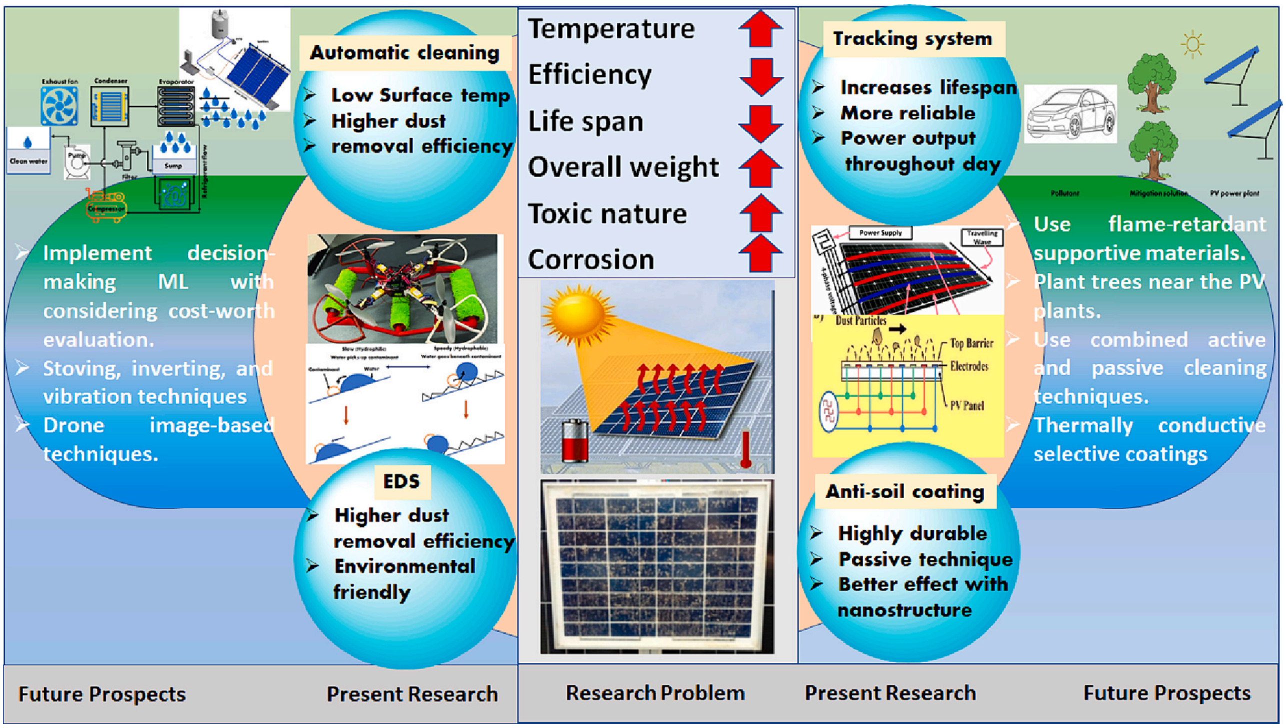

Fig. 23. Summary of present, future research of mitigation strategies in PV systems.

Table 4

Comparison between various cleaning techniques.

Method	Manual	Automatic			Coating method		Electrostatic
	Washing and brushing	**Water spray machine**	**Static robot cleaning**	**Portable robot cleaning**	**Hydrophilic coating**	**Hydrophobic coating**	**Electrode method**
Operational cost	🟥	🟦	🟩	🟩	🟩	🟩	🟥
Labor cost	🟥	🟩	NA	NA	🟩	🟩	🟩
CO_2 emission	🟦	🟦	🟩	NA	🟩	🟩	🟩
Water wastage	🟥	🟥	🟦	🟩	🟩	🟩	🟩
Air pollution	🟦	🟦	🟦	🟦	🟩	🟩	🟩
Fuel consumption	🟥	🟥	🟩	🟩	🟩	🟩	🟩
Human safety	🟩	🟥	🟥	🟥	🟥	🟥	🟥
Major advantage	Reliable	Sustainable & no human intervention			Easy method to remove dust		90 % of the dust removed
Minor advantage	Slow and labor-intensive	High maintenance cost			Due to reduced solar absorption, the electrical efficiency is reduced		Higher initial and operational cost

🟩 **Low**	🟦 **Medium**	🟥 **High**

Source: Cui et al. [168], Hassan et al. [266], Song et al. [9], Khalid et al. [32], Kazem et al. [162], Mustafa et al. [266].

design parameters influencing the efficiency of the PVT unit with the incorporation of PCM, enhancing the heat transfer effect of PCM and the PV device, optimum selection of cooling fluid and maximizing the incident irradiation.

It concluded that the selection of suitable PCMs presents a significant challenge. Paraffin, salt hydrates, and eutectics are promising candidates, each with its own strengths and weaknesses, including issues such as low thermal conductivity and possible liquid leakage. Currently, Paraffin is a PCM stands out as the most preferred solid-to-liquid phase transition material among PCMs, often augmented with internal fins or nanoparticles to enhance thermal conductivity. However, research tends to predominantly focus on the melting process of PCMs, neglecting solidification, leading to potentially inaccurate results. Additionally, in determining the optimal phase transition temperature of PCMs, both the PV and ambient temperature should be considered to ensure maximum melting during the day and night. Incorporating PCM and nano-enhanced PCM increases the heat transfer rate between PCM and PV systems and increases panel efficiency by decreasing panel temperature. Further, this article also explored the various advanced and emerging panel cleaning systems were discussed. It was concluded that regular cleaning is necessary in order to eliminate accumulated particles, this encompasses both manual and automated cleaning processes. The efficacy of mitigation techniques can be enhanced by implementing anti-soiling coatings, vibration techniques, angled mounting systems, and meticulous site selection techniques, which are potential ways to achieve better efficiency compared to other systems. Additionally, the possible sustainable solutions to mitigate the dust particles in the PV system and improve the overall performance of PV system were discussed. The economic evaluation of PV and PVT systems were extensively discussed to design the system in cost-effective manner. By implementing these principles, individuals who own and operate solar panels can enhance energy production's reliability, extend their installations' longevity, and contribute to a cleaner, more sustainable future driven by solar energy.

