Photovoltaic applications: Status and manufacturing prospects

M.H. Alaaeddin[a,*], S.M. Sapuan[a], M.Y.M. Zuhri[a], E.S. Zainudin[a,b], Faris M. AL- Oqla[c]

[a] Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia
[b] Laboratory of Bio-Composite Technology, Institute of Tropical Forestry and Forest Products, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia
[c] Department of Mechanical Engineering, Faculty of Engineering, The Hashemite University, 13133 Zarqa, Jordan

ABSTRACT

Over the last two decades, advancements in photovoltaic (PV) technology have been flourishing due to the continuous flow of valuable findings. Relevant insights on recent improvements, manufacturing approaches, and various applications of PV technology are provided. Both the PV cell structure and conversion efficiency may significantly contribute to the progression of the PV system. Currently, a wide range of advanced materials and smart technologies are employed within the PV cell's architecture, improving its structure; i.e. PERC/PERL, IBC, HIT/HJT, and MWT. The applications of nanoparticles and thin film technology in PV cell structures have successfully opened new research prospects to boost PV efficiency and overcome certain limitations with the use of CdSe, ZnCds, CdTe, a-Si/μc-Si, CIS, and CIGS. Additionally, constant development in the third generation of OSC methods using OE, OM, and COP are conducted. The improvement of PV backsheet structures and their enhanced optical properties yielded promising results in optimizing solar radiation, reflectance, and PV cell competence. The emergence of hybrid technologies (e.g. PVTE and TPV systems) led to effective solutions for reducing excessive heat that cause deficiency to a PV cell's functionality. Overall, modelling and effectively implementing appropriate parameters (such as diode parameters, optical parameters, circuit current, circuit voltage, fill factor (FF), conversion efficiency, IR, and UV spectral parameters) contributed to the total efficiency and performance modelling of the PV system.

1. Introduction

Photovoltaic technology has been exclusively urbanized and used as an alternative source of green energy, providing a sustainable supply of electricity through a wide range of applications; e.g. photovoltaic modules, photovoltaic agriculture, photovoltaic water purification

Nomenclature		h_{conv}	convection heat transfer coefficient
		h_{rad}	radiative heat transfer coefficient
δ	thickness (m)	I	output current
δ_{ad}	thickness of thermal conductive adhesive	I_0	the intensity of incident light
ε_g	front glass cover emissivity	I_{SC}	short circuit current
μc	microcrystalline	J	current density
μΩ	microohm	J_0	assumed current density
A_{ad}	area of the thermal conductive adhesive	J_{sc}	short circuit current density
T_a	environment temperature	R_c	thermal contact resistance
T_g	surface temperature (Top cover)	R_{ceram}	resistance ceramic wafers
k	thermal conductivity ($Wm^{-1}\,K^{-1}$)	R_{conv}	resistance convection
k_B	stefan– Boltzmann's constant	R_{Cu}	cu electrode
k_{ad}	thermal conductivity of thermal conductive adhesive	R_{EVA}	optical adhesive EVA resistance
i	internal	R_g	glass resistance
A	area (m2)	R_{rad}	thermal radiative heat resistance
A_{PV}	photovoltaic area	v	voltage
R	thermal resistance (K/W)	ν	normalized voltage
e	energy electrons or environment or emitter	0	in the dark or at 0 k.

systems, water pumping [1–3], cooling and heating systems [4], and numerous advanced applications [5,6]. The invariable nature of photovoltaic power generation makes it an inventible source of green energy with low operational cost, low maintenance, as well as high availability and reliability [3,7]. These advantages led to the rapid development of photovoltaic production and resulted in improved manufacturing approaches within the solar power industry, becoming one of the most promising technologies in the field of renewable energy and sustainability [8,9]. Therefore, initiating technological solutions in photovoltaic applications and structures will ensure constant development that will refine their effectiveness and efficiency, making them capable when confronted with various challenges and deficiencies [8,10–12]. In contrast, the excessive dependence on technological developments of solar cells may be considered a challenge or disadvantage [13]. The encountered challenges in photovoltaic applications and their manufacturing processes (e.g. matching photovoltaic systems to certain applications, area for installation, geographical issues, weather conditions, solar irradiation, high initial cost, and availability concerns) makes it imperative to discover effective solutions [7,14]. Therefore, to maintain a high confidence level in this energy

source, an integrated method is required; one that considers reliability by purpose, availability by demand [15,16], and sustainability to ensure the optimum value of photovoltaic utilizations in generating electricity [17].

2. Photovoltaic technologies and applications

At present, photovoltaic systems can be divided into five different categories: photovoltaic systems connected to a network, independent or isolated photovoltaic systems, hybrid photovoltaic generations, solar power plants, and photovoltaic cells employed in different goods and applications (e.g. electrical equipment, solar roofs, irrigation systems, electric vehicles, traffic lights, signals, and guide robots) [8,18–22]. Comparatively, some solar systems come in the form of modules or solar collectors with effective irradiation and solar thermal systems, or solar thermal collectors with effective irradiation [6,18]. Improving the efficiency of PV applications is an imperative issue to maintain high sustainability and reliability when employing PV as an alternative energy source [17,23]. The efficiency of PV can be improved through several methods: maintaining temperature, avoiding excessive heat
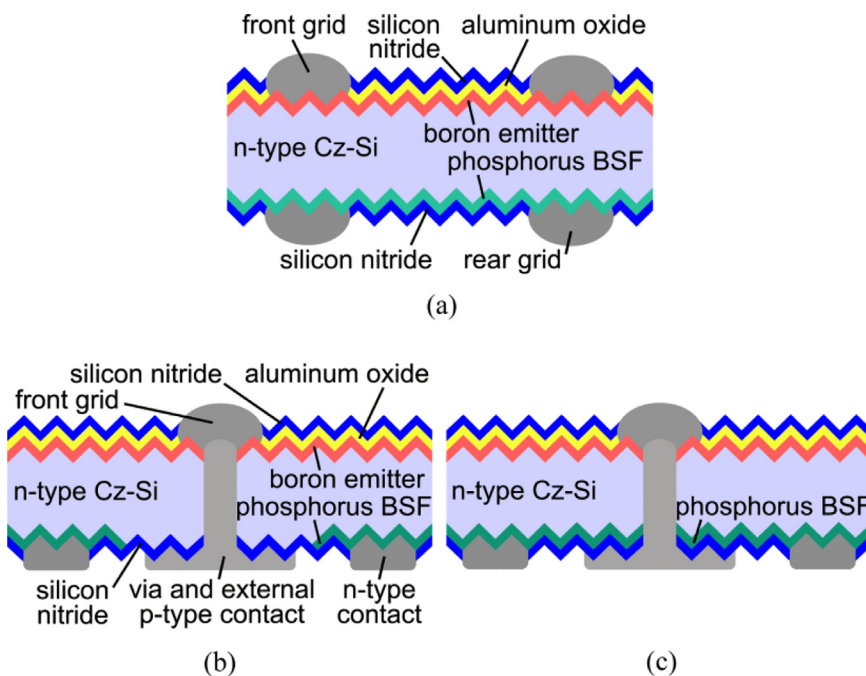
Fig. 1. A schematic cross section of n-type Cz-Si solar cell construction with conventional and MWT structures. (a) The H-pattern model of conventional cell, (b) MWT structure with a full phosphorus-doped BSF, and (c) MWT with no emitter in the via & adjacent rear, as well as no phosphorus-doped BSF underneath the external P-type contact [49].

