Transactions on Electrical and Electronic Materials (2020) 21:456–476
https://doi.org/10.1007/s42341-020-00217-9

Online ISSN 2092-7592
Print ISSN 1229-7607

REVIEW PAPER

Photovoltaic Review of all Generations: Environmental Impact and Its Market Potential

Rashmi Chawla[1] · **Poonam Singhal**[2] · **Amit Kumar Garg**[2]

Received: 17 April 2020 / Revised: 4 June 2020 / Accepted: 27 June 2020 / Published online: 6 July 2020

Abstract

With the technology and innovation rising at its peak, the demand for energy has increased exponentially. To cater this, researchers are persistently exploring ways to fulfil this deficit between demand and supply. One of the feasible solutions is the use of energy from renewable resources such as Solar Energy due to its abundance availability and easy accessibility. Seeing it's trans formative potential to address growing concerns about environment, pollution and sustainable energy integration, there is an intemperate research going on in developing highly efficient Photovoltaic Cells (PVC). The PVC's are effectuated to convert solar energy from the sunlight directly to electrical energy. Furthermore, the PVC has gone through various generations with the aim to optimise its cost/watt of delivered solar electricity and efficiency of solar cell. This paper is an effort to compare all the generations which PVC has undergone and the recent advancements in this area. The results of this research study will be fruitful for researchers working in this direction.

Keywords AM 1.5G · Fill factor · Photovoltaic technologies · Solar energy · Solar cell

1 Introduction

A sharp distinct increase in consumption of energy is seen in recent past. It is estimated that by the year 2030, the world consumption will grow up by 50% [1]. This increase in high demand of energy has forced the researchers to search new ways to match the growing demand for energy. Currently these requirements are filled using two ways: Renewable and Non Renewable Energy Resources (as shown in Fig. 1a). Although being affordable the latter cannot be replenished at sufficient rate and concern over sustainability of these resources has arisen while the former can be used repeatedly since it is replaced naturally. The non-renewable resources face the following disadvantages when compared to renewable resources.

- *Revitalization*: The non-renewable resources will soon extinct as they are depleted at a very high pace.
- *Environmental Hazard*: The mining of non-renewable energy a big damage to the environment.

The burning of fossil fuels results in production of toxic gases like sulphur dioxide and greenhouse gases which result in acid rain and global warming.

As these non-renewable resources are not sustainable in use (formation takes billions of years) and are being depleted at a high rate [1, 2]; renewable sources need to replace them. Among the renewable energy options, solar energy has proved to be a better solution to its countervail; one of the reason being energy conversion process is simplest (as shown in Fig. 1b). The total amount of sun's energy 3,850,000EJ is approximately absorbed by earth's atmosphere [3], land and oceans which corresponds to 8000 times the overall energy consumed by the whole world [3]. This solar energy cannot be used directly but has to be converted into electricity for its daily usage. For this purpose solar PVC's are used. A solar PVC system can be constructed to any size in accordance to energy requirements [4]. Furthermore, depending upon the energy change needed, the owner of a PVC system can enlarge or move it. The major disadvantage of these devices is its cost and conversion efficiency [3, 4]. Researchers are making lot of effort in studying the technologies to improve

---

✉ Rashmi Chawla
rashmichawlaymca@gmail.com

[1] Department of Electronics Engineering, J.C. Bose University of Science and Technology, YMCA, Faridabad, India

[2] Department of Electronics Engineering, Deenbandhu University of Science and Technology, Murthal, India