7.2. Future perspectives

Reducing dust on PV systems is undoubtedly essential for preserving their peak efficiency. Here are some prospective suggestions for mitigating dust in PV systems:

- Future research should employ innovative image-based drone techniques to effectively address dust deposition on PV panels. These techniques hold the potential to provide real-time e and comprehensive monitoring of dust accumulation, allowing for timely inventions and maintenance strategies. Furthermore, integrating artificial intelligence (AI) and machine learning algorithms with drone imagery holds promise for enhancing the efficiency and accuracy of dust assessment and mitigation efforts. These initiatives should prioritize the importance of regular cleaning and maintenance practices and the dissemination of comprehensive information regarding the detrimental effects of dust accumulation on system performance and longevity.
- Implement educational initiatives to inform PV system owners and operators about the significance of routine maintenance and the influence of dust on electricity generation. Additionally, future endeavors should concentrate on developing user-friendly educational materials, such as online tutorials,

interactive workshops, and informational campaigns tailored to diverse stakeholders within the solar energy sector.

- Implementing remote monitoring systems and controls that enable real-time assessment of dust accumulation and prompt cleaning activities that are highly targeted is recommended. Future advancements in this area should strive to leverage the capabilities of Internet of Things (IoT) devices, sensor networks, and data analytics to facilitate seamless monitoring and management of dust-related issues. By integrating sensors directly onto PV panels or within the surrounding environment, these systems can continuously collect data on dust levels, weather conditions, and system performance parameters, enabling proactive decision-making and targeted interventions.
- Implement community-driven strategies for dust reduction that engage local residents or groups in the upkeep and cleansing of PV installations. These strategies may entail forging partnerships with community organizations, educational institutions, or environmental advocacy groups to increase awareness of the advantages of renewable energy.
- Conduct research and design work on photovoltaic panels that have characteristics that naturally prevent dust formation, such as surfaces that are textured or anti-adhesive.
- Investigate the employment of smart materials that, by virtue of their dynamic surface qualities, are able to actively resist or shed dust particles. This approach encompasses exploring novel materials, surface treatments, and engineering techniques to develop self-cleaning or dust-resistant surfaces for PV panels.
- Overall, Stowing, inverting, and vibration procedures might be considered straightforward and resilient methods to prevent dust accumulation. An appropriately transparent and long-lasting coating is necessary to ensure the efficient functioning, protection, and enhancement of PV panels. Additionally, sensors capable of detecting the precise moment when surfaces require cleaning are necessary. These sensors can effectively address issues such as hot spots and partial shading. Hybrid techniques are recommended based on environmental and geographical needs, as well as the capacity of the solar plant.
- Most of the plants situated in Middle Eastern nations, where soil contamination poses a significant challenge, must undergo a comprehensive prerequisite assessment before implementing a cleaning system. As the system size increases, the model needs to be more precise, incorporating advanced machine learning technologies. In addition to relying solely on cleaning interventions determined by machine learning tools, it is advisable to employ a cost-value-based model to optimize the LCoE. For large solar farms, the recommendation is to clean solar panels only when their efficiency drops below a critical level. Furthermore, investors should ensure that the cost of cleaning is justified by a satisfactory rate of return on their investment. Further exploration and developing a decision-making framework that integrates cost-benefit analysis are imperative for the continual advancement of solar panel cleaning technologies.
- The selection of PCM materials with high thermal conductivity, thermal stability, chemical compatibility, and reliable containment properties can mitigate leakage and improve system reliability.
- Incorporating sensors and monitoring systems to detect PCM and nanofluid leakage in real-time can enable swift intervention, minimizing the impact on system performance and safety. Developing contingency plans and procedures for addressing PCM leakage incidents, including emergency response protocols and spill containment measures, can mitigate the adverse consequences of leakage on PVT system operation.
- Integrating smart and adaptive control systems can augment the performance and reliability of NePCM-integrated PVT systems. These systems could employ real-time monitoring, predictive analytics, and machine learning algorithms to optimize operating parameters such as fluid flow rates, temperature set points and energy storage strategies based on dynamic environmental conditions, energy demand and user preferences.

CRediT authorship contribution statement

Reji Kumar Rajamony: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kalidasan B:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Imtiaz Ali Lagari:** Conceptualization, Data curation, Investigation, Validation, Visualization, Writing – original draft. **Johnny Koh Siaw Paw:** Project administration, Resources, Supervision, Visualization, Writing – review & editing. **A.G.N. Sofiah:** Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Subbarama Kousik Suraparaju:** Writing – original draft, Formal analysis, Methodology, Validation, Visualization. **A.K. Pandey:** Writing – review & editing, Supervision, Resources, Project administration, Investigation. **M. Samykano:** Supervision, Resources, Project administration. **Manzoore Elahi M. Soudagar:** Data curation, Formal analysis, Investigation, Validation, Visualization, Writing – original draft. **T.M. Yunus Khan:** Writing – review & editing, Funding acquisition, Project administration, Supervision.

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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