[11], employing surface cooling technologies [21], improving efficiency of radiation transmission [22–25], enhancing electronic cells and cell constituents [15,26], improving semiconductor materials and deposition processes [20,27–29], refining PV-phase material technologies [27], boosting efficiency of metallurgical grade silicon, and adding attractiveness to the entire manufacturing process [11,20]. PV technologies did undergo several stages of development, including the advancement of main and sub-materials, thin-film technologies, manufacturing approaches, and operational costs [20,21]. This was due to the high demand of energy (particularly, solar power) which rapidly developed within steep potential estimates for the capability of meeting growing needs [7]. Moreover, the strong competition between some countries and manufacturers to develop these modules are ever present, either for their own uses or for trading issues [7,22]. Different techniques were employed to obtain the optimal amount of energy through the utilization of new technologies; e.g. concentrated solar power (CSP) or concentrated photovoltaic (CPV) systems [30,31], hybrid PV systems [32,33], and new PV cell technologies using advanced competent materials and high-tech approaches [34,35]. Innovative manufacturing approaches handle all aspects of solar cell development; e.g. improvement in the rate of absorption and responsiveness to solar radiation, the ability to convert absorbed energy into electricity more efficiently, and resistance to factors that cause deficiencies or the possession of better resistance [36–38]. Advancements in PV cell structure are highly effective. For instance, the technology of using interconnected cells on the rear side, such as in the metal wrap through technology (MWT) where the front phase is contacted by metallized vias that move the current onto the designed rear side, contributes to the efficiency of the solar cell by reducing shading on the front side and ohmic losses due to the interconnections made [39–41]. In any case, the technological aspects largely focus on the back-contact and conductive backsheets that

result in thinner cells with better efficiency, proficiency, and reliable manufacturing yield. This includes higher power outputs with enhanced compatibilities [42]. The technology of MWT is a collection of sophisticated methods using conductive backsheets and supportive design technology to provide praiseworthy results and elevated power outputs [42–48]. However, it is crucial to prevent existing negative voltage (NV) from damaging PV cells and to ensure that the reverse behavior is not destructive to the PV module; whether in MWT methods or Cz-Si conventional H-pattern solar cells. Fig. 1 provides a schematic cross-section of Cz-Si cell structure in conventional and MWT technologies with the consideration of two different rear construction methods for MWT: (a) represents the H-pattern model of a conventional cell, (b) displays MWT with a fully covered phosphorus-doped back surface field (BSF) (a silver-based via paste is used for the metallization of vias which performs as an external p-type contact for both structures), and (c) presents MWT with a structured phosphorus-doped BSF. Both rear assemblies were tested for reverse bias stability and shunting since the latter can be avoided by ensuring that the via paste does not have any electrical conductive contact to the adjacent n-type-doped region in the forward bias [49]. Fig. 1 provides a schematic cross-section of n-type Cz-Si solar cell construction with conventional and MWT structures.

2.1. Photovoltaic cell technology

The main function of the photovoltaic cell is to receive solar radiation in the form of pure light and convert it into electricity [50–62] through a conversion process known as the *photovoltaic effect* [53]. Several technologies have been used in the manufacturing process of PV cells. Different materials with various photoelectric conversion efficiencies in the structural component of these cells are employed; e.g. poly and mono crystalline silicon technologies, single/double crystal Si,
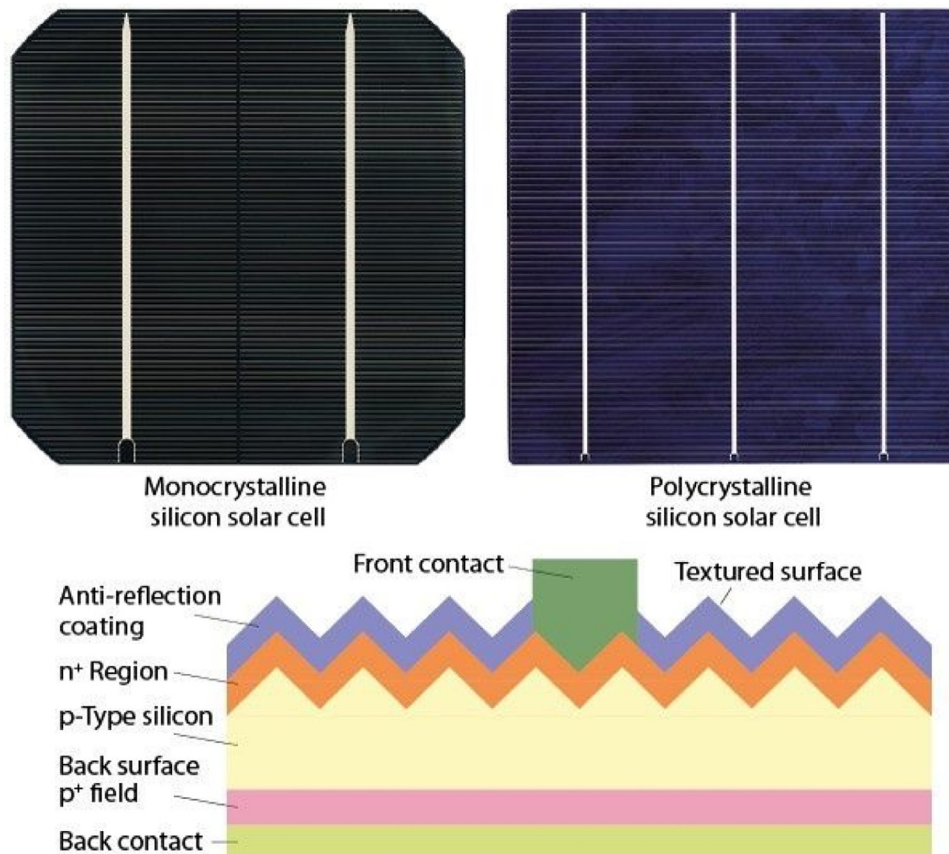
Fig. 2. Monocrystalline and polycrystalline silicon solar cells, and a basic cross-section of a commercial monocrystalline silicon solar cell, cited from (NPG Asia Mater) [73]. Springer Nature: NPG Asia Mater, Advances in crystalline silicon solar cell technology for industrial mass production, Saga T. 2010.

thin films advanced technology (such as GaAs thin films and copper indium gallium selenide (CIGS) thin films), perovskite and kesterite utilizations [34–41], and bifacial cell technologies [63]. Overall, with the advent of numerous unconventional methods to produce functional solar modules, PV technologies can be categorized into three main generations. The first generation is the conventional PV system that utilizes crystalline silicon (c-Si), whether in basic, simple (sc-Si), or multi-crystalline (mc-Si) forms [64]. The second generation of PV depends on the application of thin-film technologies including (but not limited to) three main classifications: the first is cadmium telluride (CdTe); the second includes amorphous silicon (a-Si) and micro amorphous silicon (a-Si/μc-Si); and the third is copper indium selenide (CIS) and other derivatives [65,66]. The third generation of PV technology uses organic solar cells (OSC) that apply organic electronics (OE) within the manufacturing process of PV cells, organic molecules (OM), or conductive organic polymers (COP) [67–69].

