Solar Energy Advances 5 (2025) 100084

Contents lists available at ScienceDirect

Solar Energy Advances

journal homepage: www.elsevier.com/locate/seja

Advancements and challenges in solar photovoltaic technologies: enhancing technical performance for sustainable clean energy – A review

Mahesh Raj Nagaraja [a,*], Wahidul K Biswas [b], Chithirai Pon Selvan [a]

[a] School of Science and Engineering, Curtin University Dubai, 345031, United Arab Emirates
[b] School of Civil and Mechanical Engineering, Curtin University, Perth 6102, Australia

ARTICLE INFO

Keywords:
Generation of PV panels
Soil mitigation
Cooling techniques and end of life

ABSTRACT

Given the current state of sustainable, clean energy, most researchers are concentrating on alternative energy resources. Solar photovoltaic (PV) has become especially prominent in thematic research on energy these days. Research focusing on the keys to improving the energy efficiency of solar photovoltaics and managing the end-of-life issue, more specifically in materials recycling and reusing, is emerging in the recent era. Aligning with the UN-SDGs 7, 11, 12, and 13, a comprehensive survey is done about the advancements and challenges in solar photovoltaic technologies to emphasise enhancing efficiency and addressing end-of-life management for sustainable, clean energy. Solar PV efficiency, which is still low compared to competing technologies and depends on a large space to harness solar radiation, is severely affected by dusts and high irradiance in the middle east region. The current review shows a decrease in efficiency by 0.3 % to 0.5 % with a one-degree rise in temperature and a decrease in the output performance by 16 % to 24 % with 5 g/m^2 dust accumulation on the panel. Therefore, there is a demand for mitigating strategies, such as cooling and cleaning procedures, which are critical in improving the efficiency and lifespan of PV panels. The review also confirms that the remanufacturing strategy for PV is crucially important as the feedstock (e.g., silicon rocks) for PV panels is finite and also a large amount of toxic e-waste will be produced at the end of life. Around 75 million tonnes of e-waste (solar PV waste) could be generated by 2050. This review uniquely combines advanced computational analyses, experimental findings, and mitigation strategies for cooling, cleaning, and recycling, focusing on performance optimisation and sustainable end-of-life management of solar PV panels. The readers will be aware of practical insights and a detailed framework for enhancing solar PV technology and provide useful information to researchers, policymakers, and industry stakeholders to address the barriers to the rapid uptakes of PVs in a sustainable manner.

1. Introduction

The greenhouse gas (GHG) emissions leading to climate change have become a global concern. According to IPCC (2023), there will be an increase in GHG emissions by 130 % due to a 70 % rise in the energy demand by 2050. Non-renewable sources like fossil fuels (oil, coal, and natural gases), which are very limited in nature, are consumed to meet the energy demand and are responsible for GHG emissions. The production of clean energy is critical as burning fossil fuels has increased GHG emissions. Apart from fossil fuel consumption, many parts of the world have already experienced the depletion of natural resources, resulting in rapid growth in renewable energy development to address climate change, employment creation and reduction in renewable energy costs [1]. Therefore, integrating renewable energy instead of traditional non-renewable energy into the power grid has captured global interest in overcoming environmental problems, including air and water pollution, public health concerns, and global warming. Incorporating renewable resources as alternative energy sources into the energy mix has the potential to yield economic advantages [2]. Many nations have started integrating renewable energy into the power grid. Their main objective is to meet a net zero emission (NZE) target, improve resource efficiency, ensure stability, and provide an energy supply that is both environmentally friendly and economically viable. Renewable energy sources such as wind, tidal, solar, hydropower, geothermal, and bioenergy are commonly used. According to IRENA [3], solar energy is projected to be the leading energy source in the future. The total installed solar energy capacity is expected to rise from 402 GWh in 2017 to 8519 GWh in 2050 to achieve the NZE target. Fig. 1(a) shows the global electricity generation and total installed power

* Corresponding author.
E-mail address: maheshraj.nagaraja@student.curtin.edu.au (M.R. Nagaraja).

https://doi.org/10.1016/j.seja.2024.100084
Received 3 September 2024; Received in revised form 1 December 2024; Accepted 10 December 2024
Available online 11 December 2024

Nomenclature

α_I	Temperature coefficient of I_{SC_STC}
α_P	Temperature coefficient of P_{max_STC}
α_V	Temperature coefficient of V_{OC_STC}
D_f	Deteriorate factor
I_{SC}	PV panel short circuit current at that moment, Amperes
I_{SC_STC}	PV panel short circuit current at Standard Test Condition, Amperes
P_{OUT}	PV panel power output at that moment, Watts
P_{max_STC}	PV panel power output at Standard Test Condition, Watts
SI	Solar Irradiance, W/m^2
T_{STC}	PV cell temperature at Standard Test Condition, ℃
T_{cell}	PV cell temperature at that moment, ℃
V_{OC}	PV panel open circuit voltage at that moment, Volts
V_{OC_STC}	PV panel open circuit voltage at Standard Test Condition, Volts

capacity shared by different sources from 2016 to 2050.

Focusing on Middle East region, the region holds 58 % and 37 % of the world's oil and natural gas reserves, respectively [5]. As a result, the fossil fuels are excessively used across all sectors in these nations. The use of oil and gas in desalination and power plants has experienced a significant surge. The extraction and combustion of fossil fuels result in a significant release of CO2 emissions (ranging from 400 g to 1000 g CO2 eq/kWh) into the atmosphere. This overconsumption is mainly due to the high living standards, population growth, and economic progress. [5]. Utilising renewable sources as an alternative means of power generation will reduce GHG emissions and have the potential to boost national revenue by decreasing domestic consumption of oil and natural gas, hence increasing the oil and gas exports share [6]. The renewable energy sources in the Middle East's power mix for 2021 are as follows: The energy breakdown for the given sources is as follows: 15 MWh of municipal waste (0.26 %), 18 MWh of biofuel (0.32 %), 298 MWh of hydropower (5 %), 691 MWh of onshore wind (12 %), 200 MWh of concentrated solar power (CSP) (4 %), and 4464 MWh of solar photovoltaic (PV) (79 %) (Fig. 1(b)) [4]. Solar PV technology, thus, dominates the power generation sector, surpassing other renewable energy technologies (RETs) such as wind energy. Wind energy generation has some issues like noise pollution resulting from the sound of the rotating wind turbines, prone to pose a threat to flying birds, suitable for use in specific locations, distracting aesthetic aspect of the landscape, and requiring a substantial amount of installation area. It is worth mentioning that the maintenance of windmills at high elevations in the Middle East is challenging due to the high humidity and moisture levels, which negatively impact the durability of the materials (Mokri et al. [7]). According to Solar GIS [8], the Middle East area experiences the greatest sun exposure rates worldwide, ranging from 2000 to 3200 kWh/m^2/year as opposed to world average of 1597.8 kWh/m^2/year, due to its favourable climatic conditions. The sun produces around 173,000 terawatt-hours (TWh) of energy each second, which is over 10,000 times greater than the total world energy consumption. Additionally, the Middle East experiences an average of 10 h of daily sunlight and has 350 bright days per year [9]. Therefore, harnessing solar energy would be a more favourable choice. Therefore, it is crucial to investigate solar energy to preserve the natural resources of Middle Eastern nations and improve their long-term natural gas exports by decreasing greenhouse gas emissions [10].

Further focusing on the United Arab Emirates (UAE) which is situated in the Middle East, located between 51° and 56°25′ east longitude and 22°30′ to 26°10′ north latitude. On average, the UAE experiences a solar irradiation range of 1950 to 2300 kWh/m2/year [11]. In UAE, 90 % of its electricity is generated by burning fossil fuels, which is abundantly available in this region. If the oil and gas consumption in power generation and water desalination continues similarly, the region may lose these non-renewable resources by the end of 2040, which may cause economic instability in the country [12]. The UAE has taken several steps to conserve natural oil and gases to sustain its exports and maintain the country's economy. One of the major steps of the UAE is to generate 75 % of its electricity from solar PV to conserve its fossil resources and reduce its carbon footprint to achieve a Net Zero Emission (NZE) by 2050. Thus, the novelty aspect of this paper is to find gaps via literature review to identify technical and institution challenges with the use of PV technology in the UAE to maximise the penetration of solar electricity in Dubai's grid to achieve the NZE target.

2. Method of selecting review paper

A comprehensive literature review has been performed to gather information on several aspects of solar photovoltaic technology. The review initially investigated the evolution of solar photovoltaic systems and the external factors affecting their performance, such as solar irradiation, temperature, humidity, sand, dust, air pollution, wind speed, shading, and the recycling and waste management of PV panels at the end of the lifespan. Secondly, the review on soil mitigation was investigated, including natural and artificial methods. The artificial methods classified into active and passive cleaning methods were investigated to obtain the optimised cleaning method. Thirdly, the review on the reduction of the surface temperature of PV panels with available cooling techniques like PCM, water spraying, heat pipes and radiative colling techniques were investigated to find the best-optimised cooling methods for enhancing the output performance and the life span of the PV panels. Finally, the review addressed photovoltaic waste management, investigating various strategies for managing end-of-life photovoltaic panels. Various recycling techniques from many experiments were evaluated to determine the most efficient methods for recycling and reusing solar photovoltaic panels.

The literature review included four essential steps:

- Identifying appropriate keywords and creating criteria for accessing relevant databases.
- Consolidating the collected documents into Excel spreadsheets and deleting unnecessary data.
- The initial evaluation will be performed by thoroughly reading the abstracts of articles collected through search engines.
- The final list of articles related to Solar PV technology was then categorised into four sections: evolution of Solar PV panels, soil mitigation technique by cooling techniques, surface temperature reduction by cooling techniques and end of life of solar PV panels.

The literature review was based on recent research findings published from 2014 to 2024 to identify gaps in the current research regarding Solar PV technology. The review was performed using three databases: Scopus, Web of Science, IEEE Xplore, Google Scholar and Science Direct. Keywords like Solar PV panels, generation of PV panels, efficiency, output performance, soiling migration, cooling techniques, and cleaning techniques. recycling, end of life and PV waste management were used in search engines. The scope was further refined by applying the following criteria to include publications in the survey:

- The scope was refined using scientific research publications and documents published by reputed journals from 2014 to 2024.
- Peer-reviewed articles (refereed journals and conference proceedings).
- Published in English.

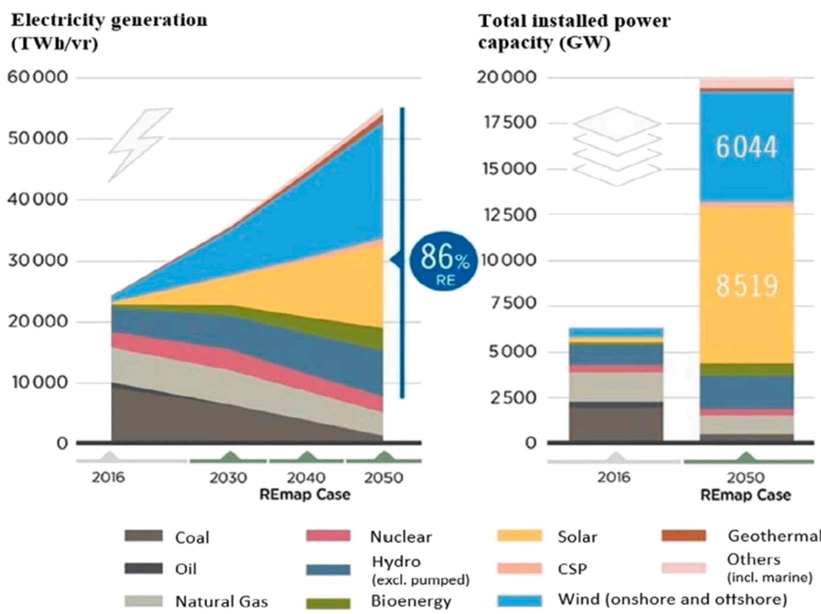
Around 300 published articles were found to address the challenges in Solar PV technologies. About half of these papers were selected based on keywords such as solar PV technological developments with 20 %, soiling and cleaning methods with 30 %, cooling strategies with 25 %, and recycling approaches to PV panel end-of-life with 25 % of selected papers, respectively.

Finally these information were categorised, synthesised and then analysed to become aware of the state of the art of PVs and to find out gaps leading to future research direction.

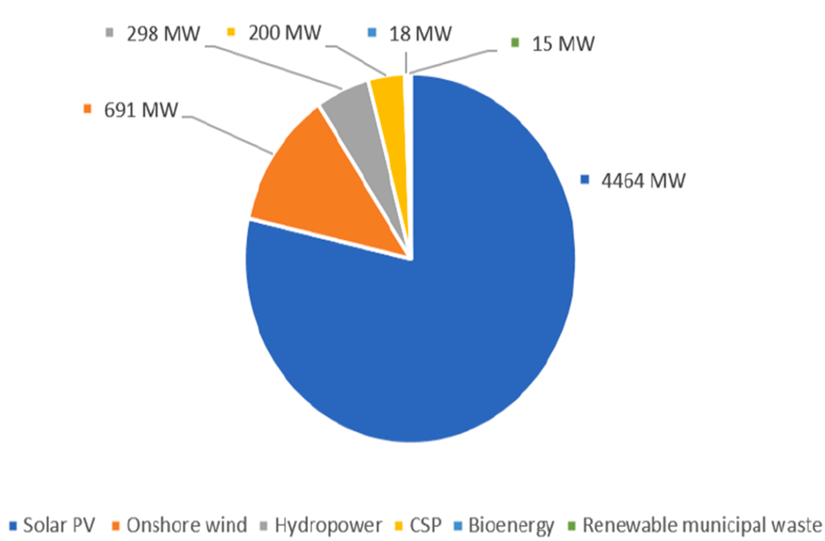
3. State of the art of solar PV technologies

3.1. Solar energy as a potential alternative option

The sun has the potential to provide solar energy for a minimum of 5 billion years [13]. The importance of solar energy for providing thermal energy and electricity the examined neighbourhoods is compared to other renewable and alternative energy supplies such as wind energy, and waste-based energy. Results demonstrate that solar energy may play extremely important role in meeting all electrical demands, even in high density and highly mixed projects, delivering between 36 %−100 % of the entire electrical energy consumption of specific neighbourhood units [14]. In 2021, the worldwide electricity production capacity from renewable energy sources' reached 3250,000 MWh [4]. Solar energy accounted for 854,796 MWh, with CSP contributing 6391 MWh and solar PV contributing 848,405 MWh [4]. Solar energy is harvested using two methods: Concentrated Solar Power (CSP), which is an indirect method, and solar photovoltaics (solar PV), which is a direct method. Solar PV systems utilise the photoelectric effect to convert sunlight irradiance into electricity directly. Solar photovoltaic (PV) panels are



(a)



(b)

Fig. 1. (a) The global electricity generation (left) and installed power capacity (right) (IRENA, [3]) and (b) The total electricity capacity of renewable energy sources available in the Middle East [4].

more affordable because of the current availability of raw materials like silicon, which constitutes 27.1 % and is the second most prevalent material on the earth's surface. Most PV panels, around 95 % available on the market, are manufactured using silicon [15]. Solar PV energy is favoured due to its easy installation, high efficiency, and relatively low installation cost (approximately 1331 USD/kWh), as well as its low operational and maintenance cost (around 15.19 USD/kWh/year) compared to wind and hydro energy [16]. There are various kinds of solar photovoltaic (PV) panels available on the market. Presently, the most common and frequently used varieties of PV panels in the market are polycrystalline, monocrystalline silicon panels and thin-film panels [17]. According to the survey conducted by Chowdhury et al. [17], the production of crystalline silicon (c-Si) is expected to decrease from 90 % to 45 % by the end of 2030. This drop is due to the ongoing decline in silicon availability. Currently, researchers and enterprises are exploring and manufacturing many types of developing PV panel technologies. These include dye-sensitizers, organic polymers, carbon nanotubes, inorganic-organic hybrid materials (such as perovskites), and inorganic materials (such as Cu2ZnSnS4 or CZTS).

Concentrated Solar Power (CSP) is a process that utilises mirrors and concentrators to turn water into steam, which is then used to generate electricity. The current technologies employed in CSP include Parabolic trough collectors (PTC), Power tower systems (PTS), Parabolic dish systems (PBS), and Linear concentrator systems (LCS) [18]. Parabolic trough collectors are used in the PBS system to concentrate sunlight onto a fluid-filled absorber tube. The fluid contained in the tube absorbs thermal energy to produce steam and operates a steam-based power plant [18]. A Photovoltaic Tracking System (PTS) is a system consisting of a series of mirrors that track the movement of the sun and concentrate sunlight onto a receiver positioned on the top of the tower. Typically, the generator in towers operates by heating a liquid to create energy. However, several experimental designs utilise molten salts to enhance the efficiency of energy transfers [19]. PBS is a compact and less efficient CSP system that uses sunlight to concentrate heat onto a liquid, which drives an engine to produce electricity. In the context of LCS, solar radiation is focused into a receiver tube containing fluid. This fluid, when heated, drives a rotor that generates electricity through a generator [20]. The PTS systems are regarded as the most sophisticated and effective because of their elevated working temperature, which spans from 300 to 2000 °C (Jin et al. [21]).