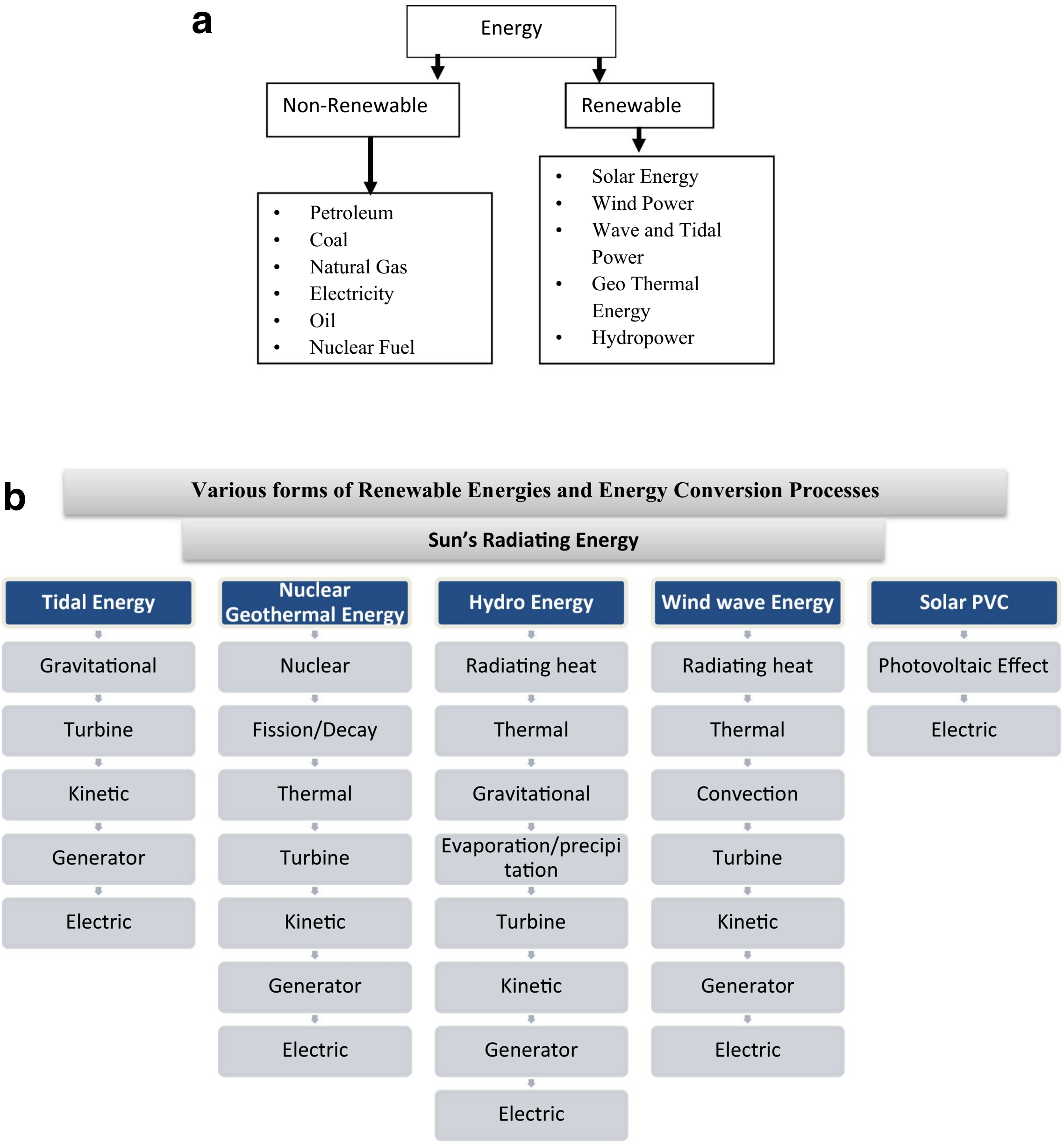

Fig. 1 **a** Various Non-renewable and renewable energy resources. **b** Various renewable energy resources with energy conversion process [2]

these parameter constraints of single junction solar PVCs and coming up with new solar architectures capable of absorbing larger solar spectrum [5]. The concern areas to be focused for research on Solar PVC technology are based on four goals: (i) achieving better Power Conversion Efficiencies (PCE) (ii) the environment impact and (iii) reduced manufacturing cost and complexity (iv) power storage as solar energy is not available 24*7. Considering these focus areas there has been lot of research done at national and international level on solar PVC to find opportunities that can enhance efficiency of the photovoltaic device [5].

This paper reviews a cumulative development through four generation journey of solar PVC. It gives a critical technology review into all the generations of solar PVC in its current and plausible future forms; considering most of the well-defined materials.

This paper is compiled as follows: Sect. 2 elucidates the basic working of solar PVC and Sect. 3 reviews solar PVC technology options, including both the Si-based technologies (which are well established) and emerging alternatives (sill on research grounds). This section also focuses on technical characteristics that play vital role in different PV applications.

The recent technology trends discussed in Sect. 3 gives a brief description of upcoming R&D technologies that claim to support higher PCE and cost efficient solar PVC alternative. Section 4 discusses various parameters which effect performance metrics of solar PVC; followed by results, future expectation and conclusions.

2 Solar Photo Voltaic Cell

Solar PVC is basically a p–n diode based on the principle of photovoltaic effect [6] that converts Sun's light energy into direct current by the photovoltaic effect [6]. This effect can be defined as the generation of charge carriers in a light absorbing material when the light radiation is incident on it [7]. The generation of charge carries actually happens when the light energy of Sun which compromises packets of energy smashes off loose electron of a semiconductor material (e.g. Si) and the electric field is created. This electric field created drives the electron in the semiconductor in orderly manner [6, 7] resulting in electric current to flow. The electrical connection (series or parallel) of no. of solar PVC's are called a solar module. The combination of solar modules is called solar PVC array. If a 10 m^2 Solar PVC array is considered then theoretically its efficiency equal to 10 km^2 array. This is in incongruity with other renewable resources like wind turbines, hydro and thermal generators which lose efficiency with reduction of size [8].