2.1.1. Crystalline silicon solar cells

The crystalline arrangements of silicon (c-Si) have made it the leading semiconducting material in use for several decades. The manufacturing history of solar cells demonstrate the significant reliance on CSSCs due to their high efficiency, reliability, and availability compared to other alternatives. In solar cell fabrication, crystalline silicon is either referred to as the multicrystalline silicon (multi-Si) or monocrystalline silicon (mono-Si) [70–72]. The multi-Si is further categorized as the polycrystalline silicon (poly-Si) or the semi-crystalline

silicon, consisting of small and multiple crystallites. This multiplicity causes a visible grain in the structure of the solar cell. On the other hand, the mono-Si is comprised of a continuous crystal without grain boundaries [70,72]. As a result, the mono-Si or single-crystal silicon is believed to have higher efficiency ratings than multi-Si or poly-Si. The technological development trend of the crystalline solar cell is drastically evolving. The mass production and development of PERC cells are expected to become the mainstream in the next generation. Increasingly progressing, the efficiency of the p-type PERC mono-crystalline cell is 22.61%; while it's 21.63% for the multi-crystalline cell. Moreover, the integrated back contact (IBC) and silicon heterojunction (SHJ) cells, also introduced as highly efficient crystalline silicon solar cells, have been enhanced and exhibit soaring efficiency that reach over 25% in some cases. By merging the merits of IBC-SHJ, the combination displayed an efficiency extending to 26.33%. These high ratings substantiate that exertions in crystalline silicon advancement do provide promising outcomes. The theoretical limit of the efficiency conversion rate in the crystalline silicon solar cell was estimated at 29%; this indicates a remarkable progress in CSSCs, which specifically provides additional prospects for single junction efficiency enhancements [72]. Fig. 2 shows monocrystalline and polycrystalline silicon solar cells with a basic cross-section of a commercial monocrystalline silicon solar cell structure.

The doping method of crystalline silicon solar cells is a stimulating topic for further research endeavors and can lead to a remarkable upsurge in solar cell performance. The p-type consists of a crystalline solar
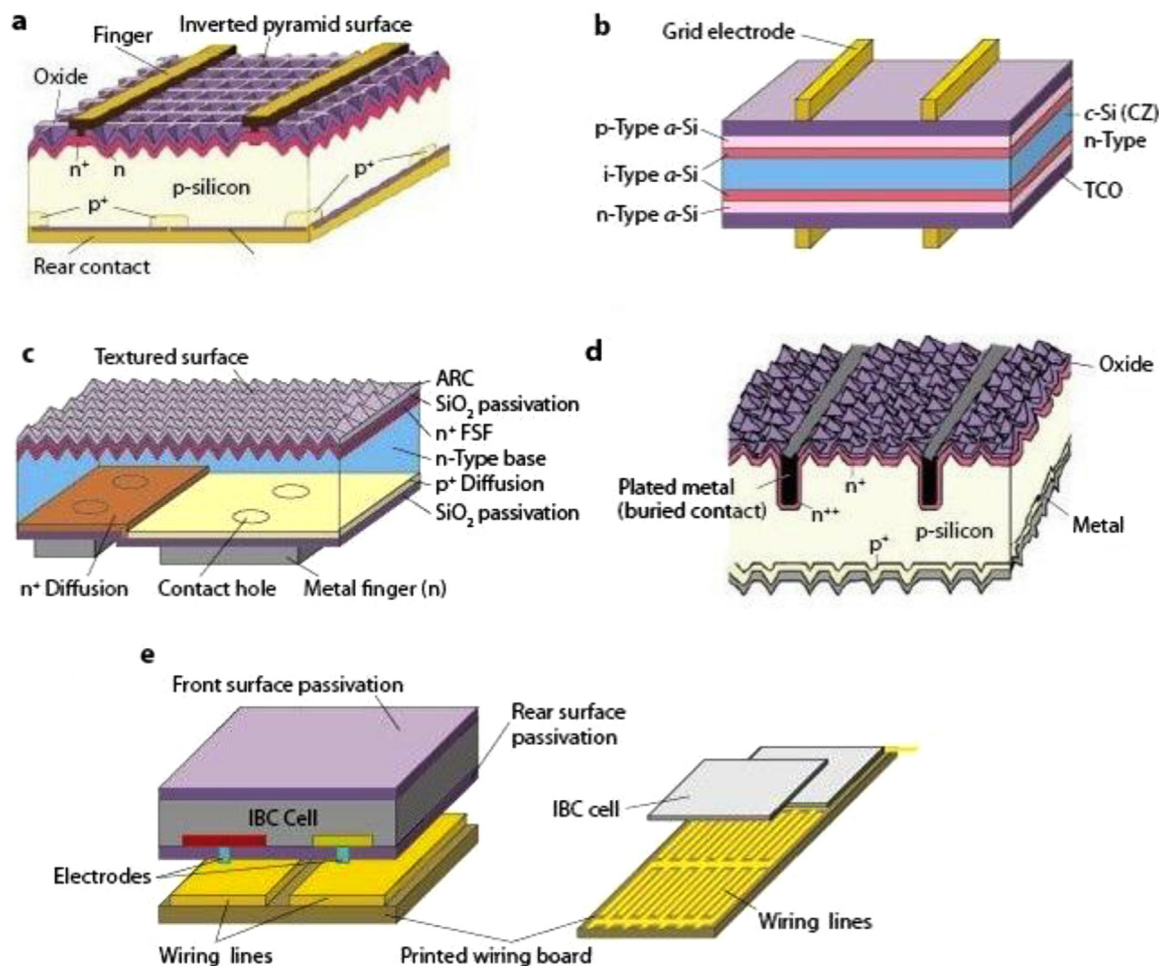
Fig. 3. Schematics of various crystalline solar cell structures. (a) PERL. (b) HIT. (c) BC-BJ. (d) Buried-contact cell structure by BP Solar (e) interdigitated back-contact (IBC) cell using surface mount technology, cited from (NPG Asia Mater) [73]. Springer Nature: NPG Asia Mater, Advances in crystalline silicon solar cell technology for industrial mass production, Saga T. 2010.

cell doped with boron which has one less electron than the silicon, making the cell positively charged; while the n-type consists of a crystalline solar cell doped with phosphorus which has one extra electron, making the cell negatively charged. Despite the fact that the manufacturing of p-type solar cells is leading the market within the solar cell industry, n-type crystalline silicon wafers have become progressively appealing and possess high potential compared to other technologies. The material properties of the n-type present advanced capacities in boosting solar cell performance when compared to the p-type. This refers to specific motives such as: possessing greater tolerance against common metal impurities, eluding boron-oxygen related defects, and its imperviousness to light-induced degradation (LID). However, the main challenge of the n-type is attaining a lower cost development process; therefore, engaging in more cost-effective and reliable methods along with current novel enhancements will aggregately contribute to more competent solar cell achievements, resulting in the reduction of cost per watt-peak (Wp) [74]. Multi and single crystalline are largely utilized in manufacturing systems within the solar cell industry. Both crystalline silicon wafers are considered to be dominating substrate materials for solar cell fabrication. However, they may not be the most suitable for all applications since the technique and method of fabrication affect their operation, which may either increase or decrease the overall performance of the solar module. For instance, the quasi-single crystalline (QSC) silicon has increasing potential in solar cell manufacturing, with a higher minority carrier lifetime compared to multi-Si materials; it maintains a smaller LID effect than what occurs in Czochralski (CZ) silicon. It can also adhere to higher levels of efficiency through the alkaline texturing approach. The QSC displayed lower loss of efficiency after exposure to sunlight; with reliable manufacturing cost. These specifications are fascinating for the fabrication of cost-effective silicon solar cells [75]. Furthermore, employing the tandem multi-junction architectures, novel carrier-selective passivating contacts schemes & techniques, and combining silicon absorbers with organic-inorganic perovskite materials in CSSCs will introduce auspicious pathways for further efficiency enhancements and cost reduction [76]. However, Fig. 3 shows schematics of various crystalline solar cell structures PERL, HIT, BC-BJ, Buried-contact cell structure and interdigitated back-contact (IBC).