CSP systems have several advantages, including a high efficiency of 98.5 % when combined with thermal energy storage (TES) (Turchi et al. [22]), low operating costs of 0.182 USD/kWh [23], and the potential to seamlessly integrate with alternative fuel power plants to satisfy demand required at nighttime. CSP has several significant drawbacks. Firstly, higher installation cost, specifically 3432.17 USD/kWh for TES systems or the cost of batteries, in contrast to solar PV systems, which cost 1331 USD/kWh (Turchi et al. [22]). Additionally, CSP can have potential environmental impacts, including increased water consumption, changes in land use, and air pollution when operated in hybrid mode with diesel generators [24]. The flaws and degradation processes, such as corrosion, absorber tube carks and deformation, thermal difficulties in storage tanks, heat losses, mirror aging and deterioration, are permanent or cannot be avoided [25]. Solar photovoltaic (PV) technologies can address these concerns successfully.

This article begins with a concise overview of the possibilities offered by solar energy in the Middle East region. The following section gives a comprehensive review of the solar PV technology. Firstly, a detailed review on the advancement in solar PV technology is presented regarding the progress in the production of solar photovoltaic (PV) panels. The focus of these advancements is on improving panel efficiency, extending lifespan, and facilitating sustainable practices like recycling. Furthermore, the emphasis is on reducing ecotoxicity and ensuring a reliable supply of essential raw materials to support the sustainable manufacturing of solar PV technologies. Secondly, the review on the mitigation technique where the performance of PV panels is significantly affected by factors including solar irradiation, temperature, humidity, sand, dust, air pollution, wind speed, and shading. The article offers valuable insights into techniques for mitigating these challenges. This involves creating technologies aimed at enhancing performance in the different climatic conditions of the Middle East, which include extreme heat and regular sandstorms that can affect efficiency. Also, the article investigates innovative techniques for the cleaning and cooling of solar PV panels, particularly in terms of the challenging environmental conditions present in the Middle East. These include robotic cleaning systems, waterless technologies, and cooling systems that utilise innovative materials to improve panel performance while decreasing resource consumption. Finally, the article explores the significance of handling solar PV panels once they reach the end of their lifecycle. Innovative recycling techniques are investigated, emphasising the extraction of precious materials like silicon, silver, and various metals. The objective is to establish a circular economy for solar technology, guaranteeing that panels are sustainably reused or recycled, therefore minimising environmental impact. By studying these vital components, the article provides a comprehensive look into the potential benefits and challenges associated with utilising solar energy in the Middle East. This highlights the necessity of incorporating cutting-edge solutions to improve the installation of solar PV, all while maintaining environmental and economic sustainability.

3.2. Solar PV panel generations

Harvesting energy from solar has become a major contributor in the energy sector. Solar PV technologies play an important role in harnessing the energy from the sun. The solar PV cells work on the principle of the photovoltaic effect, transforming the received sunlight into electricity. Solar PV cell technologies involve many techniques in manufacturing PV cells, including the use of materials to enhance efficiency, regulate cell temperature, and extend the lifespan of the cells [26].

The manufacturing procedures for solar PV cells are categorised into:

- First generation of solar PV technologies.
- Second generation of solar PV technologies.
- Third generation of solar PV technologies.
- Fourth generation of solar PV technologies.

3.2.1. First generation of solar PV technologies

The first-generation PV cell technologies are thick crystalline films made of crystalline silicon wafers (c-Si) with positive-type silicon doped with boron as a base material. There are high-efficiency n-type Si base materials cells available, but there are some technical challenges in achieving uniform doping compared to p-type (Goetzberger et al. [27]). Crystall silicon PV panels are currently the most common and frequently used in the market. In 2014, 90 % of the PV panels manufactured worldwide were manufactured using crystalline silicon [17,28]. The wafers of single crystals are called mono-crystalline, and the wafers of multiple crystals are called polycrystalline [29].

***Monocrystalline Solar PV* Cells:** The mono-crystalline PV cells are manufactured using single silicon crystals. Mono-crystalline cells have ~1.1 eV of band gap energy, with an efficiency of 27.6 % and a life span of 25 years (Sharma & Goyal [30]). These cells have high performance and stability with high manufacturing costs and are very sensitive to higher temperatures (Marques et al. [31]).

***Polycrystalline Solar PV* Cells:** Polycrystalline or multi-crystalline cells are manufactured by melting various high-purity fine silicon crystals and crystallising them by a direct solidification process (Goetzberger et al. [27]). The multi-crystalline cells have ~1.7 eV a band gap energy, with an efficiency of 23.3 % and a life span of 14 years (Sharma & Goyal [30]). Polycrystalline cells are cheaper and less efficient than mono-crystalline PV panels [32].

Passivated Emitter and Rear Solar PV Cells (PERC): The passivation layer is added to the rear surface to enhance the electrical and optical properties of the Al-BSF cells and improve passivation and internal reflection, as shown in Fig. 2(a). These cells with the passivation layer were named Passive Emitted and Rear Cell (PREC) [33]. PERC cells have ~1.4 eV of band gap energy, with an efficiency of 23 % and a life span of 18 years [31].

Silicon Heterojunction Solar PV Cells (SHJ-Type): The SHJ-type cells are made by stacking a layer of intrinsic and doped amorphous silicon on the passivated contacts of the cells. The SHJ-type cells, known as Bifacial modules, can produce more electricity than a regular module [35]. The SHJ-type cells are available in thin wafers because of their less stressed structure, as shown in Fig. 2(b). The SHJ-type cells achieved an efficiency of 24.7 % with a lifespan of 18 years and a high manufacturing cost compared to other crystalline cells (Taguchi et al. [36]).

Gallium Arsenide (GaAs) based III-V junction's Solar PV Cells: The GaAs cells are thinner, lightweight, flexible, and easily placed on curved surfaces. These cells have greater absorption levels and stability and are very sensitive to low temperatures [31]. The GaAs cells have ~1.7 eV of band gap energy, with an efficiency ranging from 28 % to 30 % and a life span of 14 years (Sharma & Goyal [30]).

3.2.2. Second generation of solar PV technologies

Solar PV cell technologies are based on thin film cells used for roof tiles, windows, and curved surfaces due to their light, flexible and thin features. The cells are less efficient and cheaper than the crystalline PV cells as they use 99 % less semiconducting Si materials in manufacturing [37].

Copper Indium Gallium Selenide (CIGS) Solar PV Cells: CIGS cells are thin-film cells multilayered with nanocrystalline Cu-(In1-x Gax)-Se2 materials to absorb the majority of semiconductors as shown in Fig. 3(a). CIGS cell technologies use magnetron sputtering to stack thin films on the glass substrate [38]. The CIGS cells have ~1.7 eV of band gap energy, with an efficiency of 20 % and a life span of 12 years (Sharma & Goyal [30]). Due to the low availability of indium, which is 0.1 parts per million on the earth's surface, production has become less popular.

Cadmium Telluride (CdTe) Solar PV Cells: Cadmium Telluride cells are thin, flexible, lighter, and transparent. It consists of the multilayers with a back contact, a layer of CdTe and CdSeTe, a buffer and a transparent conductive oxide (TCO) layer made of Zn2SnO4 (Fig. 3(b)) [34]. The CdTe cells have ~145 eV of band gap energy, with an efficiency of 15 % to 16 % and a life span of 20 years (Sharma & Goyal [30]). The disadvantage of CdTe cells is that they use cadmium, which is very toxic and hazardous to the environment, and their efficiency gradually decreases with increased transparency [40]. These cells have many applications in building integrated photovoltaics and rooftop systems.

Amorphous Silicon (a-Si) solar PV cells: The a-Si PV cells are the last type and most used thin film technology, and the cells are formed using a gas phase deposition technique with metals or gas as the substrate (Fig. 3(c)) [41]. The a-Si: H cells with a thickness of 300 nm have a 90 % absorbing capability of photons in a single pass above the passband, making the cells lighter and more flexible [42]. These cells have an efficiency between 5 % and 7 %, which can be increased to 8 % to 10 % with double and triple junction structures and a life span of 15 years (Sharma & Goyal [30]).

3.2.3. Third generation of solar PV technologies

The first- and second-generation PV cells have drawbacks such as technical, economic, and social aspects. To overcome these issues, third-generation solar PV cell technologies were introduced. These technologies include high-efficient, expensive, and low-efficient, inexpensive solar cells based on their applications. Due to its low popularity in the market, it is referred to as an "emerging concept". Third-generation cell technologies include Dye-sensitized, organic, perovskite, quantum dots and multi-junction solar PV cells [43].

Organic Solar PV Cells (OSC): These cells are lightweight, inexpensive, semi-transparent, flexible, and can be manufactured on a large scale. These cells are made up of organic semiconductors, which include polymers, pentacene, polyphenylene vinylene, carbon fullerene, and copper phthalocyanine, as shown in Fig. 4(a) [44]. The OSCs are available with a thickness of 100 nm, an efficiency of 18.20 %, and a life span of 20 years [31].

Dye-Sensitized Solar PV Cells (DSC): These are hybrid organic-inorganic cells that use nanotechnology materials to harvest solar energy. The DSCs, as shown in Fig. 4(b), work on principle photo-sensitisation, where the titanium dioxide (TiO2) nanocrystalline layer is used as a conductor in contact with organic dyes to absorb light [48]. The DSCs have an efficiency between 5 % and 20 %, and 13 % is the highest efficiency reported to date, with a lifespan of 12 years [49]. Due to their simple fabrication, manufacturing these cells is much cheaper, flexible, colour-capable, and transparent.

Perovskite Solar PV Cells (PSC): Perovskite solar cells were introduced to improve the material quality through synthetic methods, which relied on the metal halide perovskite (MHP) mechanism. The MHPs have a high absorption coefficient, longer life span, high diffusion length, higher band gap energy and lower defect density [50]. A single PSC junction with an MHP mechanism has an efficiency that has increased to 25.2 % in the last decade and has a lifespan of 23 years [50]. The PSCs are revolutionary PV cells with a simplified structure, are lightweight, flexible, highly efficient, and have low manufacturing costs. The only disadvantage is that the PSCs are unstable, deteriorating faster and shortening working life (Sharma & Goyal [30]).

Quantum Dots Solar PV Cells (QD): Quantum dots (QDs) are used in manufacturing solar PV cells, also known as Nanocrystalline solar cells. QDs cells have high absorption coefficients, small exciton diffusion length of 10–20 nm, poor electron mobility, and a short lifetime of excitons, due to which there will be a drop in the conversion efficiency (Fig. 4(c)) [51]. QDs have an efficiency of 11 % to 17 %, and a record efficiency of 16.6 % was achieved using mixed colloidal QDs with PSCs and a lifespan of 18 years (Sharma & Goyal [30]). Nanocrystalline solar

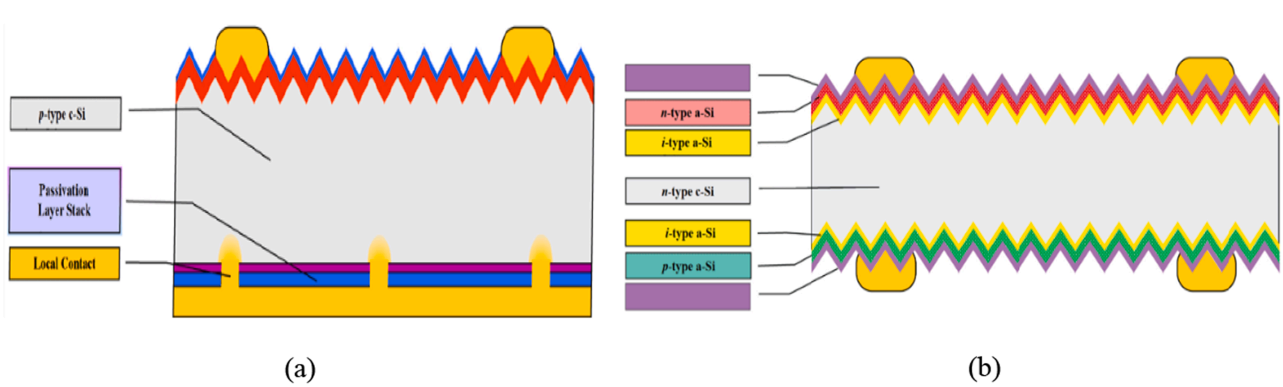


Fig. 2. (a) Solar PV cell structure: PERC (b) Silicon Heterojunction solar cell structure [34].

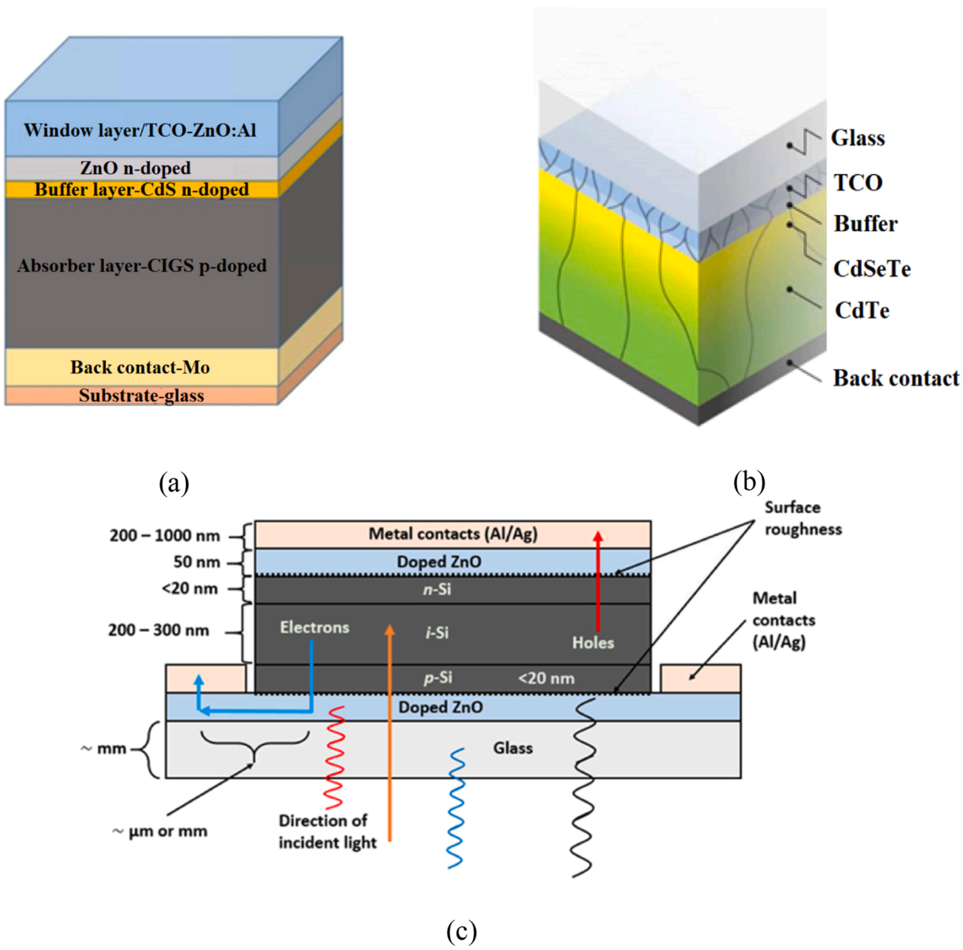


Fig. 3. Schematic diagram of (a) CIGS cells [38], (b) CdTe cells [34], and (c) Amorphous silicon (a-Si) cells [39].

cells using nanomaterials are very simple to fabricate and have good band gap tuning and control ability, which allows PV technologies to push the field even further.

Multi-Junction Solar Cells: These PV cells are fabricated using various semiconductor materials to form the p-n junctions; each junction has a different wavelength in response to light to produce electricity, increasing the conversion efficiency, as shown in Fig. 4(d). This concept is called tandem solar cells [47]. These cells have an efficiency of 45 % and a lifespan of 25 years (Sharma & Goyal [30]). Manufacturing these multi-junction cells is complex and expensive due to stacking multiple layers of different cells [52].

3.2.4. Fourth generation of solar PV technologies

The fourth-generation solar PV technologies are based on low-cost, flexible thin-film polymer with stable organic nanomaterials such as graphene and its derivatives, carbon nanotubes, and hybrid inorganic cells [53].

Graphene-Based Solar PV Cells: Graphene is considered the future of nanomaterials because of its unique properties, such as flexibility and compatibility with metal oxides, high transmittance, high carrier mobility, 2D lattice packing and low resistivity [54]. The advantage of combining graphene with other PV cell materials is that it can be used as a hole/electron transport material, transparent electrode, and interfacial buffer layer [55]. The graphene-based perovskite and heterojunction organic cells showed an increase in their efficiency by 20.3 % and 10 %, respectively (Geim & Novoselov [56]). Also, these cells have a life span of 25 to 45 years, and due to their 2D lattice packing structure, graphene-based solar cells have less environmental degradation and ensure long-term stability [57]. The cross-sectional view and schematic representation of the Graphene-silicon Schottky junction solar cell are shown in Fig. 5.

Further, the PV panel's performance can be improved by continuous monitoring and real-time control of PV panels without any human interaction are very essential. To optimize the performance of PV technologies, the Internet of Things (IoT) and blockchain technology can be integrated. The Internet of Things (IoT) enables the convenient use of interconnected technologies for ongoing monitoring and regular evaluations of PV module performance, enabled by the widespread adoption of wireless networking. Continuous monitoring would be conducted on several factors like surface temperature, defect diagnosis, output power, dust buildup, air quality, weather conditions, shading, battery usage, and energy consumption by the user (Kumar et al. [58]). This data will be sent to the cloud using the most compact communication packages. The user may get the uploaded information from the cloud regardless of location, and any choice made can be sent back to the cloud to be reversed (Nallapaneni et al., 2017). The transfer of data and decisions will be regulated by a secure network created by state-of-the-art blockchain technology. PV technologies may be integrated into a condition monitoring system connected to an Internet of Things (IoT) model and a blockchain platform. This integration aims to enhance the PV panel's performance, reduce costs, and optimise energy usage.

3.2.5. Summary of generation of solar PV panels

From the literature on the solar PV generation, the inferences are drawn. The mono and polycrystalline silicon cells from first-generation technologies are the most popular and widely used market, producing 80 % of the total. It has an efficiency ranging from 23 % to 28 % and a better lifespan of 25 to 30 years. The major drawbacks were the

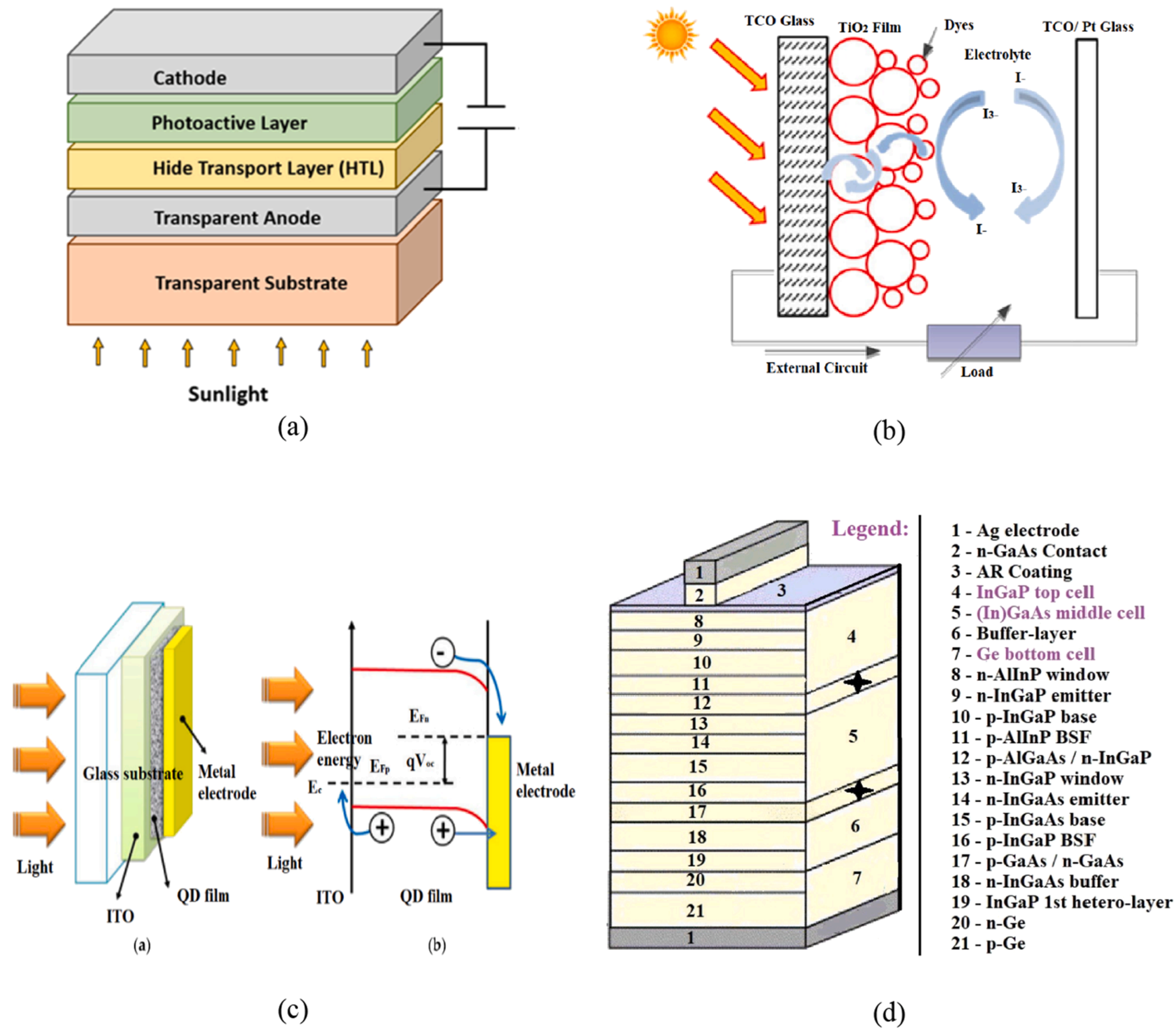


Fig. 4. Schematic representation of (a) Organic photovoltaic cell [45], (b) DSSCs [42], (c) Quantum Dots cell [46], and (d) Multi-Junction Cells [47].

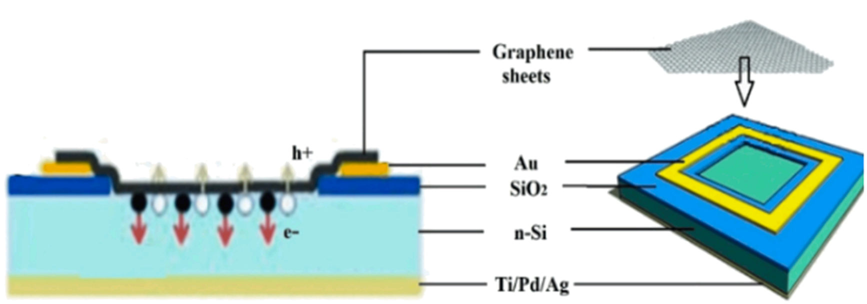


Fig. 5. Cross-sectional view and a schematic representation of Graphene–silicon Schottky junction PV cell [54].

manufacturing cost, high-temperature sensitivity, and low absorption level and thickness. Later, these issues were covered in the second-generation PV panels, which required fewer materials for production, making the panels much cheaper and lighter and having high absorption levels. The materials used to manufacture second-generation panels are cadmium, gallium, and selenide, which are highly toxic and temperature-sensitive, making panels less efficient. Third-generation and fourth-generation solar PV cell technologies were introduced to overcome all the drawbacks of first- and second-generation solar cells, such as technical, economic, and environmental aspects. Due to its low popularity in the market, it is referred to as an “emerging concept”. The comparison between the generation of solar PV technologies based on efficiency, lifespan, advantages and disadvantages is shown in Table 1.

Based on the generation of solar PV technologies, there are many factors affecting the PV panel’s output performance, such as soiling, shading, module temperature, material degradation, tilt angle, and

Table 1
Comparison between the generation of solar PV technologies.

Generations of Solar PV Cells	Types of Solar PV Cells	Efficiency	Lifespan	Advantages	Disadvantages	Refs.
First Generation	Mono-crystalline	27.60 %	25 years	Higher performance and stability, longer life span	High manufacturing cost, high-temperature sensitivity and low absorption level.	(Sharma & Goyal [30]).
	Polycrystalline	23.30 %	14 years	Easy to manufacture, profitable, low silicon waste, high absorption level compared to m-si	Low efficiency and high-temperature sensitivity.	(Sharma & Goyal [30]).
	Passivated Emitter and Rear (PERC)	23 %	18years	Decrease in thermal losses and gives better performance with high temperature.	Higher manufacturing cost	(Sharma & Goyal [30]).
	Silicon Heterojunction Cells (SHJ-Type)	24.70 %	18 years	Manufactured in thin films with a thickness of 50 µm, it is more feasible and efficient.	Very rigidity and high production costs	(Taguchi et al. [36]; Sharma & Goyal [30]).
Second Generation	Gallium Arsenide (GaAs) based III-V junctions	29.10 %	14 years	High efficiency, greater stability, low-temperature sensitivity and high absorption level.	Extremely expensive	(Sharma & Goyal [30]).
	Copper Indium Gallium Selenide (CIGS)	23.30 %	12 years	Requires less materials for production	Unstable, more temperature-sensitive and unreliable	(Ghosh & Yadav, [28]; Sharma & Goyal [30]).
	Cadmium Telluride (CdTe)	22.10 %	20years	High absorbing capability, requires less materials for production	Low-efficient, highly toxic and temperature-sensitive	(Sharma & Goyal [30])
	Amorphous Silicon (a-Si)	12 %	15 years	Less expensive, non-toxic, high level of absorption	With low efficiency, the selection of dopant materials is difficult	(Sharma & Goyal [30])
	Cadmium Sulfide (CdS)	22.10 %	20 years	High absorption level and requires less materials for production	Low-efficient, highly toxic and temperature-sensitive	(Sharma & Goyal [30])
Third Generation	Organic Solar PV Cells (OSC)	18.20 %	20 years	Low production cost, very lightweight, flexible and has high thermal stability	Low efficient	(Sharma & Goyal [30]).
	Dye-Sensitized Solar PV Cells (DSC)	13 %	12 years	Low cost, very light and wide-angle operation and rigid	temperature instability and highly toxic	([49]; Sharma & Goyal [30])
	Perovskite Solar PV Cells (PSC)	25.20 %	23 years	Simplified structure, very flexible, lightweight, low production cost and highly efficient	Unstable	([50]; Sharma & Goyal [30])
	Quantum Dots Solar PV Cells (QD)	16.60 %	18 years	Low manufacturing cost and lower energy consumption	High toxic and degradation	([59]; Sharma & Goyal [30]).
	Multi-Junction Solar PV Cells	45 %	25 years	High performance	Complex, expensive	([52]; Sharma & Goyal [30])
Fourth Generation	Graphene-Based Solar PV Cells	20 %	25–45 years	It has a low manufacturing cost, is highly conductive, good transparency level, low degradation, and a better lifespan.	Low Hydrophilicity	([57]; Geim & Novoselov [56]).

orientation of panels. Also, there are some challenges involved in the recycling/remanufacturing of PV panels at EOL, which will lead to an increase in e-waste in the next 20–25 years. This e-waste will have a greater impact on the environment by increasing GHG emissions. In the following sections, the types of mitigation techniques (cleaning and cooling) used to address the factors affecting PV panel's performance and eco-friendly recycling techniques used to extract silicon wafers from the waste panels and use them for remanufacturing PV panels and other applications to reduce GHG emissions are discussed.

4. External factors affecting the performance of solar panels

4.1. Soiling

Apart from efficiency, there are additional problems in installing PV systems in the Middle East. Several external factors, such as sun irradiation, temperature, humidity, sand, dust, air pollution, wind speed, and shadow, can influence the performance of PV panels. It is necessary to consider and reduce these effects while installing solar PV systems [60].

Dust accumulation is one of the main factors affecting the PV panel's efficiency and longevity. The dust accumulated on the PV panels reduces transparency and blocks sunlight from reaching the surface. As a result, the PV panel's efficiency, overall performance, and lifespan will be reduced [61]. The experimental model was proposed to monitor and show the effect of dust on grid-connected PV systems containing 1.4 kW PV and 1.7 kW inverter performance, yield and profitability. The results demonstrate that the suggested model accurately predicted system performance and was confirmed by experimental findings. The photovoltaic, inverter, and performance efficiencies are 10.80 %, 94.00 %, and 73.00 %, respectively. Also, the average yield factor is 141.39 kWh/kWp, and the capacity factor is 19.64 % [62]. To maximise output power and efficiency during periods of dusty storms, it is necessary to clean the accumulated dust on the PV panels daily. Frequent cleaning and maintenance of PV panels result in improved performance and increased lifespan. When the cleaning frequency was decreased from 1 to 3 weeks, it was found that the amount of dust accumulating on the panels increased from 1 g/m^2 to 5 g/m^2. This led to a decrease in energy production by 16 to 24 % and caused the average temperature in the panels to drop by 5.38 %, 2.17 %, 7.05 %, and 4.28 %, regardless of the panel types used [63]. Research to examine the effects of dust accumulation on PV panels over five months was conducted in Sharjah, UAE. The research findings indicated that a dust density of 5.44 g/m2 resulted in a 12.7 % reduction in the efficiency of the PV panels [64]. Furthermore, the performance of the PV panels, when equipped with a real-time monitoring system, exhibited a 10 % loss in output power because of the accumulation of dirt [65].

4.1.1. Soiling mitigation techniques

This article explores several mitigating strategies to minimise dust accumulation on PV panels. These approaches include natural cleaning methods such as rain, wind, snow, and tilt angle, as well as artificial cleaning methods, including manual and self-cleaning. Fig. 6 depicts the categorization of soil mitigation approaches.

4.1.2. Natural cleaning techniques

Natural cleaning approaches rely on environmental elements such as

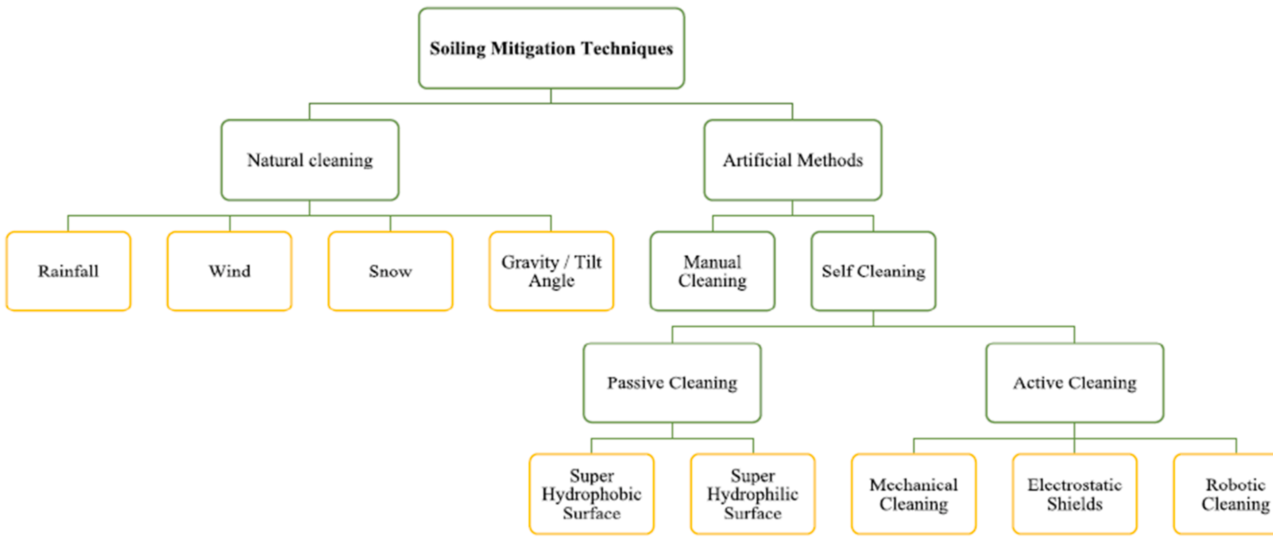


Fig. 6. Soil mitigation techniques [66].

precipitation, air movement, frozen precipitation, gravitational force, and the angle at which solar PV panels are positioned. Natural elements play a crucial role in cleansing solar panels by eliminating dirt and dust particles, with the effectiveness of wind and rain being contingent on the specific geographical location. A study conducted in the desert climate of Qatar over six years recorded the effect of environmental difficulties on the PV panel's output performance [67]. The study found that 75 % of the days had a decrease in output power owing to dirt accumulation, while 25 % of the days had an increase in output power caused by the resuspension of dust. The average yearly soiling rate had a 23 % rise during winter due to more severe dust storms compared to those in the summer. This resulted in a decrease in PV panel efficiency by 3 % [67]. A study conducted in Saudi Arabia examined the difference in energy consumption between clean and dust-coated photovoltaic (PV) panels tilted at a 24.6-degree angle over eight months. The findings revealed that the dust-coated PV panels experienced a 32 % reduction in energy consumption [68].

In Riyad, Saudi Arabia, the dust-coated solar PV panels were exposed to rainfall in the winter season, resulting in only a 2 % increase in output energy [67]. During the rainy season, the soiling rate was moderate. A rainfall of just 3 mm was sufficient to clean the PV panels completely [69]. An experiment was conducted in Sharjah, UAE, to investigate the output performance of PV panels at various tilt degrees, both indoors and outdoors [70]. An indoor experiment showed that the relation between dust accumulation and output power was linear, with a slope decreasing by 1.7 % g/m^2. By varying the tilt angles of the indoor and outdoor PV panels to 0°, 25°, and 45°, it was observed that the dust buildup increased to 37.63 %, 14.11 %, and 10.95 %, respectively. The observation was carried out for five months, and the outdoor experiment result showed an increase in dust accumulation by 5.44 g/m2 with a decrease in the output power by 12.7 % compared to the indoor experiment [70]. Natural cleaning techniques are not as effective as other cleaning techniques as the rain leaves water spots, accumulates dust, and further reduces efficiency. On the other hand, wind in the opposite direction could cause scratches and abrasion on the panel by flinging dust deposited on the PV panel's surface. Natural cleaning methods are found to be cost-effective, and they do not involve manpower or external power to clean the panels.