Since the beginning of solar manufacturing, numerical modelling methods were established to produce Si solar cells. Simulations processed and examined fabricated cells to envisage the effects and performances of PV functionality [77–79]. As a result, numerical and analytical data were provided which can be applied in potential developments of cell optimization processes. By using clear defined models to attain sufficiently accurate predictions, the precision of the investigative process will be enhanced; e.g. the use of the optical model, auger recombination model, recombination at passivated surfaces, mobility model, intrinsic carrier density, etc. [77,78]. More importantly, adopting or maintaining appropriate parameters can significantly affect their outcomes [80–82] such as the fill factor, conversion efficiency, circuit current, open circuit voltage, closed circuit voltage, diode parameters, thickness parameters, electric parameters, and special parameters for organic solar cells [81,83,84]. Table 1 presents a systematic analysis on PV cell architecture to provide a comprehensive understanding of models and parameter efficiency. The five selected structures include the conventional, PERC, IBC, HIT/HJT, and MWT. The cells were compared to another five components: implemented technology, functionality, front grid, rear metal, and rate of efficiency classified for optical and device simulations of Si solar cells. The use of single cells, unmodified cells, hybrid cells, or cells of the same type may yield similar or different results depending on the surrounding environments and quality standards [85–97].

2.1.2. Thin-film technologies

Thin-film technologies provide desirable and effective models in the field of energy (particularly, solar energy) with distinctive

Table 1
PV cell architecture for selected solar cell technologies.

	Conventional	PERC	IBC	HIT/ HJT	MWT
Technology	Varied chemical properties of poly-si and mono-si [8] silicon wafer-based solar cells [98–100]	Dielectric passive layer [35,101]	Multi-contact on the rear of the cell [77,102,104]	Ultra-thin amorphous surrounding mono-thin wafer [40,50,105]	Interconnection of bus-points to rear side replacing busbars [78,106]
Functionality	Direct converting process [13,107] using silicon wafer-based solar cells [108]	Reflects back unabsorbed light [109,110]	Prevents shading losses [103,111]	Intrinsic a-Si passivation layer for c-Si wafer [98,103]	Reduces shading loss [50,103,112] and ohmic loss [102,106]
Front grid	Screen printing technology using silver-paste contact to produce conductive lines [9]	Front fingers: 91 with 1.7 mm pitch, 60 μm wide, and 720 μm² cross section [9,111] and Ag-paste with 3μΩcm CR 2mΩcm². [101]	P-fingers usually designed 40 with 4 μ high, 285 μ wide, and CR 20μΩ. N-fingers 40, 4 μ high, 135 μm wide 15μΩ [111]	Front fingers 86 with 1.7 mm pitch, 13 μm high, and 110 μm wide [111]	Intelligent computer aided design (ICAD) for complex metallization patterns [102,113] and technology computer-aided design (TCAD)
Rear metal	Al-paste with 35-μΩ [64,69]	Boron-added Al-paste with 35-μΩ and selective emitters [101,111]		μm. CR = 10 μΩcm², Ag based polymer [111]	Specific approaches consider 3-row contacts of 5 linked points to the front [42]
Approximate rate of efficiency	10–21% [114–121]	19–24% [101,122]	19–26% [122–124]	19–24% [50,57,98]	17.0–24% [37,50,125]

characteristics in manufacture, conductivity, efficient conversion and preservation of energy, photoconductive possessions, and solar control features [9,25]. Perovskites have been previously utilized as sensitizers in nanostructured photovoltaic cells. Perovskite solar cells (PSCs) are rapidly flourishing due to broadening research exertions. The employment of perovskite-based materials is currently the exhilarating alternative to traditional device architectures, especially the hybrid organic-inorganic devices that apply perovskite-based materials as light-absorbing elements. Thin-film photovoltaic cells (such as dye-sensitized solar cells, colloidal nanocrystal solar cells, and organic solar cells) are considered very promising in solar energy advancements and renewable energy technologies. Now, they can be manufactured and assembled through cost-effective methods while using low-cost materials. Alkylammonium lead (II) halides (e.g. CH3NH3PbI3 and CH3NH3PbIxCI3-x) are proven to be efficient photovoltaic materials with high carrier mobility, facile solution processability, and outstanding light harvesting [126]. Early efforts applied CH3NH3PbI3 nanoparticles to sensitize TiO2. Advanced works have demonstrated PSCs with an efficiency of up to 15.4%. They can be produced in the absence of a mesoporous matrix through a vapor-phase deposition process [127], A higher rate of efficiency (16.2%) was confirmed by utilizing the mixed-halide CH3NH3PbI3-xBrx and a poly-triarylamine hole-transporting medium. Another rate of efficiency (17.9%) was established due to the key factor of using a continuous perovskite layer with a thickness ratio of perovskite-infiltrated TiO2 scaffolding relative to that layer [128]. In current research scenarios, most state-of-the-art perovskite-based devices employ a mesoporous metal-oxide scaffold. These exertions offer a porous substrate in which the CH3NH3PbI3 light absorber can be developed. Titania scaffolds can also function by allowing electrons from the absorber to be conveyed to the electrode surface [127]. Other endeavors further discovered that ZrO2, as a mesoporous-based solar cell, provides higher photovoltage. It also exhibited longer electron lifetime than the TiO2-based solar cell [129]. Numerous research results proved the efficiency of photovoltaic conversion and its influences. Thin-film technologies cost less in production and have attractive manufacturing approaches, representing an adequate alternative to conventional solar cells [117,121,130,131]. Despite the various rates of efficiency, there are different types of PV thin-film technology, including the use of dye-sensitized solar cells (DSSCs), quantum-dot photovoltaics (QDPVs), and organic photovoltaics (OPVs) with high and reliable specifications; they are light weight, relatively lower in cost, and possess many other related advantages compared to bulk crystalline silicon (c-Si) [105,132,133]. The technologies of PV thin-films adopt several diverse materials; e.g. cadmium telluride (CdTe) [134–136], cadmium selenide (CdSe) [137,138], nanocrystalline cadmium selenide (nc-CdSe) [62], zinc cadmium sulfide (ZnCdS) [24,135], copper indium selenide (CIS) [7,64], copper indium gallium selenide (CIGS) [139,140], zinc oxide (ZnO), indium zinc oxide (IZO) [141], indium-doping zinc oxide (ZnO:In) [142], and copper zinc tin sulfide (CZTS/CZTSSe) [143].

2.1.3. Photovoltaic cells based on organic composites

With increasing research and constant development of PV applications based on organic micro and macromolecules to boost efficiency and preserve the environment, the need for additional investigations on the use of organic and natural materials are in constant and increasing demand [144–146]. Organic photovoltaic cells (OPVs) based on π-conjugated polymers or organic macromolecules characterize new research prospects which have been observed in continuous and fruitful developments [146–148]; for instance, the bulk-heterojunction (BHJ) is a polymeric blend of organics and small molecules (SM-OPVs), exhibiting good characteristics in solar cells and PV devices [149,150]. In BHJ, there is a determined temperature effect on CuPc performance in PV devices [56,151]. Using BHJ with CuPc/C60 yielded efficient organic solar cells since the fabrication of integrated OPV modules with ascendable voltage outputs can be made using a blend of "Poly(3-

hexylthiophene) and phenyl C61 butyric acid methyl ester" (P3HT/PCBM-70) [151]. However, the technology of photogeneration (PG) in polymer-fullerene organic solar cells bank on the nano/picosecond dynamics occurring in these complex blends and on the nanostructures or microstructures at the dimensional nanoscale [152]. In the CuPc/C60, the C60 is fully n-conjugated and forms HJ with p-type molecular semiconductors [151]; e.g. the silicon-poly [2-methoxy-5-(2-ethylhexyloxy)-p-phenylenevinylene] (MEH- PPV) layers [153,154], tetrathiafulvalene [155], and poly (3-alkyl-thiophene) [151]. The following mathematical model of the spice simulation software reflects on the optimization of the HJ ITO/CuPc/C60/Al using different diodes [151]:

$$J = J_{SC} - J_0 \ \left(e^{\frac{v}{vT}} \ -1 \right) \tag{1}$$

$$I = I_{SC} - I_0 \ \left(e^{\frac{v}{vT}} -1 \right) \tag{2}$$

$$I_{SC} = AJ_{SC} \tag{3}$$

$$I_0 = AJ_0 \tag{4}$$

Eq. (1) provides the current density (CD) of SC, which passes to the given voltage and irradiance. The value of the current generated (CG) by SC is given in Eq. (2) where $I_{SC} - I_0$ belongs to the respective CDs, $J_{SC} - J_0$ are in Eqs. (3) and (4), and A is the total area of the device. The PSpice code can also model a PV cell by the current source of assumed values [151]. On the other hand, the interest in fiber-based PV for cell development has substantially increased, which led to favorable attainments in this field. These achievements enhanced optical performances, especially when used with low optical density absorbers [156,157]. More importantly, the use of natural fibers (NF) in such applications may open new scientific horizons. Besides their significant properties, NFs can be important alternatives to harmful synthetic materials since they are environmentally friendly and sustainable resources [158–160]. Natural fiber composites (NFCs) have become crucial alternatives for numerous industrial applications [160–163]. A wide range of NFs are applied in filler forms and reinforcement materials which result in various NFCs [163,164], such as natural fiber reinforced polymers or conductive polymers [158,160,165,166]. From the electrical standpoint, conductive polymers demonstrate eminent control over electrical stimuli and possess distinguished features compared to other electroactive biomaterials; i.e. piezoelectric, electrets, and photovoltaic materials [163]. Short NFs could adjust the dielectric response of selected polymeric matrices, therefore, they are applicable for anticipating different factors that affect the possessions of NFCs to determine the electrical, mechanical, and biological properties [163]. Numerous solutions were introduced to improve the compatibility and bonding of NFs; i.e. the use of surface treatments through chemical, physical, and mechanical modifications or the employment of suitable coupling agents [158,167]. These agents contribute to the dispersibility and affinity of the filler (e.g. silane CA as surface modifying agent [168,169] and rectify the hydrophilicity or hydrophobicity when necessary [170]. Furthermore, dielectric properties affect the conversion process of electromagnetic radiant energy when transformed into heat radiation [171] as the received energy from the sun is a form of electromagnetic radiation that attains a wide range of wavelengths [172]. Since the conversion of electromagnetic energy (EME) into heat is determined by dielectric properties, a better understanding of these properties, especially in natural compounds, is required [173]. Conductive polymers constantly evaluate and adjust various textile fibers and fabrics, resulting in numerous applications that rely on them; e.g. conductive fabrics, antimicrobial fabrics, electromagnetic interference shielding (EMIS), and heating devices [163,174]. Only a few reports investigated conducting polymer-textile composites employed as electrodes in applications where the supercapacitor (SC) or the electric double-layer capacitor (EDLC) is used. The cellulosic substrate influence on the performance of electrochemical properties based on polypyrrole (PPy) electrode exhibited top results under specific conditions

[174]. PPy can be coated on the cellulosic film using selective materials and its attributes can be evaluated through the employment of dedicated energy-storing devices [174–176]. Fig. 4 represents a schematic illustration of the unit cell super-capacitor designed using textile electrodes.

Biomaterials can be used in finding practical solutions that provide new potentials in PV advances [177,178]. They can also provide innovative prospects for PV thermal management through the construction of an integrated Bio-phase change material (BioPCM) [12]. PCMs were initially designed for use in solar collectors and other relevant parts to reduce heat waste, therefore, contributing to the efficiency of PV modules. They are further utilized in building integrated photovoltaic systems (BIPV) and concentrating photovoltaic applications (CPA) [179–181]. PCM methods are also employed in thermal PV systems; as a result, environmental issues, health, and safety aspects must be considered when using such devices. This led to the emergence of applying bio-based products in PCM systems, introducing additional sustainable solutions to the environment and eliminating long-term negative impacts and risks that may exist [27]. Fig. 5 presents a schematic diagram of energy flow and the mechanisms of PV-PCM systems.

3. Hybrid systems technology

Solar radiation and thermal energy both require sufficient electric supply. Using PV hybrid thermoelectric (TE) systems and/or thermophotovoltaic (TPV) technologies led to potential prospects in energy conversion techniques; PV converts UV and visible spectrum from sunlight, and TE utilizes infrared spectroscopy (IR) [183–186]. The thermoelectric generator (TEG) has a strong conversion capability that enables the entire system to work more efficiently [186–189]. There are different forms and methods of hybridizing PV with ET, such as the spectrum splitting concentrating system (SSCS) [190,191], non-concentrating methods [160,161], or adding the TE system to the backside of the PV module [190–193]. It can also be integrated with different PV materials. Polycrystalline silicon thin-film PV cells are recommended for concentrating PVTE hybrid systems, whereas polymer PV cells are recommended for non-concentrating PVTE hybrid systems [194]. Recently, the idea of combining PV cells and TE generators (TEGs) has attracted much attention due to the effectiveness of boosting efficiency [195,196]. PV-TEG technology aims to reduce temperature, which enhances PV functionality; TEG can be hybridized with both Poly-Si and dye-sensitized cells using altered thermoelement geometries [192]. In

each unit of the PVTE/ PVTEG, there is an internal thermal resistance (TR) that considers the convection and radiation TR from the glass. In Eq. (5), the radiation TR R_{rad} is the radiation heat loss, and h_{rad} is the radiative heat transfer coefficient (RHTC) [195]. HTC is usually larger than the one in single PV/ambient/HTC [196]. The A_{PV} represents the area of a PV cell which calculates all radiation heat loss from the front glass cover (FGC) as follows [195]:

$$R_{rad} = \frac{1}{h_{rad}A_{PV}} \tag{5}$$

$$R_{conv} = \frac{1}{h_{conv}A_{PV}} \tag{6}$$

While the radiative heat transfer coefficient (RHTC) is:

$$h_{rad} = \varepsilon_g k_B (T_g^2 + T_a^2)(T_g + T_a) \tag{7}$$

ε_g reflects the emissivity of FGC, k_B indicates Stefan's constant, T_a refers to the temperature of the environment, and T_g is the temperature of the surface of GC. The R_{conv} determines the convection TR that averts the convection heat loss from the surface of the hybrid system, as in Eq. (6). Eq. (8) exemplifies the TR of the glass cover (GC) R_g, the EVA R_{EVA}, the Ceramic wafer R_{ceram}, the Cu electrode, and the R_{Cu} as follows:

$$R_i = \frac{\delta_i}{k_i A_i} \tag{8}$$

δ represents the thickness, k is the value of TC, and A is the area of GC. In addition, to calculate the thermal contact resistance (TCR) R_c in the hybrid system of the PV cell, the TE module and cooling system (CS) were connected, respectively, using thermal conductive adhesive (TCA). Therefore, Rc was explained as follows [195]:

$$R_c = \frac{\delta_{ad}}{k_{ad}A_{ad}} \tag{9}$$

Where k_{ad} is the thermal conductivity, (TC) and A_{ad} are the areas of TCA, and δ_{ad} is the thickness [195]. The dualistic thermal contact resistances (TCR) are between the PV cell and TE generator, as well as the TE generator and cooling system (CS) [108,195,197]. Notwithstanding the former, an indirect method for the hybrid system of PV/TE was developed in some studies, taking into consideration that all temperatures are strongly linked to the output powers of PV and TE subsystems [197–199]. Controversially, some challenges were explored using the indirect-coupling approach (ICA); these challenges were encountered to resolve the related non-linear equations [198]. Overall, PV/TE