4.1.3. Artificial cleaning techniques

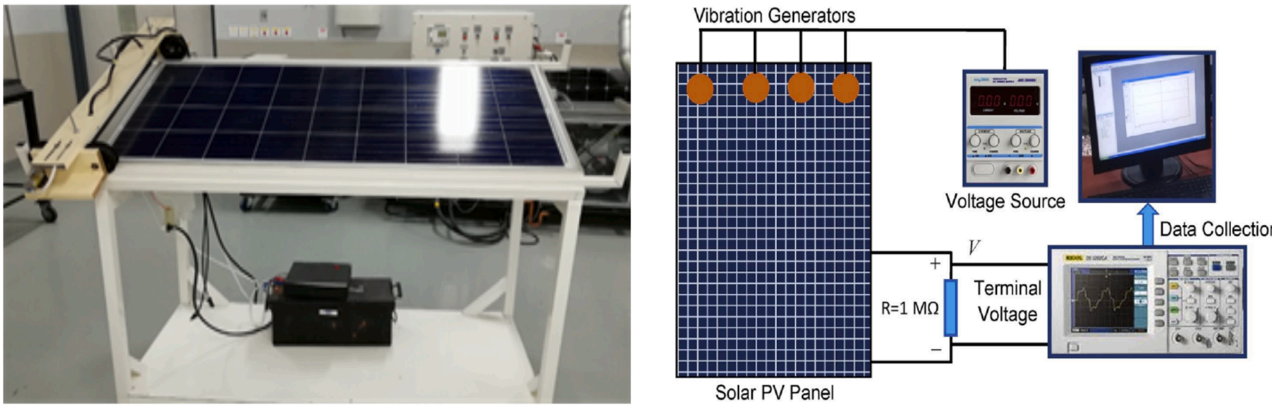
The artificial technique is classified into two methods: Manual cleaning and Self-cleaning.

Manual cleaning techniques: This technique utilizes manpower to clean the PV panels' surface with the help of equipment like spraying water, brushing, cleaning liquids, clothes, etc. The manual cleaning is very effective, and the panels are expected to give very good output performance after cleaning. The experiment was carried out on a 5.85 kW grid-tie ground mount system with two strings of 9 modules in series. Two manual cleaning intervals have been applied on each string to observe the influence of the dust on the PV system performance. The results demonstrate that the dust collection lowered the PV modules' current performance by up to 28 %, with the average current output of the uncleaned string measured at 4.1 A compared to 5.6 A from the cleaned string [71]. The major drawbacks of manual cleaning include water wastage, especially in an environment with water scarcity, needing more manpower, high labour costs, and time-consuming. Furthermore, manual cleaning can cause frame corrosion of the PV panel [69].

Self-cleaning techniques: The most recent approaches for enhancing the efficiency of a solar PV panel by self-cleaning have been categorised into Active and Passive methods. The mechanical and electrostatic techniques are active and need external power. The coating method is basically passive, as it is not dependent on any external power source [67]. The two coating methods are superhydrophobic and superhydrophilic coatings.

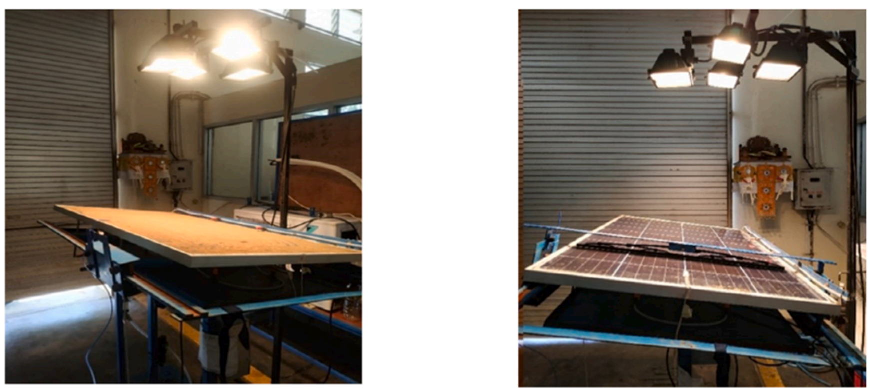
Active cleaning methods are classified into mechanical, electrostatic and robotic and require an external power source. The active cleaning technique involves mechanical cleaning, which utilizes microfiber brushes, blowers, wipers, and electrodynamic shields with high voltage input in generating electrostatic forces causing vibration and robotic cleaning with a controlled motor, wipers, spray, and sensors controlled by microcontrollers to clean the panels [72]. The self-cleaning system shown in Fig. 7(a) was built in Medina, Saudi Arabia, to compare the efficiency of clean and uncleaned PV panels under two different solar irradiances. The result showed an increase in output power by 4.78 % at 805 W/m^2 and a 5.3 % increase at 460 W/m2 [73].

The motor-controlled semi-automatic wiper cleaning system was developed with a manual button to override if extra rotation was required. The performance of cleaning the panel was based on several rotations of the wiper. The wiper rotations were performed in 10, 20 and 30 repetitions, resulting in 57 %, 79.1 % and 86.7 % cleaning on the solar panels [72]. Fig. 8 shows the experimental setup of self-cleaning with and without a dusty surface. Similarly, an experiment was conducted to compare between a brush cleaning method and a microfiber cloth cleaning method for with and without a vacuum cleaner. It was found that both brush and microfibre cloth with and without vacuum



(a) (b)

Fig. 7. (a) Self-cleaning system [73] and (b) Experimental setup and measurement system [74].



(a) (b)

Fig. 8. Experimental setup for self-cleaning with (a) dusty surface and (b) clean surface [72].

cleaners had a better performance as it increased overall efficiency by 6 % when the panels were cleaned every week [75].

The wind-powered dust removal system using a mechanical vibrator was compared with the electrical vibrator system under certain parameters like dust removal index, surface response and variance of the PV panels. Their results showed that the system using a mechanical vibrator had 91 % cleaning efficiency over the electrical vibrator for the same dust quantity [76]. In Doha, Qatar, the PV panels integrated with electrodynamic shield electrodes covered with polymer dielectric were carried out in winter and spring weather conditions. The experiment was performed on soiling losses, relative humidity, and cleanliness index change rate. There was a significant reduction of 16 % to 33 % in soiling losses over 9 kVp hours of operation compared to non-electrodynamic shielded PV panels [77]. The PV panel's surface decontamination using surface acoustic waves (SAW) was used to remove contaminants and dust on the panels, which increased efficiency [74]. Fig. 7(b) shows the experimental setup of SAW with the vibration generators connected to the panel and the power supply.

The detailed optimised model was studied to improve the optical and electrical configuration of electrodes used in electrodynamic shields [78]. Cleaning devices that use electrodynamic forces generated by high AC voltages were developed to clean strong and adhered dust particles. As a result, the cleaning included better airflow utilisation, operational adjustment and improved electrode configuration. Also, these cleaning devices with electrodynamic forces were highly efficient and consumed less power [79].

A study of superhydrophobic and superhydrophilic coating methods on PV panels was conducted in dark and shady regions. The result showed that a superhydrophobic coating was more efficient than a superhydrophilic one, where the photocatalysis reaction did not work in the dark and shady regions [69]. An experiment was conducted to understand the effect of antireflective, self-cleaning and photocatalytic coating on PV panels. The result improved the panel's efficiency by improving the self-cleaning characteristics, achieving a better absorption level, and reducing dust accumulation. A similar test was conducted on the coating of PV panels to analyse the photocatalytic capabilities using UV–vis spectroscopy and degradation of the Methylene Blue (MB). The result showed that a coated PV panel had a high light transmittance when exposed to light and better self-cleaning abilities than an uncoated PV panel [80]. Fig. 9 shows the graphical comparison of both coated and uncoated PV panels under light transmission spectra.

4.1.4. Summary of cleaning techniques

From the literature on soil mitigation techniques, the inferences are drawn. As the frequency of cleaning was decreased from 1 to 3 weeks, it was found that the amount of dust accumulating on the panels increased from 1 g/m^2 to 5 g/m^2, which showed a decrease in energy production by 16 to 24 %. Also, only 3 mm of rain was adequate for cleaning the solar panels. The artificial cleaning techniques combined with active and passive methods (jet spray and hydrophobic coating) showed a significant increase in efficiency by 6 to 8 % with one clean. The natural cleaning technique, such as for rain, tilt angle, and wind direction, was

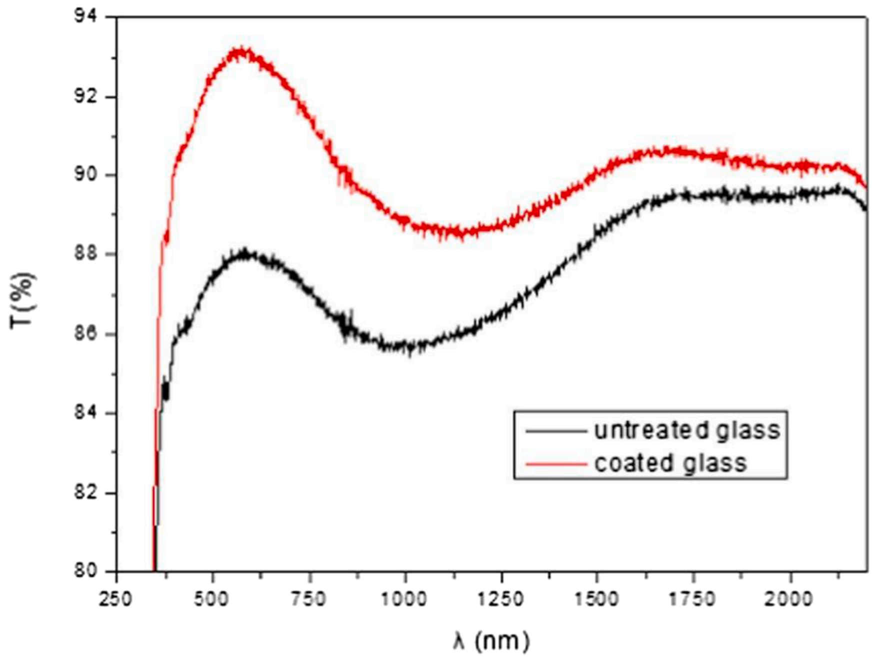


Fig. 9. Graphical comparison of coated and uncoated glass displaying light transmission spectra [80].

more ineffective in regions like the Middle East than the artificial cleaning techniques. Table 2 shows the comparison between different types of soil mitigation techniques.

4.2. Effect of increased surface temperature

The PV panel's surface temperature plays an essential role in improving its efficiency. The PV panels capture solar irradiance and convert it into heat and electricity. The rise in the temperature of the surface due to heat leads to a loss in cell efficiency and causes degradation [81–83]. The study was conducted on the rate of deterioration and efficiency of solar panels in Sohar, Oman, over seven years. The result showed that the PV panel's efficiency decreased by 1 % every year, and the degradation rate gets worse during the summer months due to higher temperatures resulting from intense sun radiation and surrounding air heat [84]. The PV panel's performance is determined by the relationship between its open circuit voltage (V_{OC}), short-circuit current (I_{SC}), and temperature, as shown in Fig. 10. At high temperatures, the increased thermal energy within the semiconductor material results in a greater excitation of electrons, causing them to move randomly, leading to increased electrical resistance and reduced voltage output. Thus, the total efficiency of the PV cell decreases with increasing temperature [85]. The temperature coefficient is a parameter that quantifies the impact of temperature on the overall output power of the cell.

Eqs. (1)–(3) show the relation between current (short circuit), output power, and voltage (open circuit) with cell temperature [86].

$$I_{SC} = I_{SC\_STC} * \left(\frac{SI}{1000}\right) * \left(1 + \left(\frac{\alpha_I (T_{cell} - T_{STC})}{100}\right)\right) \quad (1)$$

$$V_{OC} = V_{OC\_STC} * \left(1 + \left(\frac{\alpha_V (T_{cell} - T_{STC})}{100}\right)\right) + V_{OC\_SI} * \ln\left(\frac{SI}{1000}\right) \quad (2)$$

$$P_{OUT} = P_{\max\_STC} * D_f * \left(\frac{SI}{1000}\right) * \left(1 + \left(\frac{\alpha_P (T_{cell} - T_{STC})}{100}\right)\right) \quad (3)$$

The increase in cell temperature has become a major issue in the Middle East region. Many researchers have introduced several concepts and cooling techniques to enhance the PV panel's efficiency by decreasing the cell temperature close to the manufacturing standard temperature.

4.2.1. Cooling techniques for solar PV panels

The cooling systems are classified into active and passive cooling systems. The active cooling system uses fans and motor pumps to circulate air or water as a coolant, while the passive cooling system uses no external power to cool the panels. The passive cooling system is further classified into water, air and conductive cooling. Passive cooling methods use heat pipes, sinks, or exchangers for natural convection cooling [87]. The heat sinks are placed at the backside of the PV panel to transfer heat and are highly thermally conductive. Therefore, passive cooling methods are very effective, easy to implement and cost-effective compared to active cooling methods [88]. Later, many complex cooling technologies like phase change materials (PCM), nanofluids, thermoelectric generators (TEG) and the hybrid cooling system and their combinations were evolved.

4.2.2. Phase change material (PCM) cooling technique

In the PCM cooling technique, the latent heat is extracted from the PV panel's surface by inducing a change in the panel's physical states, namely melting and freezing. This process effectively reduces the surface temperature and enhances the PV panel's efficiency. The selection of the PCM can be determined by considering its melting temperature and latent heat [81]. The PCM cooling technique exhibits higher thermal conductivity and maintains a consistent surface temperature. An essential characteristic of the PCM technique is its ability to absorb heat during the day and release it at night. Fig. 11(a) depicts the commonly used PCM and its melting temperature. These techniques are classified into PCM-PV, PCM-PV/T, and PCM-PV/T-Nanofluids [89].

The experiment was carried out using two prototypes, one equipped with Phase Change Material (PCM) and the other without PCM. found that increasing the temperature by 1 °C over the laboratory test temperature of 25 °C leads to a drop in output power ranging from 0.3 % to 0.5 % [90]. An analogous experiment was carried out to assess the effectiveness and surface temperature of solar photovoltaic (PV) panels equipped with phase change material (PCM)-PV cooling systems in comparison to uncooled PV panels. The addition of a cooling system in the PV panels resulted in a decrease in surface temperature from 4 °C to

Table 2
Comparison between different types of soil mitigation techniques.

Soil Mitigation Techniques	Descriptions	Advantages	Disadvantages	Refs.
Natural cleaning method	It depends on external factors like wind, rainfall, snow, orientation, and tilt angles. Uses no additional power or technology for cleaning	Zero investment and zero expense on cleaning	The geographical area is dependent, unpredictable and less effective for strongly adhered dust particles.	[70, 67, 69]
Manual cleaning method	It depends on manpower to clean PV panels using water, brushes, a table or ladder, and cloth.	Very effective with 100 % cleaning efficiency	High labour costs, waste of water and time-consuming	[67, 69]
Mechanical cleaning method	It uses mechanical parts like a blower, wipers, motor-controlled brushes and microcontroller and requires external power sources for cleaning.	Works on both automatic and on command have a cleaning efficiency of 96 % and reduce labour costs.	High maintenance cost and consumes energy from the power produced by the panels	[73, 72]
Electrodynamic Screens/ Shields cleaning method	It works on electrodynamic or electrostatic forces generated by high voltage input and uses sensors controlled with programable logic microcontrollers.	It works on automatic and manual control, consumes very little power, is highly effective with 90 % cleaning and cleans faster.	It is less effective and has a high investment cost depending on humidity.	[74, 79, 73, 72]
Robotic cleaning method	It uses a microcontroller and Arduino to work on equipment like brushes, water spray and sensors.	Very efficient cleaning, controlled and monitored wireless, can be recharged and less water wastage.	High initial cost, high maintenance cost and very slow cleaning process	[73, 72]
Passive cleaning method	Uses chemical coating with hydrophobic and hydrophilic properties	Requires no external power source and highly effective cleaning of 75 %	The lifetime of coating on the panel is very limited and can reduce the optical performance of the panels.	[80, 69]

5 °C, while also enhancing efficiency by an additional 3 % compared to panels without a cooling system [91]. An organic phase change material (PCM) with a thickness of 0.03 m and an aluminium sheet spanning an area of 0.036 m2 was positioned on the back of the panels. The experiment was conducted for a duration of three months (Fig. 11(b)) [90]. The result indicated a decrease in the surface temperature of the panel by 10.35 °C, a 2 % enhancement in the overall average electrical efficiency, and a 24.4 % improvement in the conversion efficiency of the PCM-PV system with aluminium-cooled PV panels compared to the uncooled PV panels [90]. Hybrid phase change materials are synthesised and examined for their solar energy storage ability. The results indicated that hybrid PCMs have the best conversion efficiency, around 92.9 %, for solar to thermal energy. These PCMs shown exceptional performance in storing applications [92].

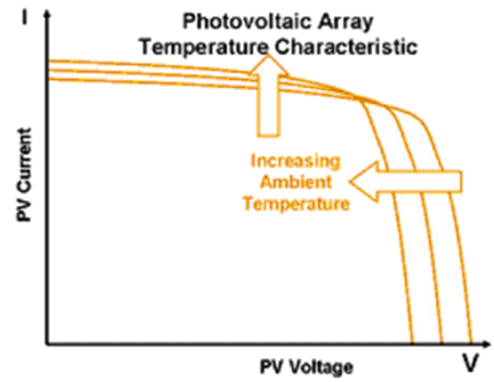


Fig. 10. Characteristics of a solar: Effect of temperature [81].

The experiment was conducted on panels with and without organic paraffin wax PCM. It was found that the panel with PCM reduced the panel temperature by 15 °C and showed a 5.39 % increase in efficiency [93]. Also, it was shown that organic paraffin wax is a widely used PCM for thermal storage due to its low thermal conductivity [81].

4.2.3. Water spraying cooling technique

Water is used as a cooling agent and sprayed on the PV panel to improve the output power by reducing the surface temperature. The water spraying technique uses the sprinkler placed on the panels connected to the DC pump through pipes. The water spraying technique can be used on both sides of the PV panels, as shown in Fig. 12(a). The water spray system was constructed to cool both sides of the panel. The PV panel's output power with water spraying system increased by 14.6 % than the panel without a water spraying system [85]. The water spraying system, including the pump, storage tank, spray nozzles and circulation system, was constructed to reduce the panel's temperature. The result showed the PV panel temperature decreased by 35 °C [94]. This technique not only cools but also cleans the panel, and the water used can be reused and circulated, making the system cost-effective [85].

4.2.4. Heat pipe cooling technique

The heat pipes are sealed and employ passive cooling mechanisms, constructed from highly thermally conductive materials such as copper or aluminium, to dissipate heat from the panels efficiently. The extracted heat is transformed into water or air through evaporation and condensation, which involve phase transitions. As a consequence, there was an increase in PV panel efficiency by decreasing the surface temperature [81]. A schematic model of the PV panel integrated with the Heat pipe is shown in Fig. 12(b). The experiment was conducted to study an array of heat pipes circulated with air and water to cool the PV panel [95]. The result showed that the heat pipe with air circulation decreased the surface temperature by 4.7 °C and increased output power by 8.4 %, but the heat pipe with water circulation had an 8 °C decrease in temperature and the output power increased by 13.9 % [95]. A similar experiment on the cooling of PV panels using a single pulsating heat pipe was conducted by [96]. It was observed that the temperature was reduced by 16.1 °C and increased output power by 18 % [96]. The numerical simulations on flat plate pulsing heat pipe with forced cooling were conducted, subjected to a solar irradiation of 1235 W/m2. The implementation of the pulsing heat pipe resulted in a decrease in temperature by 22.2 °C and increased output power of the PV panel by 35 %, demonstrating its high effectiveness in cooling the PV panel (Alizadeh et al., 2020).

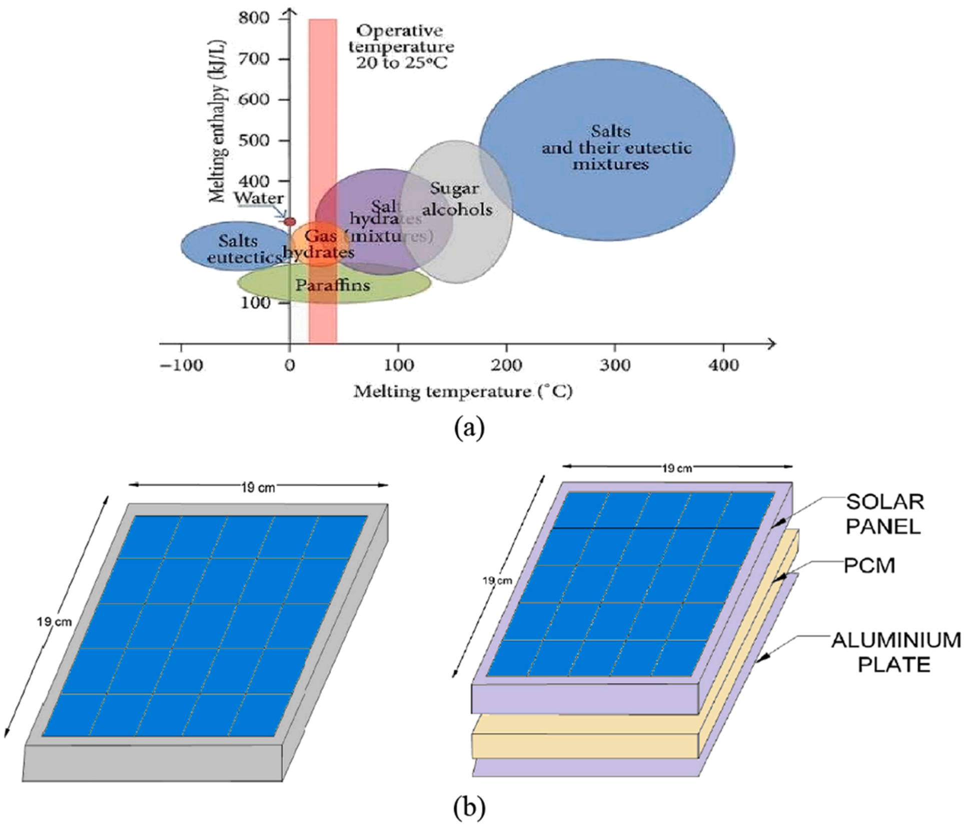


Fig. 11. (a) Commonly used PCM and its melting temperature [81] and (b) Three-dimensional sketch of without PCM (left) and with PCM PV (right) panels [90].

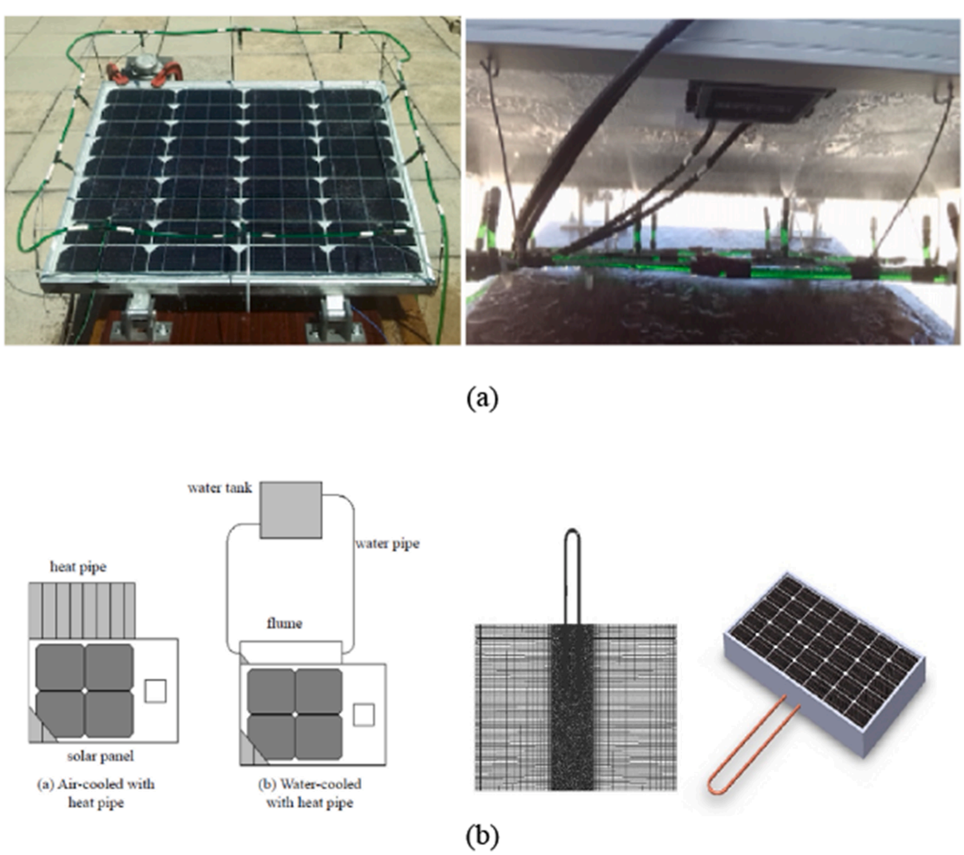


Fig. 12. Cooling techniques (a) water spraying (Nižetić et al. [85]) and (b) Heat pipe [95].

4.2.5. Thermoelectric cooling technique

This cooling technique consists of thermoelectric modules, which convert the heat dissipated at low temperatures into electricity, known as thermoelectric generators (TEG). The TEGs work on the principle known as the Peltier effect (Seeback effect). The electricity in TEGs is generated with the temperature difference; that is, TEGs are sandwiched between the rear side of the PV panel and the cooling system, which produces heat on one junction and cooling on another [97]. The Figure of Merit is the parameter used to characterise the efficiency of a thermoelectric device, and it depends on the physical properties and operating temperature of the material [98]. The experimental study on thermoelectric cooling of PV panels was conducted by (Broker et al., 2014). The results showed an improvement in the panel output performance, ranging from 8.35 to 11.46 % to 13.27 %. The PV panel embedded with the thermoelectric module decreased in temperature from 83 °C to 65 °C [99]. The design evaluation of polycrystalline PV panels embedded with the hybrid PV-TEG (Fig. 13(a)) with Bi2Te3 thermoelectric modules was performed. The hybrid PV-TEG showed an efficiency and output power of 6 % and 5 %, respectively, higher than the conventional module (without PV-TEG) [98].

4.2.6. Radiative cooling technique

Radiative or photonic cooling works on the difference in temperature between objects on Earth and outer space [81]. Radiative cooling (Fig. 13(b)) is a passive method used in thermoelectric-based cooling systems to provide the cool side on one of the junctions, creating a temperature difference between outer space and the Earth's surface [100]. The test was conducted on radiative cooling by placing a photonic structure beneath the panel [100]. it was observed that there was a drop in cell temperature by 13 °C. The test was conducted on PV-T collectors using radiative cooling, which resulted in a better performance of PV collectors by reducing the operating temperature by 11 °C with nocturnal thermal behaviour [102,103].

4.2.7. Finned cooling technique

The finned or heat sink or heat exchanger cooling system works by sinking the heat generated by the PV panel and protecting it from overheating, which in turn decreases the PV panel's efficiency. The fins are usually made of copper or aluminium, are highly thermally conductive, and are placed behind the panel to absorb panel heat [104]. The experimental and economic studies on the PV panel with and without heat sinks were conducted by [105]. The result showed that the PV panel with fins had better performance, with a 7.4 °C reduction in temperature and a 2.72 % increase in efficiency. A study to estimate the PV panel's efficiency and the output performance with copper and aluminium heat sinks was conducted by [106]. The result indicated that copper heat sinks with a thermal conductivity of 385 W/mK had better efficiency and electrical performance than aluminium fins with a thermal conductivity of 205 W/mK [106]. Fig. 13(c) shows an experimental arrangement that analysed various passive cooling systems' impact on the surface temperature, output power, and efficiency of photovoltaic (PV) panels. The solar PV panels were subjected to three different cooling methods, namely PCM, TEM (Thermoelectric material), and aluminium fins, under the same circumstances [101]. The aluminium fin cooling system had a significantly higher output power of 47.88 W compared to the PCM and TEM systems, which provided an output

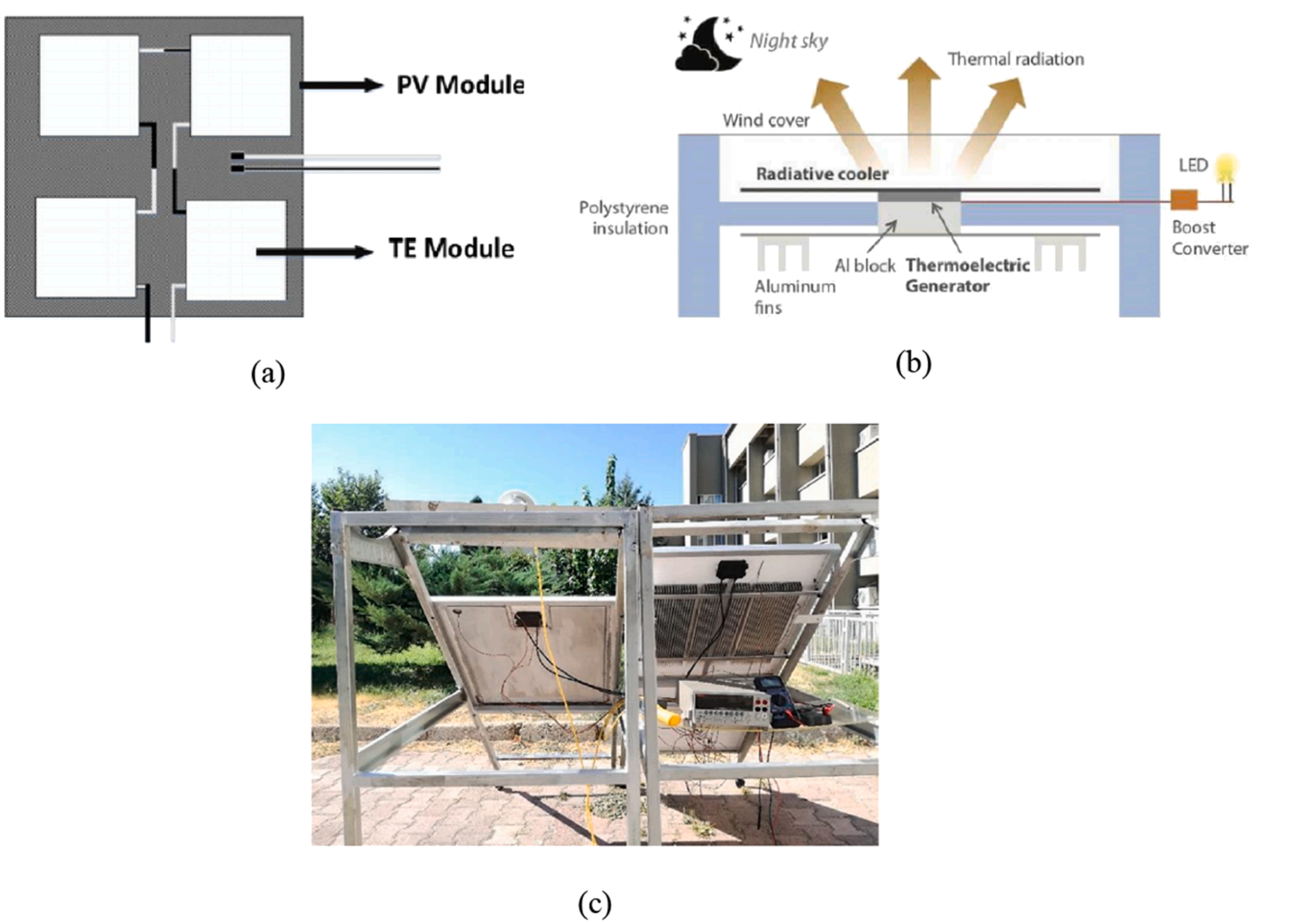


Fig. 13. Schematic representation of (a) hybrid PV-TEG module [98], (b) Passive radiative cooling [100], and (c) Rear side of PV panels (left) PV + PCM, (right) PV + fin3 [101].

power of 44.26 W [101]. Additionally, the aluminium fin cooling system is more cost-effective, remarkably efficient, and yields greater power output compared to PCM and TEM [107].

4.2.8. Summary of cooling techniques

From the literature on cooling techniques, the inferences are drawn. The PV panel's performance is dependent upon their surface temperature. It has been determined that raising the temperature by 1 °C over the laboratory test temperature of 25 °C will cause a decrease in output power ranging from 0.3 % to 0.5 %. The use of an organic phase change material (PCM) with a thickness of 0.03 m, together with an aluminium sheet covering an area of 0.036 m2, resulted in a drop in surface temperature of 10.35 °C. Additionally, this arrangement led to a 7 % gain in efficiency and an increased conversion efficiency of 24.4 %. Aluminium fins were used for the cooling system. The result showed an output power increase of 47.88 W, with a 3 % increase in efficiency. A similar cooling system with TEG was conducted, which decreased temperature by 18 °C and increased efficiency and output power by 6 % and 5 %, respectively. The cooling system with aluminium fins performed better than the PCM and TEG cooling systems. Also, the combination of Al fins with the TEG module will be a better option to improve the efficiency and output power of the PV panel. Table 3 shows the comparison between types of cooling techniques.

Table 3
Comparison between types of cooling.

Cooling Technique	Working	Advantages	Disadvantages	Refs.
PCM cooling	PCM works on the property that it absorbs heat during the day (melting) and releases it at night (solidification)	High heat absorption and heat transfer, maintenance-free, no power consumption and noise-free process	Materials are expensive and may cause toxicity, corrosion, and disposal problems.	[81, 108, 109]
Water spraying cooling	Water is used as a cooling agent and sprayed using centrifugal pumps, spraying nozzles and suction pipes to cool the PV panel.	It is a very efficient, simple process and less expensive. It also provides cleaning to the panels.	Water wastage, partial cooling	[81, 85, 94]
Heat pipe cooling	It works on the principle of thermal conductivity and phase transition of liquids.	Low material cost, simple and easy integration	Minimal reduction in temperature and low heat transfer rate	[81, 95]
Thermoelectric cooling	TEGs work on the principle known as the Peltier effect, which Consumes electrical energy to remove heat.	Simple integration, no moving parts, low maintenance cost, and it is noise-free	It Consumes output energy, is very expensive and depends on ambient conditions.	[97, 98, 81]
Radiative cooling	It works on the difference in temperature between objects on Earth and outer space.	It is a passive method with no material cost, low maintenance and noise-free	It depends on the ambient conditions and is less efficient.	[81, 100]
Finned cooling	It works by sinking the heat generated by the PV panel and protecting it from overheating, which in turn decreases the PV panel's efficiency.	High efficiency, low maintenance cost, and has no moving components. Additionally, it decreases the average temperature of the panel by 8.2 %.	Unstable under turbulent airflow, heat loss	[81, 104, 106]

5. Recycling challenges with the PV panels

5.1. End-of-Life of panels and recycling techniques

PV technology has emerged as one of the world's primary power production technologies over the past two decades. Around 80 to 90 % of PV panels installed around the globe are crystalline silicon and are made up of silicon [17]. Silicon is the second most available material on earth, at 27 %, and is the primary source for the manufacturing of PV panels. Also, the world is phasing out coal to meet the Net zero target. So, the share of renewable in the electricity mix will gradually increase, creating pressure on non-renewable silicon resources; due to which there is a decrease in the availability of silicon materials by 60 % on the earth's surface in the coming years [17,15]. As the use of solar PV panels spreads across the globe, e-waste has also increased. Solar panels have a life span of 20 to 25 years, leading to a large spike in e-waste, estimated at around 75 million tonnes of PV waste at the end of these 20–25 years [110]. Based on the performance of PV panels, aging, and other issues at EOL, the panels need to be disposed of and replaced. If not handled properly, the PV waste landfill can have a big impact on the environment, causing air and water pollution, public health issues and global warming [111]. Therefore, there is a need for ecologically friendly and effective PV waste processing and recycling technology [112]. Recycling solar PV panel components has environmental benefits by reducing GHG emissions by up to 42 % by reducing the mining of silicon ore from the earth's surface (Rahman & Chowdhury, [113]). Recycling PV panels also serve as a great resource for the country's economy by extracting valuable metals like copper (Cu), silver (Ag), and aluminium (Al) up to 90 % during the recycling process and are used for different applications [114,115].