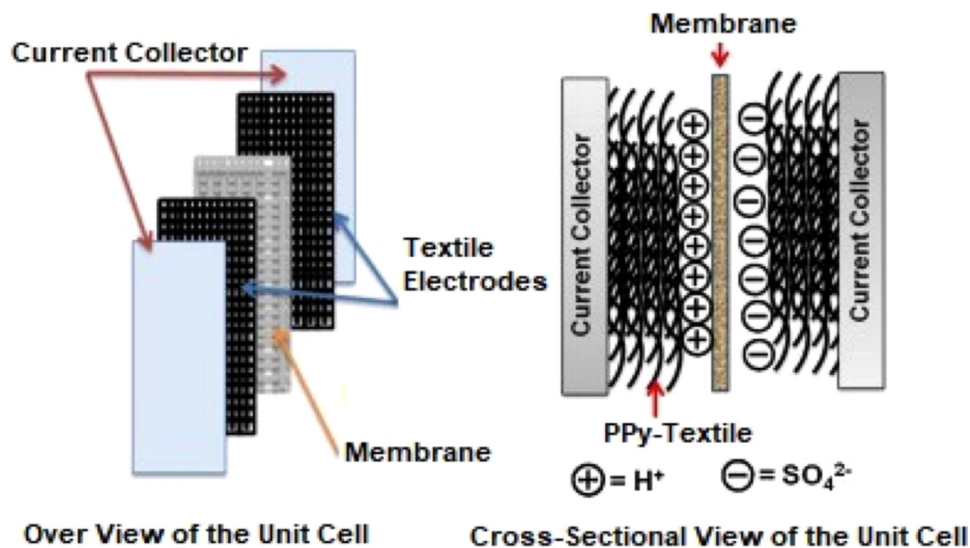**Fig. 4.** A schematic illustration of the unit cell (UC) super-capacitor using textile electrodes; (a) An overview of the UC structure, and (b) A cross sectional view of the UC structure [163,174].
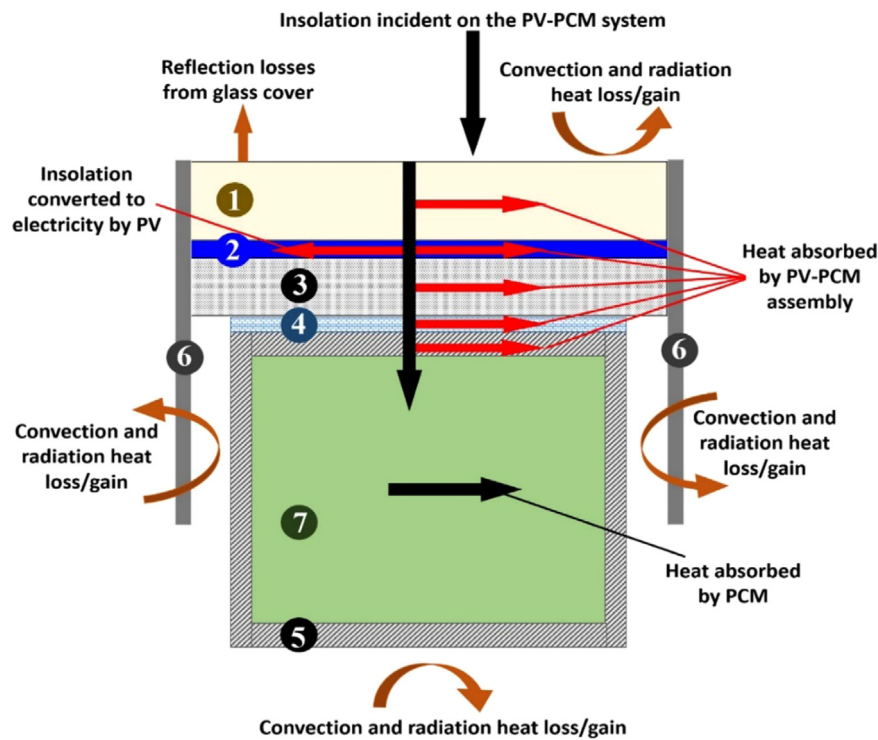
Fig. 5. A schematic diagram of energy flow in PV-PCM systems [27,182].
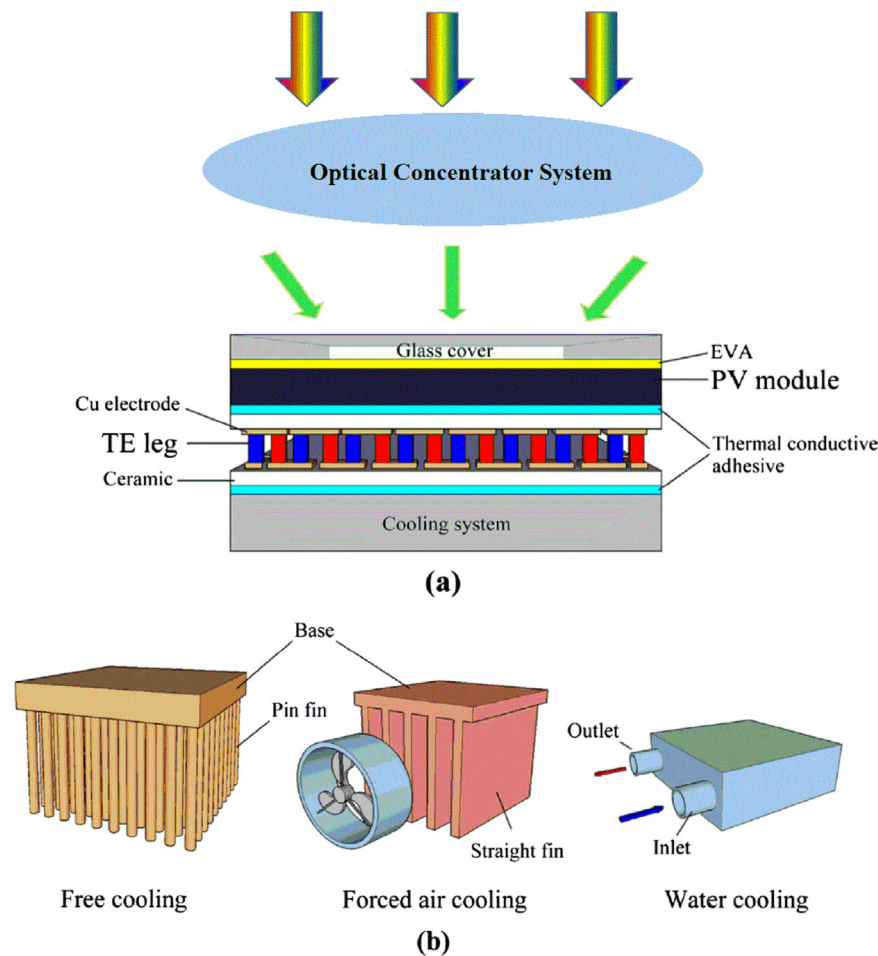

Fig. 6. (a) A schematic diagram of PV-TE hybrid structure, (b) Three types of cooling methods; free cooling, forced air cooling and water cooling [195].

efficiency was projected to be around 30% following the theoretical calculations [200]; from 25% to 30% in the direct coupling, and 30–40% in the indirect coupling [197]. However, the factual efficiency can be determined depending on used materials and selected approaches since the results vary from case to case and under different factors and unpredicted circumstances [201]. Fig. 6 presents a schematic diagram of a PV-TE hybrid structure and shows three different types of cooling methods; free cooling, forced air cooling and water cooling.