The economic and environmental evaluation was conducted on waste PV panels in Turkey [116]. The evaluation showed that the recovery ratio of raw materials (Al, Cu, Ag and glass) reached 94 %, and an economic income of 35 million USD in can be generated and million tonnes of glass waste can be recovered during the recycling process. Also, it can save 43 million tonnes of CO_2 by reducing the mining process and reusing the extracted materials [116]. A brief analysis of PV panel production was conducted by [117], which includes the mining of materials, production of semi-raw materials and solar cells, assembling, transportation, installation and EOL recycling. The analysis showed that mining, smelting and high-grade purification of silicon ore had a very high impact on the environment, such as high energy consumption, wastewater creation and production of toxic waste [117]. Also, around 80,113 kg of CO_2 is estimated to be released when producing 1 kW of PV panel [118]. The 1m^2 CIGS PV panels emit 230 kg of CO_2 during the recycling process. So, having a cost-effective and organized recycling technique, the emission of CO_2 can be significantly reduced [119].

Much research has been carried out on PV wastes at EOL, mainly in countries like the United States, Europe, and some Asian countries. The main focus of the recycling techniques is to extract the raw materials Al, Cu, Ag and glass from the crystalline PV panels and remove toxic materials like Ethylene Vinyl acetate (EVA) encapsulant, cadmium, and lead, which are highly toxic and hazardous to the environment [120, 119]. The prices for raw materials extracted from recycling like Al, Cu, and Ag are 2200 USD/t, 7000 USD/t, and 514.47 USD/t, respectively, which generate high economic income for the PV production industries at the EOL. There are three major types of recycling methods: physical recycling, thermal recycling, chemical recycling, and a combination of all three recycling methods, which includes technical, economic and environmental benefits and challenges (Rahman & Chowdhury, [113]).

The experiment was conducted to recycle and recover silicon from the PV waste using spark plasma sintering (SPS) and chemical processes [121]. The aluminium frame and junction box were recovered using mechanical delamination, and the silicon fragments were extracted by thermal treatment at 480 °C. In the SPS technique shown in Fig. 14(b), a graphite die is used to sinter the silicon powder at 1100 °C-1200 °C at a pressure of 60 MPa. The result obtained had circular economic and environmental benefits as the silicon ingots recovered with a purity of 3 N (Nines), good enough for producing other applications like aluminium alloys in automobile industries and electrodes for batteries and the mining silicon ore can be reduced to 20 % which leads to high emission of CO_2 [121]. The hydrometallurgical processes shown in Fig. 14(c) were designed to recycle and recover silicon, silver (Ag) and aluminium (Al) from the waste PV panels and to capture lead (Pb) from waste liquid treatment, which are harmful to the environment [122]. Sodium hydroxide (NaOH) and Nitric acid (HNO_3) were used to extract Al and Ag in the leaching process. The results showed that HNO_3 had a better performance under optimal conditions, with a leaching rate of 98.12 % for Ag and 99.57 % for Al [122].

The waste solar panels were immersed in acetone solution for two days to separate glass, silicon wafers and ethyl vinyl acetate (EVA) by manual dismantling. Copper (Cu), Ag, and Al were extracted from silicon wafers by treating them with acid leaching, hydrothermal reaction, and chemical precipitation [112]. 1.5 M HNO_3 was used as an acid solution to extract Cu, Ag and Al. The result showed that 99 % of Al was precipitated as aluminium phosphate ($AlPO_4$), and >99 % of Ag was extracted from acid leaching by introducing phosphate and organic matter to react at 190 °C for ten hours [112]. The study says that the delamination of PV panels and EVA encapsulants is the most difficult stage during the recycling process, and this can be separated in an efficient way by the pyrolysis technique [124]. The pyrolysis process has many benefits, such as the clean separation of EVA encapsulant and delamination without chemical oxidation. This process uses no chemicals that are hazardous to the environment, and it is economically feasible [125]. The method to recover silicon (Si) wafers from the PV waste after the thermal process was investigated by utilising different chemical processes to dissolve Ag and Al, using nitric acid for Ag and potassium acid for Al recovery [123]. In addition, as shown in Fig. 14(a), phosphoric acid is used as an etching paste to remove the impurities on the water surface while extracting silicon wafers. The result showed that the recycled silicon wafers extracted had a thickness of > 180 μm, sufficient to manufacture the solar cells and had a carrier lifetime of 17.4–24.7 μs which is the same as Multi-crystalline Si wafers and increasing the circular economy income for the industries [123].

A similar experiment was conducted on CIGS thin-film PV panels where the panels were immersed in liquid N2 for manual dismantling. After dismantling, Cu, In, and Ga were extracted by treating the materials with acid leaching, solvent extraction, chemical precipitation, and

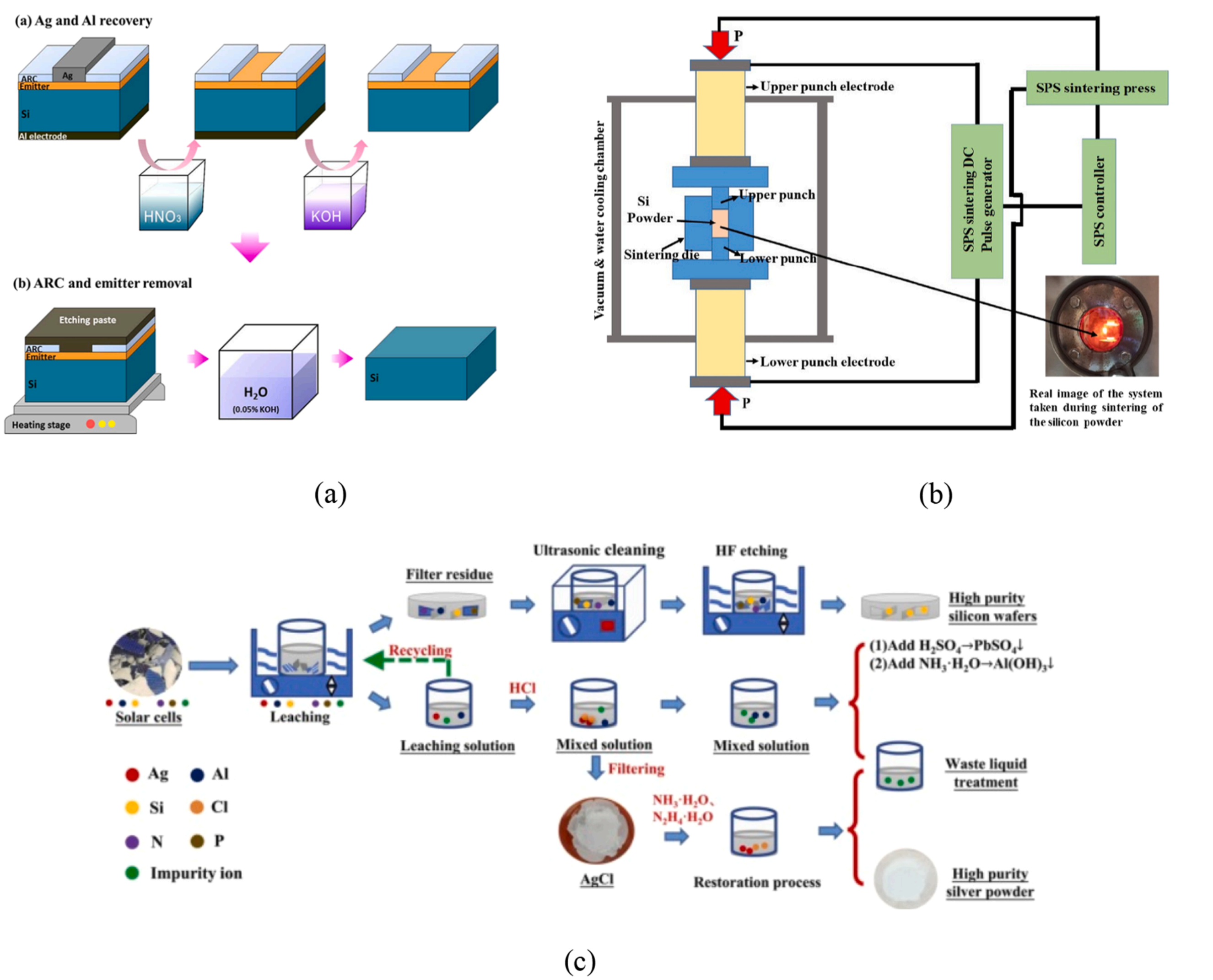


Fig. 14. Schematic diagram of (a) recycling processes to extract Ag, Al, ARC and emitter layer [123], (b) spark plasma sintering (SPS) system [121], and (c) The hydrometallurgical process flow chart for recovery of metals from waste PV panels [122].

calcination [11]. Phosphoric and hydrochloric acids were used to extract Cu, In and Ga from the materials under optimum conditions. The recovery rates from the extraction were 88.9, 98.2, and 97.1 % for Cu, In, and Ga, respectively. It can boost the economy by producing similar PV panels as these materials are expensive and rare metals available on the earth's surface. The extracted materials are free from cadmium and lead, which are highly toxic and have a high impact on the environment [11].

5.2. Summary

From the above literature, 80 to 90 % of solar PV panels installed globally are crystalline silicon panels and a certain percentage of thin film solar PV panels. These panels have a lifespan of 20 to 25 years, and around 75 million tonnes of solar PV waste are estimated to be generated by 2050. This e-waste must be disposed of and landfilled. The landfill of this e-waste (waste PV panels) is hazardous to the environment, causing an increase in GHG emissions if not handled properly. Therefore, recycling PV panels at EOL is a better option, which has both economic and environmental benefits. During recycling, raw materials such as Si, Al, Cu, and Ag can be extracted from the waste PV panels up to 90 % with a high-grade purity level, which generates a high economic income for the PV industries. Also, landfilling of e-waste is very expensive and hazardous as it consists of toxic materials like EVA encapsulant, cadmium and lead, which can be removed during recycling by an etching process.

6. Future research

In the above literature review, many research and experiments have been conducted on solar PV technologies. The research includes the generation of PV panels, the mitigation techniques (cleaning and cooling methods) to improve efficiency, the recycling of PV waste at EOL, and the use of technical tools like IoT and Blockchain to maximise the energy share of solar PV systems. There are some research gaps that motivate future work in the field of PV technologies, which are discussed below.

The PV panel's surface cleaning and cooling play critical roles in enhancing the output performance of the panels. There is not much research on hybrid systems with both cleaning and cooling techniques to enhance the efficiency of PV panels in extreme dust conditions. There are currently no cooling systems available that utilise TEGs and aluminium, together with automated dust-cleaning equipment that employs both active and passive techniques. These systems are designed to improve and maintain the efficiency of PV panels in very dusty environments. Therefore, to maximize output power and improve efficiency, there should be an optimum approach for cleaning, cooling, and maintaining PV panels in the Middle East during dust storms.

In designing a solar PV system, it is very important to do a techno-economic analysis. This analysis helps study some important technical parameters, such as a tilt angle, orientation, operating temperature, shading, string connection and the output power of the PV panels. The economic parameters include panel specification, internal payback period, net present value (NPV), and benefit-cost ratio (BCR) of the PV system. RETScreen, HOMER, PV Syst and Helioscope are the available software for techno-economic analysis. There is very limited research on the techno-economic analysis of PV systems in the UAE. Therefore, an optimal approach to conducting techno-economic analysis that considers the efficiency, lifespan, and overall cost of PV systems is very much needed in the UAE to maximizing the solar electricity share.

The performance and maintenance of the PV panels can be enhanced by continuously monitoring parameters like surface temperature, solar irradiance, voltage, current, output power, tilt angle, orientation, and battery capacity. Also, to calculate the demand to meet end-use technology and transmission losses for the rooftop applications on the residential and commercial buildings and back to the utility grid. The technologies used to monitor and analyse these parameters are found to be inferior in the UAE. Therefore, optimization tools like IoT and blockchain technologies to improve the performance and maintain the PV panels are important and can result in low energy consumption and reduced carbon footprint.

The PV panels at EOL have become a global threat to the environment, leading to a large spike in PV waste (e-waste) in the next 25 years. It is hazardous to dump the e-waste back into the earth as it causes severe impacts on the environment by increasing GHG emissions. It found very little active research on the recycling/remanufacturing policies for handling e-waste generated by PV panels at EOL. There is a need for optimum recycling techniques and policies to extract the semiconductors (Si), metals (Cu, Al, and Ag), and other materials (Glass) from the PV panels and use them for various applications, such as in the semiconductor and automobile industries.

7. Conclusions

The current survey focused on photovoltaic technologies, specifically examining the efficiencies of cells, the costs of PV systems, soil mitigation and cooling techniques, EOL of PV panels and the developments in the PV industries. The extensive literature study identifies several key findings that can assist individuals and communities in selecting appropriate technologies for adoption.

- From the above literature review, the mono and polycrystalline cells from the first generation are the most popular and widely used. These cells have an efficiency ranging from 23 % to 25 % with a life span of 25 to 30 years. The major drawbacks were the manufacturing cost, high-temperature sensitivity, and low absorption level and thickness. Second-generation thin-film panels address some challenges by using less materials, hence producing more economical and lightweight panels. However, their dependence on hazardous and temperature-sensitive materials like cadmium, gallium, and selenide restricts their efficiency and creates environmental issues. The third- and fourth-generation technologies aim to address previous generations' technological, economic, and environmental problems. Considering their potential, many innovative technologies remain in their early stages, exhibiting minimal marketing production and distribution. However, these generation PV cells are still in the emerging phase, and an enhanced investment in research, development, and commercialisation is necessary to achieve their full potential.
- Efficiency plays an important role in the selection of PV panels for any application. To date, crystalline silicon cells dominate the market with an efficiency of up to 25 %. The technologies, including CIGS (26.1 %), CdTe (22.9 %), and a-Si (14.0 %), have distinct benefits but often face limitations with material toxicity and production difficulties. Perovskite cells signify a potential option for future advancement, with a laboratory efficiency of 23.3 %. However, environmental factors such as temperature, contamination, and deterioration often decrease the operational efficiency of photovoltaic panels, highlighting the necessity for robust technology and mitigation strategies.
- The soiling effect (dust accumulation) has become a major problem in PV technologies. The soiling (dust accumulation) causes shading, blockage of solar radiation, and increasing module temperature. Also, factors such as relative humidity can contribute to the accumulation of dust and dirt through the formation of water droplets and can further increase the module temperature. The result showed a decrease in energy production by 16 to 24 % with 5 g/m^2 of dust on the panel. Also, only 3 mm of rain was adequate for cleaning the solar panels. The artificial cleaning techniques combined with active and passive methods (jet spray and hydrophobic coating) showed a significant increase in efficiency by 6 to 8 % with one clean Hence, a comprehensive evaluation of newly created techniques, such as robotic cleaning, electrodynamic screen/shields, mechanical cleaning, and chemical coating methods, was conducted. The PV panel, combined with active (mechanical/robotic) and passive (anti-reflective

coating) methods, was found to be very promising in maintaining and increasing output performance.

- The study included evaluating the impact of environmental variables, including temperature, wind velocity, and humidity, on the output performance of the PV panel. Recent investigations have consistently shown that PV modules perform optimally at a module temperature of approximately 40 °C and in an environment with low humidity. It was found that raising the temperature by 1 °C over the laboratory test temperature of 25 °C will cause a decrease in output power ranging from 0.3 % to 0.5 %. Furthermore, studies have found that increased wind velocities and rainfall positively affect module performance as they help cool down and remove some dust that accumulates on the PV panel surface. Hence, a detailed review of the different cooling methods, such as PCM, heat pipe, water spraying, TEG and fins, was analysed and compared. The result showed an increase in the efficiency and output power by 6 % and 5 %, respectively, using TEGs and a 3 % to 5 % increase in efficiency and output power by Aluminum fins. The PV panel, with the combination of TEG with aluminium fins with water circulation to cool the system, was found to be a very promising technique.
- From the review, around 75 million tonnes of e-waste (solar PV waste) are estimated to be generated by 2050. This e-waste has to be disposed of and landfilled, which causes a greater impact on the environment as it consists of toxic materials like lead, cadmium and EVA encapsulant. Recycling solar PV panels at EOL is the better option and has economic, technical, and environmental benefits and challenges. During the recycling process, materials like Si, Al, Ag, and glass can be recovered from PV waste, generate high economic income, and be used for different applications. HNO3 had a better performance in extracting Al and Ag from PV waste than NaOH under optimal conditions, with a leaching rate of 98.12 % and 99.57 %, respectively. Also, pyrolysis is the best technique to remove EVA encapsulant and delamination of PV panels without using hazardous chemicals. The toxic materials like lead and cadmium from the solar PV waste can be removed by the leaching process using acids.
- Photovoltaic (PV) waste recycling poses major challenges due to the absence of standardised rules, regulations, and standard procedures for managing this waste flow. Currently, the landfilling of e-waste, including solar photovoltaic panels, is both expensive and harmful to the environment due to the disposal of toxic substances such as lead, cadmium, and other dangerous elements. Furthermore, traditional recycling techniques frequently depend on toxic chemicals and significant amounts of water is required to extract and process components from photovoltaic panels. These approaches provide both environmental hazards and economic unsustainability. Consequently, there is a need to develop and implement sustainable, economical recycling systems that may effectively reclaim precious materials such as silicon, glass, and metals while reducing environmental impact and resource utilisation. The design for the environment concept should be considered that reduces the use of toxic additives while enabling dissembling at the end of life for fulling 3Rs strategies, including recovery, recycling and remanufacturing. Given silicon rocks (feedstocks for PV) are finite, remanufacturing in the design stage is a must to consider. There are health benefits associated with the use of nontoxic additives as the recyclers health is not affected.

CRediT authorship contribution statement

Mahesh Raj Nagaraja: Writing – original draft, Resources, Investigation, Conceptualization. **Wahidul K Biswas:** Writing – review & editing, Conceptualization. **Chithirai Pon Selvan:** Supervision, Conceptualization.

Declaration of competing interest

There is no conflict of interest among authors for this manuscript.

References

[1] E. Omri, N. Chtourou, D. Bazin, Rethinking the green recovery through renewable energy expansion, Int. J. Sustain. Dev. 18 (2) (2015).
[2] D. Maradin, Advantages and disadvantages of renewable energy sources utilization, Int. J. Energy Econ. Policy 11 (3) (2021) 176–183, https://doi.org/10.32479/ijeep.11027.
[3] International Renewable Energy Agency, Future of solar photovoltaic: deployment, investment, technology, grid integration and socio-economic aspects, A Glob. Energy Transformation (2019).
[4] IRENA, Renewable capacity statistics 2023, Int. Renew. Energy Agency (2023). Abu Dhabi.
[5] Q. Hassan, M. Al-Hitmi, V.S. Tabar, A.Z. Sameen, H.M. Salman, M. Jaszczur, Middle East energy consumption and potential renewable sources: an overview, Clean. Eng. Technol. 12 (2023), https://doi.org/10.1016/j.clet.2023.100599.
[6] R. Shenouda, M.S. Abd-Elhady, H.A. Kandil, A review of dust accumulation on PV panels in the MENA and the Far East regions, J. Eng. Appl. Sci. (2022), https://doi.org/10.1186/s44147-021-00052-6 (Vol. 69, Issue 1). Springer Science and Business Media B.V.
[7] A. Mokri, M. Aal Ali, M. Emziane, Solar energy in the United Arab Emirates: a review, Renew. Sustain. Energy Rev. 28 (2013) 340–375, https://doi.org/10.1016/j.rser.2013.07.038.
[8] Solar G.I.S., 2021. Solar resource maps of Germany. Solar resource maps and GIS data for 180+ countries 2019.
[9] IRENA, 2015. Renewable Energy Prospects: united Arab Emirates.
[10] Philibert, C. (2011), "Interactions of Policies for Renewable Energy and Climate", IEA Energy Papers, No. 2011/06, OECD Publishing, Paris, https://doi.org/10.1787/5kggc12rmkzq-en.
[11] F.W. Liu, T.M. Cheng, Y.J. Chen, K.C. Yueh, S.Y. Tang, K. Wang, C.L. Wu, H. S. Tsai, Y.J. Yu, C.H. Lai, W.S. Chen, Y.L. Chueh, High-yield recycling and recovery of copper, indium, and gallium from waste copper indium gallium selenide thin-film solar panels, Sol. Energy Mater. Sol. Cells 241 (2022), https://doi.org/10.1016/j.solmat.2022.111691.
[12] J. Xu, J. Wang, Y. Chen, Z. Xu, P.D. Lund, Thermo-ecological cost optimization of a solar thermal and photovoltaic integrated energy system considering energy level, Sustain. Prod. Consum. 33 (2022) 298–311, https://doi.org/10.1016/j.spc.2022.07.011.
[13] Vourvoulias A., 2019. Advantages and disadvantages of solar energy.
[14] C. Hachem-Vermette, Role of solar energy in achieving net zero energy neighborhoods, Sol. Energy Adv. 2 (2022) 100018.
[15] D.Y. Goswami, F. Kreith, Handbook of Energy Efficiency and Renewable Energy, Crc Press, 2007.
[16] U. EIA, Cost and performance characteristics of new generating technologies, Annu. Energy Outlook 2021 (2022).
[17] M.S. Chowdhury, K.S. Rahman, T. Chowdhury, N. Nuthammachot, K. Techato, M. Akhtaruzzaman, S.K. Tiong, K. Sopian, N. Amin, An overview of solar photovoltaic panels' end-of-life material recycling, Energy Strategy Rev. (2020), https://doi.org/10.1016/j.esr.2019.100431 (Vol. 27).
[18] M.B. Hayat, D. Ali, K.C. Monyake, L. Alagha, N. Ahmed, Solar energy—A look into power generation, challenges, and a solar-powered future, Int. J. Energy Res. (2019) 1049–1067, https://doi.org/10.1002/er.4252 (Vol. 43, Issue 3.
[19] H.L. Zhang, J. Baeyens, J. Degrève, G. Cacères, Concentrated solar power plants: review and design methodology, Renew. Sustain. Energy Rev. (2013) 466–481, https://doi.org/10.1016/j.rser.2013.01.032 (Vol. 22.
[20] D.R. Mills, G.L. Morrison, Compact linear Fresnel reflector solar thermal powerplants, Sol. Energy 68 (3) (2000) 263–283.
[21] H.G. Jin, H. Hong, R. Wang, Hybridization with conventional fossil plants. Concentrating Solar Power Technology: Principles, Developments, and Applications, Elsevier, 2020, pp. 443–475, https://doi.org/10.1016/B978-0-12-819970-1.00018-9.
[22] Turchi C.S., Boyd M., Kesseli D., Kurup P., Mehos M., Neises T., Sharan P., Wagner M., & Wendelin T. (2016). CSP Systems Analysis - Final Project Report. www.nrel.gov/publications.
[23] K.M. Kennedy, T.H. Ruggles, K. Rinaldi, J.A. Dowling, L. Duan, K. Caldeira, N. S. Lewis, The role of concentrated solar power with thermal energy storage in least-cost highly reliable electricity systems fully powered by variable renewable energy, Adv. Appl. Energy 6 (2022), https://doi.org/10.1016/j.adapen.2022.100091.
[24] F. Trieb, T. Fichter, M. Moser, Concentrating solar power in a sustainable future electricity mix, Sustain. Sci. 9 (1) (2014) 47–60, https://doi.org/10.1007/s11625-013-0229-1.
[25] A. Peinado Gonzalo, A. Pliego Marugán, F.P. García Márquez, A review of the application performances of concentrated solar power systems, Appl. Energy (2019), https://doi.org/10.1016/j.apenergy.2019.113893 (Vol. 255).
[26] S. Almosni, A. Delamarre, Z. Jehl, D. Suchet, L. Cojocaru, M. Giteau, B. Behaghel, A. Julian, C. Ibrahim, L. Tatry, H. Wang, T. Kubo, S. Uchida, H. Segawa, N. Miyashita, R. Tamaki, Y. Shoji, K. Yoshida, N. Ahsan, J.F. Guillemoles, Material challenges for solar cells in the twenty-first century: directions in emerging technologies, Sci. Technol. Adv. Mater. (2018) 336–369, https://doi.org/10.1080/14686996.2018.1433439 (Vol. 19, Issue 1.

[27] Goetzberger A., Hebling C., & Schock H.-W. (n.d.). 2003 Photovoltaic materials, history, status and outlook.
[28] S. Ghosh, R. Yadav, Future of photovoltaic technologies: a comprehensive review, Sustain. Energy Technol. Assess. 47 (2021), https://doi.org/10.1016/j.seta.2021.101410.
[29] Sands K., 2019. A colorful collection of first-generation solar cells natl. Aeronaut. Sp. Adm.
[30] Suman, P. Sharma, P. Goyal, Evolution of PV technology from conventional to nano-materials, Mater. Today Proc. 28 (2020) 1593–1597, https://doi.org/10.1016/j.matpr.2020.04.846.
[31] R.A. Marques Lameirinhas, J.P.N. Torres, J.P de Melo Cunha, A photovoltaic technology review: history, fundamentals and applications, Energies (2022), https://doi.org/10.3390/en15051823 (Vol. 15, Issue 5). MDPI.
[32] Nayeripour M., Mansouri M., Orooji F. and Waffenschmidt E. eds., 2020. Solar cells. BoD–Books on demand.
[33] A. Metz, D. Adler, S. Bagus, H. Blanke, M. Bothar, E. Brouwer, S. Dauwe, K. Dressler, R. Droessler, T. Droste, M. Fiedler, Y. Gassenbauer, T. Grahl, N. Hermert, W. Kuzminski, A. Lachowicz, T. Lauinger, N. Lenck, M. Manole, K. Wangemann, Industrial high performance crystalline silicon solar cells and modules based on rear surface passivation technology, Sol. Energy Mater. Sol. Cells 120 (PART A) (2014) 417–425, https://doi.org/10.1016/j.solmat.2013.06.025.
[34] G.M. Wilson, M. Al-Jassim, W.K. Metzger, S.W. Glunz, P. Verlinden, G. Xiong, L. M. Mansfield, B.J. Stanbery, K. Zhu, Y. Yan, J.J. Berry, A.J. Ptak, F. Dimroth, B. M. Kayes, A.C. Tamboli, R. Peibst, K. Catchpole, M.O. Reese, C.S. Klinga, D. B. Sulas-Kern, The 2020 photovoltaic technologies roadmap, J. Phys. D Appl. Phys. (2020), https://doi.org/10.1088/1361-6463/ab9c6a (Vol. 53, Issue 49). IOP Publishing Ltd.
[35] H. Huang, J. Lv, Y. Bao, R. Xuan, S. Sun, S. Sneck, S. Li, C. Modanese, H. Savin, A. Wang, J. Zhao, 20.8% industrial PERC solar cell: ALD Al2O3 rear surface passivation, efficiency loss mechanisms analysis and roadmap to 24%, Sol. Energy Mater. Sol. Cells 161 (2017) 14–30, https://doi.org/10.1016/j.solmat.2016.11.018.
[36] M. Taguchi, A. Yano, S. Tohoda, K. Matsuyama, Y. Nakamura, T. Nishiwaki, K. Fujita, E. Maruyama, 24.7% Record efficiency HIT solar cell on thin silicon wafer, IEEe J. Photovolt. 4 (1) (2014) 96–99, https://doi.org/10.1109/JPHOTOV.2013.2282737.
[37] L. el Chaar, L.A. Lamont, N. el Zein, Review of photovoltaic technologies, Renew. Sustain. Energy Rev. 15 (5) (2011) 2165–2175, https://doi.org/10.1016/j.rser.2011.01.004.
[38] B. Salhi, The photovoltaic cell based on CIGS: principles and technologies, Materials (2022), https://doi.org/10.3390/ma15051908 (Vol. 15, Issue 5).
[39] Yang, T.C.-J., 2020. Amorphus Silicon Cell Conceptual Diagram [WWW Document].
[40] X. Wu, High-efficiency polycrystalline CdTe thin-film solar cells, Sol. Energy 77 (6) (2004) 803–814, https://doi.org/10.1016/j.solener.2004.06.006.
[41] J. Jean, P.R. Brown, R.L. Jaffe, T. Buonassisi, V. Bulović, Pathways for solar photovoltaics, Energy Environ. Sci. 8 (4) (2015) 1200–1219.
[42] B.P. Singh, S.K. Goyal, P. Kumar, Solar pv cell materials and technologies: analyzing the recent developments, Mater. Today Proc. 43 (2021) 2843–2849, https://doi.org/10.1016/j.matpr.2021.01.003.
[43] P. Peumans, A. Yakimov, S.R. Forrest, Small molecular weight organic thin-film photodetectors and solar cells, J. Appl. Phys. 93 (7) (2003) 3693–3723, https://doi.org/10.1063/1.1534621.
[44] M. Kumar, A. Kumar, Performance assessment and degradation analysis of solar photovoltaic technologies: a review. Renew. Sustain. Energy Rev., Elsevier Ltd, 2017, pp. 554–587, https://doi.org/10.1016/j.rser.2017.04.083 (Vol. 78.
[45] D. Laird, J. Choi, Organic PV Cell Structure Plexcore® PV Inks Print, Sol. Power Syst. (2020).
[46] Jasim KE (2015) Quantum Dots Solar Cells. Solar Cells - New Approaches and Reviews. InTech. Available at: doi:10.5772/59159.
[47] M. Yamaguchi, T. Takamoto, K. Araki, N. Ekins-Daukes, Multi-junction III-V solar cells: current status and future potential, Sol. Energy 79 (1) (2005) 78–85, https://doi.org/10.1016/j.solener.2004.09.018.
[48] M. Law, L.E. Greene, J.C. Johnson, R. Saykally, P. Yang, Nanowire dye-sensitized solar cells, Nat. Mater. 4 (6) (2005) 455–459, https://doi.org/10.1038/nmat1387.
[49] S. Mozaffari, M.R. Nateghi, M.B. Zarandi, An overview of the challenges in the commercialization of dye sensitized solar cells, Renew. Sustain. Energy Rev. (2017) 675–686, https://doi.org/10.1016/j.rser.2016.12.096 (Vol. 71.
[50] H.S. Kim, C.R. Lee, J.H. Im, K.B. Lee, T. Moehl, A. Marchioro, S.J. Moon, R. Humphry-Baker, J.H. Yum, J.E. Moser, M. Grätzel, N.G. Park, Lead iodide perovskite sensitized all-solid-state submicron thin film mesoscopic solar cell with efficiency exceeding 9%, Sci. Rep. 2 (2012) https://doi.org/10.1038/srep00591.
[51] D. Bera, L. Qian, T.K. Tseng, P.H. Holloway, Quantum dots and their multimodal applications: a review, Materials (2010) 2260–2345, https://doi.org/10.3390/ma3042260 (Vol. 3, Issue 4.
[52] H. Gao, R. Yang, Y. Zhang, Improving radiation resistance of GaInP/GaInAs/Ge triple-junction solar cells using GaInP back-surface field in the middle subcell, Materials 13 (8) (2020), https://doi.org/10.3390/MA13081958. . (Basel).
[53] A. Luque, S. Hegedus, Handbook of Photovoltaic Science and Engineering, John Wiley & Sons, 2011.
[54] S. Das, D. Pandey, J. Thomas, T. Roy, The role of graphene and other 2D materials in solar photovoltaics, Adv. Mater. (2019), https://doi.org/10.1002/adma.201802722 (Vol. 31, Issue 1).
[55] T. Mahmoudi, Y. Wang, Y.B. Hahn, Graphene and its derivatives for solar cells application, Nano Energy (2018) 51–65, https://doi.org/10.1016/j.nanoen.2018.02.047 (Vol. 47.
[56] Geim A.K., & Novoselov K.S. (n.d.). 2007 The rise of graphene. www.nature.com/naturematerials.
[57] D. Jovanović, M. Petrović, T. Tomašević-Ilić, A. Matković, M. Bokalič, M. Spasenović, K. Rogdakis, E. Kymakis, D. Knežević, L. Cinà, R. Gajić, Long-term stability of graphene/c-Si Schottky-junction solar cells, Sol. Energy Mater. Sol. Cells 258 (2023), https://doi.org/10.1016/j.solmat.2023.112414.
[58] N.M. Kumar, P.R.K. Reddy, K. Praveen, Optimal energy performance and comparison of open rack and roof mount mono c-Si photovoltaic systems, Energy Procedia 117 (2017) 136–144, https://doi.org/10.1016/j.egypro.2017.05.116.
[59] J. Yuan, A. Hazarika, Q. Zhao, X. Ling, T. Moot, W. Ma, J.M. Luther, Metal halide perovskites in quantum dot solar cells: progress and prospects, Joule (2020) 1160–1185, https://doi.org/10.1016/j.joule.2020.04.006 (Vol. 4, Issue 6.
[60] Z. Ahmed, H.A. Kazem, K. Sopian, Effect of dust on photovoltaic performance: Review and research status, Latest trends in renewable, energy and environmental informatics 34 (6) (2013) 193–199.
[61] H.A. Kazem, M.T. Chaichan, A.H.A. Al-Waeli, K. Sopian, Effect of dust and cleaning methods on mono and polycrystalline solar photovoltaic performance: an indoor experimental study, Sol. Energy 236 (2022) 626–643, https://doi.org/10.1016/j.solener.2022.03.009.
[62] H.A. Kazem, M.T. Chaichan, A.H. Al-Waeli, K. Sopian, A novel model and experimental validation of dust impact on grid-connected photovoltaic system performance in Northern Oman, Sol. energy 206 (2020) 564–578.
[63] L. Al-Ghussain, O. Taylan, M. Abujubbeh, M.A. Hassan, Optimizing the orientation of solar photovoltaic systems considering the effects of irradiation and cell temperature models with dust accumulation, Sol. Energy 249 (2023) 67–80, https://doi.org/10.1016/j.solener.2022.11.029.
[64] T.M.A. Alnasser, A.M.J. Mahdy, K.I. Abass, M.T. Chaichan, H.A. Kazem, Impact of dust ingredient on photovoltaic performance: an experimental study, Sol. Energy 195 (2020) 651–659, https://doi.org/10.1016/j.solener.2019.12.008.
[65] A. Allouhi, S. Rehman, M.S. Buker, Z. Said, Up-to-date literature review on Solar PV systems: technology progress, market status and R&D, J. Clean. Prod. (2022), https://doi.org/10.1016/j.jclepro.2022.132339 (Vol. 362).
[66] V. Gupta, M. Sharma, R.K. Pachauri, K. Dinesh Babu, Comprehensive review on effect of dust on solar photovoltaic system and mitigation techniques, Sol. Energy 191 (2019) 596–622, https://doi.org/10.1016/j.solener.2019.08.079.
[67] W. Javed, B. Guo, B. Figgis, L. Martin Pomares, B. Aïssa, Multi-year field assessment of seasonal variability of photovoltaic soiling and environmental factors in a desert environment, Sol. Energy 211 (2020) 1392–1402, https://doi.org/10.1016/j.solener.2020.10.076.
[68] A.A. Salim, F.S. Huraib, N.N. Eugenio, PV power-study of system options and optimization. EC Photovoltaic Solar Conference 8, 1988, pp. 688–692.
[69] A. Syafiq, A.K. Pandey, N.N. Adzman, N.A. Rahim, Advances in approaches and methods for self-cleaning of solar photovoltaic panels, Sol. Energy (2018) 597–619, https://doi.org/10.1016/j.solener.2017.12.023 (Vol. 162.
[70] A.A. Hachicha, I. Al-Sawafta, Z. Said, Impact of dust on the performance of solar photovoltaic (PV) systems under United Arab Emirates weather conditions, Renew. Energy 141 (2019) 287–297, https://doi.org/10.1016/j.renene.2019.04.004.
[71] I.S. Al Jassasi, H.S. Al Hashmi, A. Al Humairi, Y. Bulale, A. Husain, M. Al-Azzawi, P. Jung, Experimental investigation of the soiling effect on the PV systems performance and the cleaning intervals in Oman, Sol. Energy Adv. 3 (2023) 100045.
[72] N. Sugiartha, I.G.N. Ardana, I.M. Sugina, I.B.G. Widiantara, I.N. Suparta, I.K. Adi, Preliminary design and test of a water spray solar panel cleaning system, J. Phys. Conf. Ser. (1) (2020) 1450, https://doi.org/10.1088/1742-6596/1450/1/012108.
[73] K.S. Qdah, S.A. Abdulqadir, N.Y. Harbi, A.Z. Soqyyah, K.J. Isa, M.Y. Alharbi, N. M. Binsaad, Design and performance of PV dust cleaning system in medina region, J. Power Energy Eng. 07 (11) (2019) 1–14, https://doi.org/10.4236/jpee.2019.711001.
[74] S. Alagoz, Y. Apak, Removal of spoiling materials from solar panel surfaces by applying surface acoustic waves, J. Clean. Prod. 253 (2020), https://doi.org/10.1016/j.jclepro.2020.119992.
[75] M. Al-Housani, Y. Bicer, M. Koç, Assessment of various dry photovoltaic cleaning techniques and frequencies on the power output of CdTe-type modules in dusty environments, Sustainability 11 (10) (2019), https://doi.org/10.3390/su11102850 (Switzerland).
[76] Attia O.H., Optimization of wind-powered dust removal parameters for photovoltaics solar panel, (2019).
[77] B. Guo, W. Javed, Y.S. Khoo, B. Figgis, Solar PV soiling mitigation by electrodynamic dust shield in field conditions, Sol. Energy 188 (2019) 271–277, https://doi.org/10.1016/j.solener.2019.05.071.
[78] J Bone, R Eriksen, C Ellinger, K O'Connor, D Garman, A Bernard, M Mazumder, M Horenstein, Electrical and Optical Modeling of Electrode Configuration for Optimal Dust Removal in Electrodynamic Screens (EDS). 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC), IEEE, 2019, pp. 2854–2858.
[79] H. Kawamoto, Improved detachable electrodynamic cleaning system for dust removal from soiled photovoltaic panels, J. Electrostat. 107 (2020), https://doi.org/10.1016/j.elstat.2020.103481.
[80] I. Arabatzis, N. Todorova, I. Fasaki, C. Tsesmeli, A. Peppas, W.X. Li, Z. Zhao, Photocatalytic, self-cleaning, antireflective coating for photovoltaic panels: characterization and monitoring in real conditions, Sol. Energy 159 (2018) 251–259, https://doi.org/10.1016/j.solener.2017.10.088.