Hybrid systems contribute to the enhancement of the power capacity of solar cells and maximize the power output within designed operating settings, which increases the electrical efficiency of the PV system and eliminates relevant causes of inadequacy or deficiency [202–205]. Fig. 7 provides information on the efficiency of hybrid systems that employ Si PV cells for coupling systems, demonstrating the influence of the cooling condition on total efficiency, in this figure, the given is total efficiency versus concentrating ratio for the PV-TE hybrid system.

In the dye-sensitized solar cell (DSSC), the PVTE hybrid system increases the total efficiency to around 13% with a temperature gradient (TG) of 6.2 °C between the TE junctions [205]; the Seebeck coefficient links TG with the given electric current in an indirect method [191].

4. PV structure and backsheet design

PV modules are designed to generate alternative energy, therefore, solar cells are usually made of crystalline [206], polycrystalline, and

monocrystalline silicon [55]. The efficiency of these cells have been improved in continuous and multiple stages through various methods, such as light capture enhancements and photovoltaic thin film processing [207]. PV modules are semiconductor components with good electrical efficiency [208]. They have different rates of absorbing solar radiation [209]. It has been asserted that less than 20% of solar supply is converted into electricity, while 50% or more is transformed into heat which reduces efficiency. New methods and techniques are needed to avoid excessive heat so as to enhance the electrical performances of these modules [19,210]. PV modules are designed to be exposed to various natural conditions, involving stress factors in outdoor environments and other factors that influence efficiency such as resistance to acid, water, seawater, thermal shock, and UV radiation [33–35]. However, as one of the most important and promising source of energy, PV faces two major challenges: performance improvement and cost reduction [37,38]. In certain cases, these two challenges are critically linked together; for instance, if the PV module employs monocrystalline silicon instead of polycrystalline silicon, the efficiency and cost are estimated to increase [51]. With extensive and continuous studies to improve this alternative source of energy, the conversion process of solar energy to electricity through the use of PV technologies is expanding due to enhancements and significant contributions made to overcome the aforementioned challenges [40,41].

4.1. Backsheet design

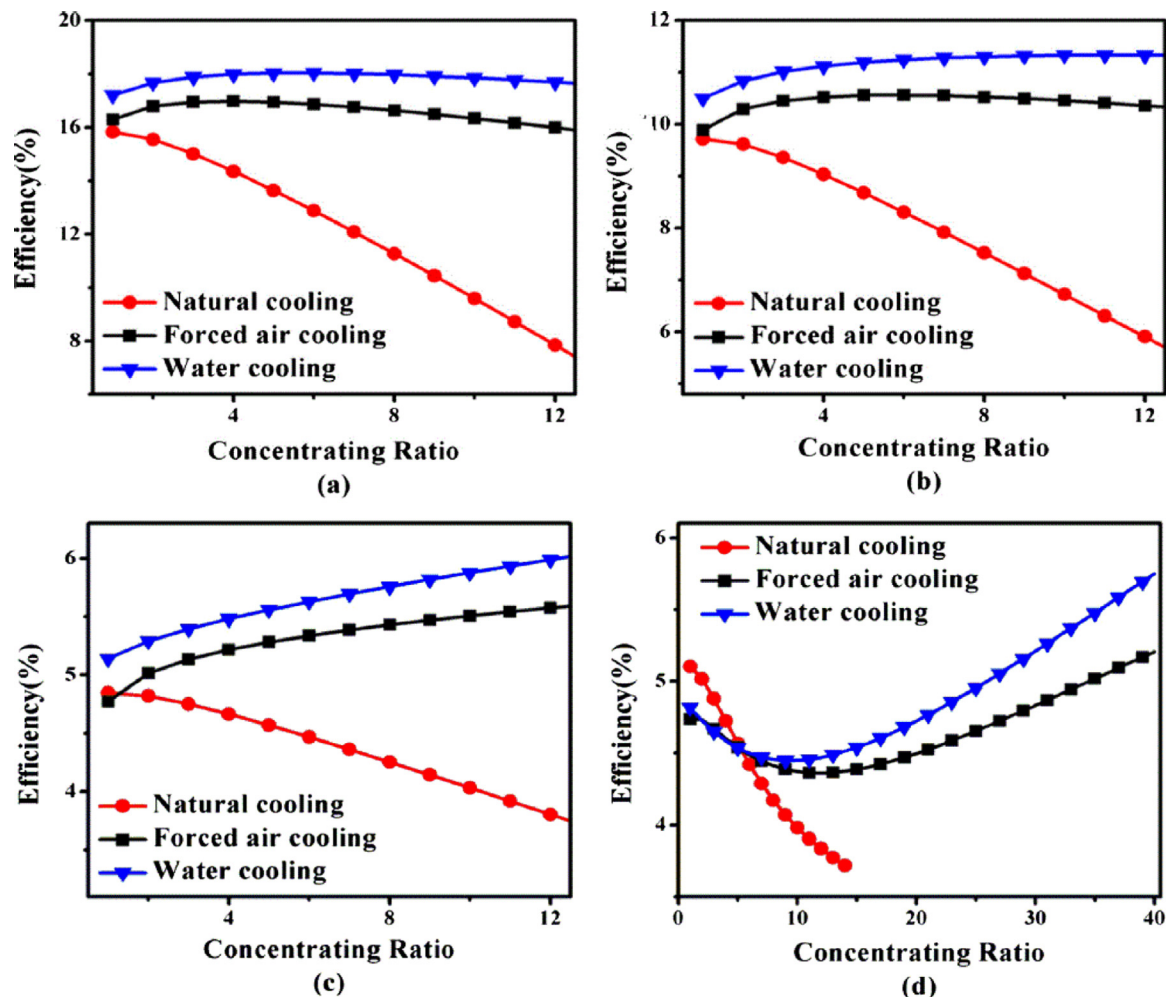The PV backsheet is designed to protect the inner parts of the PV

Fig. 7. Total efficiency of PV-TE hybrid systems utilizing different PV cells and cooling approaches; (a) c-Si PV, (b) p-Si PV, (c) a-Si PV, and (d) Polymer PV [195].

modules; e.g. PV cells, ribbons, encapsulants, and electrical materials [211–213]. It is located on the outermost part of the PV module and functions as an electrical insulator [211–214]. The PV backsheet structure is designed to effectively function under various conditions with the ability to resist difficult and changing environmental situations; this may include (but not limited to) moisture, temperature cycles, mechanical loads, and other relevant factors [151,189–191]. Additionally, the optical properties and durability should be accounted for since both contribute to the life-span of a PV module [214]. The optical properties of the PV backsheet are important in determining the performance of each module; higher reflectance of the inner side of the backsheet itself should be present, which in turn, helps redirect more reflected light to the PV cell [215–219]. The higher the reflectance of irradiation caused by backsheets, the better the performance gained [218–221] and vice versa [220]. The non-utilized energy is converted to heat which causes further degradation on the performance of a PV cell. This accelerates the aging factor (AF) and increases cell loss,

resulting in accumulated deficits [216,222]. However, the performance of a PV backsheet can be evaluated through various tests; usually, the peeling strength and tensile strength. These tests are performed after exposure to high temperatures and humid environments [223]. Employing appropriate coatings and enhancing optical properties will significantly contribute to the improvement of PV backsheets, which will boost overall efficiency [193,200]. The optical properties of PV backsheets symbolize important features that influence different aspects in backsheet simulations; e.g. the gain or loss in short circuit current, effective area optimization and connectivity, light harvesting and light recovery, ray tracing simulations, ray optics and reflection at various interfaces, and outdoor characteristics [224–228]. In addition, there is a need to increase compatibility in silicone-based electrically conductive adhesives and different surface finishes, as well as obtaining better performance through (low cell-to-module losses) [229]. Fig. 6 provides a schematic illustration of the most common back-contact and back-sheet structures systematically used in both conventional and
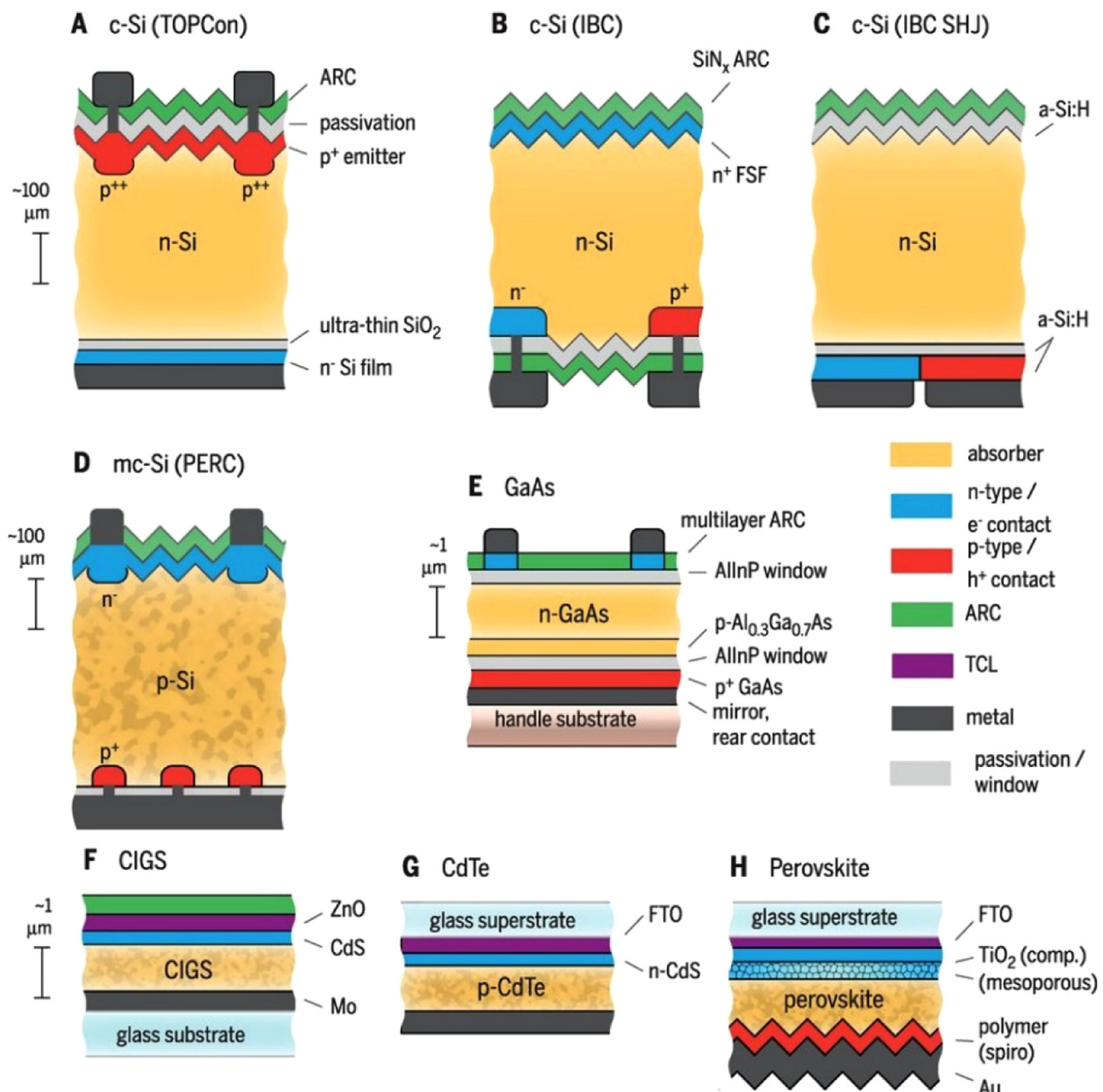

Fig. 8. A schematic illustration of the most common back-contact and back-sheet structures used in conventional and hybrid PV systems, (Science, 2016) [230].

hybrid structures (Fig. 8).

4.2. Conductive backsheets

Currently, the models of conductive backsheets (CBS), electrically conductive adhesives (ECA), [229,231,232] and conductive adhesives have high compatibility and excellent performance in improving the overall conversion efficiency through certain methodologies [233–235]. Silicon-based ECA and CBS in MWT manufacturing techniques yielded dramatic changes in electrical contact; reaching a stable contact rate and low ohmic contact by applying ECA in low-cost surface finishes is more challenging [236,237]. ECA using Ag filler with certain conducted methods is highly recommended for durability. In a developed silicon ECA experiment, the mini-modules did not degrade after 1000 h in damp heat (DH) settings, nor after 200 thermal cycles (*TC*) [238]. In another experiment, ECA and CBS foils were tested up to 2000 h in DH and 400 *TC*. The ECA and CBS foils were analyzed for contact resistance and peel strength. Dot geometry test was made for the separate components of ECA and CBS. The results demonstrated that one of three ECAs performed well on three different CBS foil types, while other results showed that combinations of CBS and ECA should be tested at module level [239]. The ECA and conductive adhesives have the potential to reduce the inclusive complexity of manufacturing solar modules and decrease cost/watt peak. Despite compatibility issues that can occur between ECAs and CBS, a new cost-minimizing ECA was developed that had achieved good contact on organic solderability preservative (OSP)-finished CBS [240]. The need for reduced cost, high durability, interconnection technology, and low temperature components in the structure of a solar module makes the ECA appear as a propitious alternative to existing methods. Soldering and maintaining higher possibilities of the required interconnection bond during the lamination process will simplify a solar module's assembly procedure, subsequently contributing to cost reduction [241]. Additionally, silicon heterojunction solar cells with thin wafers possess the high potential of providing reliable efficiency rates since 21% cell efficiency can be maintained on the 170-micron thin wafers. A remarkable reduction of cost-performance ratio can result if a reliable integration process is considered [242], The new high efficiency of heterojunction reaches well above 24%. This requires a low temperature interconnection procedure to structure an efficient solar module; therefore, conductive adhesive and ECA have proven to be reliable alternative solutions with their low processing temperatures, becoming a key interconnection technology. However, reducing the cost of ECA and obtaining long-term experience for further sustainable analyses will contribute to better and faster utilizations [243]. ECA and conductive adhesives are highly recommended as effective alternatives for the existing standard interconnection technology. They provide low temperature interconnection processes in the manufacturing of modules [244,245], as required for the production process of heterojunction cells since high soldering temperatures may cause damage to cell surfaces [245,246].

5. Conclusions

Milestones have been achieved in PV technology and solar energy optimization on all levels and categories; e.g. solar cell structures, efficiency and durability, fabrication methods, hybridization, concentration techniques, and organic orientation. However, many challenges face the attempts to enhance PV efficiency, including (but not limited to) the development of solar cell absorption and conversion efficiency, heat transfer, performance of parameters under various conditions, and production costs. The PV cell architecture has been improved using advanced methods; i.e. PERC, IBC, HIT/HJT, and MWT technologies. These new models can either function separately or be hybridized with other cell models to increase competence. Despite all improvements, the actual efficiency of PV modules is mostly varied; ranging between ~ 20% and ~ 30%. The PVTE and TPV hybrid systems can reduce

heat by utilizing infrared spectroscopy. Moreover, the advancements in PV backsheet structures and their optical properties have led to further prospects in boosting PV cell efficiency. Overall, the discovery of various technologies has broadened the applications of PV and led to the emergence of new generations of solar power energy such as the second generation of thin-film technologies using CdTe, CdSe nanoparticles, ZnCds, a-Si/μc-Si, CIGS, and CIS, as well as the third generation of OSC which employs OM and COP technologies.

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