[81] P. Dwivedi, K. Sudhakar, A. Soni, E. Solomin, I. Kirpichnikova, Advanced cooling techniques of P.V. modules: a state of art, Case Stud. Therm. Eng. 21 (2020), https://doi.org/10.1016/j.csite.2020.100674.

[82] BAS H., 2021. Strong growth predicted for middle eastern solar PV. PV Mag.

[83] D.T. Cotfas, P.A. Cotfas, Multiconcept methods to enhance photovoltaic system efficiency, Int. J. Photoenergy (2019), https://doi.org/10.1155/2019/1905041 (Vol. 2019).

[84] H.A. Kazem, M.T. Chaichan, A.H. Al-Waeli, K. Sopian, Evaluation of aging and performance of grid-connected photovoltaic system northern Oman: seven years' experimental study, Sol. Energy 207 (2020) 1247–1258.

[85] S. Nižetić, D. Čoko, A. Yadav, F. Grubišić-Čabo, Water spray cooling technique applied on a photovoltaic panel: the performance response, Energy Convers. Manag. 108 (2016) 287–296, https://doi.org/10.1016/j.enconman.2015.10.079.

[86] D.T. Cotfas, P.A. Cotfas, O.M. Machidon, Study of temperature coefficients for parameters of photovoltaic cells, Int. J. Photoenergy (2018), https://doi.org/10.1155/2018/5945602. , 2018.

[87] S. Mohammed Salih, O. Ibrahim Abd, K. Waleed Abid, Salih Mohammed Salih, Osama Ibrahim Abd, Kaleid Waleed Abid. Performance enhancement of PV array based on water spraying technique, Int. J. Sustain. Green Energy 4 (1) (2015) 8–13, https://doi.org/10.11648/j.ijrse.s.2015040301.12. . Special Issue: Engineering Solution for High Performance of Solar Energy System.

[88] H.G. Teo, P.S. Lee, M.N.A. Hawlader, An active cooling system for photovoltaic modules, Appl. Energy 90 (1) (2012) 309–315, https://doi.org/10.1016/j.apenergy.2011.01.017.

[89] H.M. Ali, Recent advancements in PV cooling and efficiency enhancement integrating phase change materials based systems – A comprehensive review, Sol. Energy (2020) 163–198, https://doi.org/10.1016/j.solener.2019.11.075 (Vol. 197.

[90] M. Rajvikram, S. Leoponraj, S. Ramkumar, H. Akshaya, A. Dheeraj, Experimental investigation on the abasement of operating temperature in solar photovoltaic panel using PCM and aluminium, Sol. Energy 188 (2019) 327–338, https://doi.org/10.1016/j.solener.2019.05.067.

[91] Akshayveer, A. Kumar, A.P. Singh, O.P Singh, Effect of novel PCM encapsulation designs on electrical and thermal performance of a hybrid photovoltaic solar panel, Sol. Energy 205 (2020) 320–333, https://doi.org/10.1016/j.solener.2020.05.062.

[92] H.M. Ali, Phase change materials based thermal energy storage for solar energy systems, J. Build. Eng. 56 (2022) 104731.

[93] L. Tan, A. Date, G. Fernandes, B. Singh, S. Ganguly, Efficiency gains of photovoltaic system using latent heat thermal energy storage, Energy Procedia 110 (2017) 83–88, https://doi.org/10.1016/j.egypro.2017.03.110.

[94] K. Moharram, M. Abd-Elhady, H. Kandil, H. El-Sherif, Enhancing the performance of photovoltaic panels by water cooling, Ain Shams Eng. J. 4 (4) (2013) 869–877, https://doi.org/10.1016/j.asej.2013.03.005.

[95] X. Tang, Z.h. Quan, Y.h. Zhao, Notice of Retraction: Experimental Investigation of Solar Panel Cooling by a Novel Micro Heat Pipe Array. 2010 Asia-Pacific Power and Energy Engineering Conference, Chengdu, China, 2010, pp. 1–4, https://doi.org/10.1109/APPEEC.2010.5449518.

[96] H. Alizadeh, R. Ghasempour, M.B. Shafii, M.H. Ahmadi, W.M. Yan, M.A. Nazari, Numerical simulation of PV cooling by using single turn pulsating heat pipe, Int. J. Heat Mass Transf. 127 (2018) 203–208, https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.108.

[97] A. Allouhi, Advances on solar thermal cogeneration processes based on thermoelectric devices: a review, Sol. Energy Mater. Sol. Cells 200 (2019), https://doi.org/10.1016/j.solmat.2019.109954.

[98] C. Babu, P. Ponnambalam, The theoretical performance evaluation of hybrid PV-TEG system, Energy Convers. Manag. 173 (2018) 450–460, https://doi.org/10.1016/j.enconman.2018.07.104.

[99] M. Benghanem, A.A. Al-Mashraqi, K.O. Daffallah, Performance of solar cells using thermoelectric module in hot sites, Renew. Energy 89 (2016) 51–59, https://doi.org/10.1016/j.renene.2015.12.011.

[100] L. Zhu, A. Raman, K.X. Wang, M.A. Anoma, S. Fan, Radiative cooling of solar cells, Optica 1 (1) (2014) 32, https://doi.org/10.1364/optica.1.000032.

[101] F. Bayrak, H.F. Oztop, F. Selimefendigil, Experimental study for the application of different cooling techniques in photovoltaic (PV) panels, Energy Convers. Manag. 212 (2020), https://doi.org/10.1016/j.enconman.2020.112789.

[102] M. Hu, B. Zhao, X. Ao, Suhendri, J. Cao, Q. Wang, S. Riffat, Y. Su, G. Pei, An analytical study of the nocturnal radiative cooling potential of typical photovoltaic/thermal module, Appl. Energy 277 (2020), https://doi.org/10.1016/j.apenergy.2020.115625.

[103] M. Hu, B. Zhao, X. Ao, C. Suhendri, W. J, R. Q, Su S, Y, G. Pei, An analytical study of the nocturnal radiative cooling potential of typical photovoltaic/thermal module, Appl. Energy 277 (2020), https://doi.org/10.1016/j.apenergy.2020.115625.

[104] S. Sargunanathan, A. Elango, S.T. Mohideen, Performance enhancement of solar photovoltaic cells using effective cooling methods: a review, Renew. Sustain. Energy Rev. (2016) 382–393, https://doi.org/10.1016/j.rser.2016.06.024 (Vol. 64.

[105] M. Firoozzadeh, A. Shiravi, M. Shafiee, An experimental study on cooling the photovoltaic modules by fins to improve power generation: economic assessment, Iran. (Iran.) J. Energy Environ. 10 (2) (2019) 80–84.

[106] N. Parkunam, L. Pandiyan, G. Navaneethakrishnan, S. Arul, V. Vijayan, Experimental analysis on passive cooling of flat photovoltaic panel with heat sink and wick structure, Energy Sources A Recovery Util. Environ. Eff. 42 (6) (2020) 653–663, https://doi.org/10.1080/15567036.2019.1588429.

[107] M. Shafiee, M. Firoozzadeh, M. Ebrahimi, A. Pour-Abbasi, The effect of aluminum fins and air blowing on the electrical efficiency of photovoltaic panels; environmental evaluation, Chem. Eng. Commun. 210 (5) (2023) 801–813, https://doi.org/10.1080/00986445.2022.2067534.

[108] N. Soares, J. Costa, A. Gaspar, T. Matias, P. Simões, L. Durães, Can movable PCM-filled TES units be used to improve the performance of PV panels? Overview and experimental case-study, Energy Build. 210 (2020) 109743, https://doi.org/10.1016/j.enbuild.2019.109743.

[109] A. Kumar, A. Pratap Singh, R. Sreeram Kotha, O. Singh, Thermal energy storage design of a new bifacial PV/PCM system for enhanced thermo-electric performance, Energy Convers. Manage. 250 (2021) 114912, https://doi.org/10.1016/j.enconman.2021.114912.

[110] C.C. Farrell, A.I. Osman, R. Doherty, M. Saad, X. Zhang, A. Murphy, J. Harrison, A.S.M. Vennard, V. Kumaravel, A.H. Al-Muhtaseb, D.W. Rooney, Technical challenges and opportunities in realising a circular economy for waste photovoltaic modules, Renew. Sustain. Energy Rev. (2020), https://doi.org/10.1016/j.rser.2020.109911 (Vol. 128).

[111] P. Nain, A. Kumar, A state-of-art review on end-of-life solar photovoltaics. J. Clean. Prod., Elsevier Ltd, 2022, https://doi.org/10.1016/j.jclepro.2022.130978 (Vol. 343).

[112] Q. Han, Y. Gao, T. Su, J. Qin, C. Wang, Z. Qu, X. Wang, Hydrometallurgy recovery of copper, aluminum and silver from spent solar panels, J. Environ. Chem. Eng. 11 (1) (2023), https://doi.org/10.1016/j.jece.2022.109236.

[113] M.M. Rahman, F.N. Chowdhury, Recycling of solar PV panels in Bangladesh along with South and South East Asia, Curr. Opin. Green Sustain. Chem. (2023), https://doi.org/10.1016/j.cogsc.2023.100862 (Vol. 44).

[114] I. D'Adamo, F. Ferella, M. Gastaldi, N.M. Ippolito, P. Rosa, Circular solar: evaluating the profitability of a photovoltaic panel recycling plant, Waste Manag. Res. 41 (6) (2023) 1144–1154, https://doi.org/10.1177/0734242X221149327.

[115] P.R. Dias, L. Schmidt, N.L. Chang, M. Monteiro Lunardi, R. Deng, B. Trigger, L. Bonan Gomes, R. Egan, H. Veit, High yield, low cost, environmentally friendly process to recycle silicon solar panels: technical, economic and environmental feasibility assessment, Renew. Sustain. Energy Rev. 169 (2022), https://doi.org/10.1016/j.rser.2022.112900.

[116] Ç. Gönen, E. Kaplanoğlu, Environmental and economic evaluation of solar panel wastes recycling, Waste Manag. Res. 37 (4) (2019) 412–418, https://doi.org/10.1177/0734242X19826331.

[117] Y. Xu, J. Li, Q. Tan, A.L. Peters, C. Yang, Global status of recycling waste solar panels: a review, Waste Manag. (2018) 450–458, https://doi.org/10.1016/j.wasman.2018.01.036 (Vol. 75.

[118] A. Domínguez, R. Geyer, Photovoltaic waste assessment in Mexico, Resour. Conserv. Recycl. 127 (2017) 29–41, https://doi.org/10.1016/j.resconrec.2017.08.013.

[119] I.M. Peters, S. Sofia, J. Mailoa, T. Buonassisi, Techno-economic analysis of tandem photovoltaic systems, RSC Adv. (2016) 66911–66923, https://doi.org/10.1039/c6ra07553c (Vol. 6, Issue 71.

[120] A. Doni, F. Dughiero, June. Electrothermal heating process applied to c-Si PV recycling, in: Proceedings of the In 2012 38th IEEE Photovoltaic Specialists Conference, IEEE, 2012, pp. 000757–000762.

[121] D. Sah, Chitra, N.K. Upadhyay, S. Muthiah, S. Kumar, Growth and analysis of polycrystalline silicon ingots using recycled silicon from waste solar module, Sol. Energy Mater. Sol. Cells 261 (2023), https://doi.org/10.1016/j.solmat.2023.112524.

[122] M. Luo, F. Liu, Z. Zhou, L. Jiang, M. Jia, Y. Lai, J. Li, Z. Zhang, A comprehensive hydrometallurgical recycling approach for the environmental impact mitigation of EoL solar cells, J. Environ. Chem. Eng. 9 (6) (2021), https://doi.org/10.1016/j.jece.2021.106830.

[123] J. Shin, J. Park, N. Park, A method to recycle silicon wafer from end-of-life photovoltaic module and solar panels by using recycled silicon wafers, Sol. Energy Mater. Sol. Cells 162 (2017) 1–6, https://doi.org/10.1016/j.solmat.2016.12.038.

[124] C. Farrell, A.I. Osman, X. Zhang, A. Murphy, R. Doherty, K. Morgan, D.W. Rooney, J. Harrison, R. Coulter, D. Shen, Assessment of the energy recovery potential of waste photovoltaic (PV) modules, Sci. Rep. 9 (1) (2019), https://doi.org/10.1038/s41598-019-41762-5.

[125] I. D'Adamo, M. Miliacca, P. Rosa, Economic Feasibility for recycling of waste crystalline silicon photovoltaic modules, Int. J. Photoenergy 2017 (2017), https://doi.org/10.1155/2017/4184676.