2.1 Working Principle of Solar PVC

The Solar PVC working can be enlisted in following steps and is represented in Fig. 2 with how energy from sun flows to output load through panel.

- At first photons (packets of energy) in sunlight smashes the solar PVC in panel and are then absorbed by photoactive semiconductor materials in the cell [9]. The energy equation Eq. (1) of the absorbed photon is given in by

  $$E = hc/\lambda = hv \tag{1}$$

  where E is defined as the photon energy, h as Planck's constant (equal to ~ 6.6×10^{-34} Joule-s), c as the speed of light (equal to ~ 3.0×10^{8} meters per second), λ as the photon wavelength, and v as the photon frequency [9, 10].

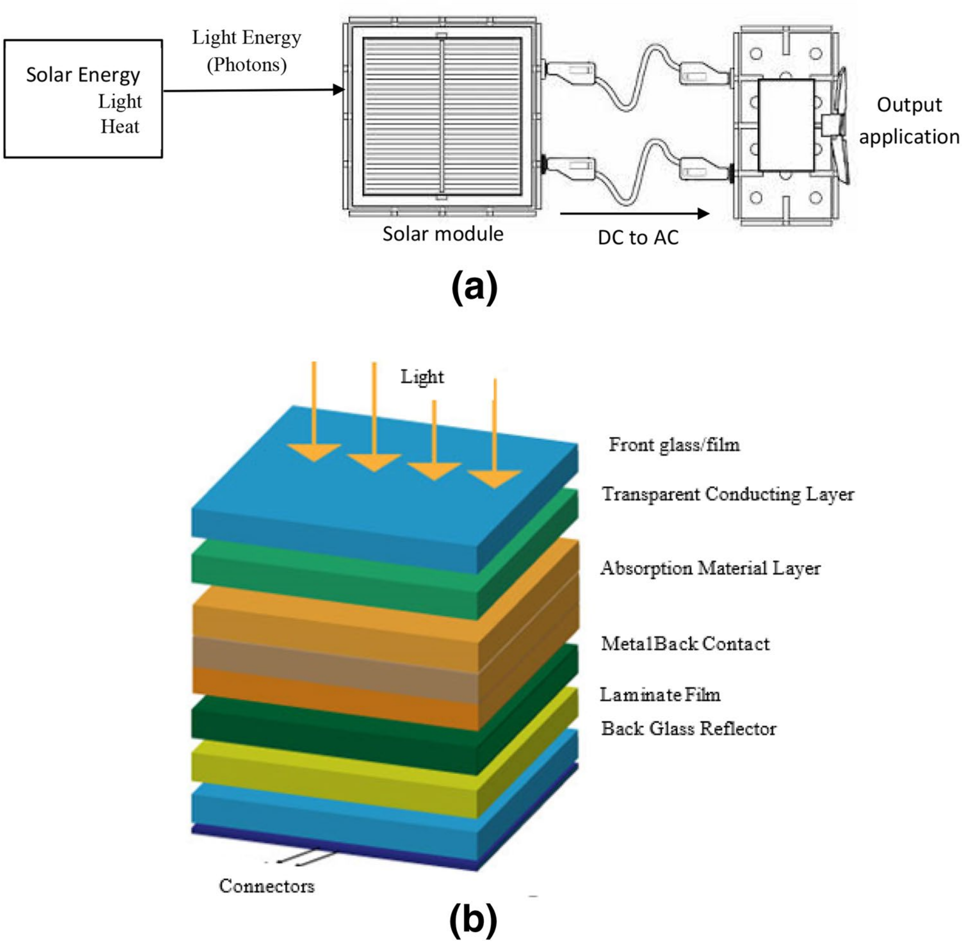

Fig. 2 **a** Working principle of solar PVC. **b** Basic structure of solar PVC

- The electrons of this semiconductor material now get excited from their current molecular/atomic orbital and are called excitons. This exciton can now be categorized in one of the three working mechanism: (i) it either dissipates the energy as heat (as in case of thermal-applications) (ii) return to its orbital (recombination mechanism) (iii) highly energized so that it can travel through the solar PVC to reach an electrode (photo-voltaic effect). Solar PVC employs the third mechanism and due to these photo-voltaic effect current flows through the material to cancel the potential and the electricity so produced is captured [10]. The chemical bonds of the semiconductor photovoltaic material paramount for this process to work.
- An array of solar PVCs called solar panel converts this solar energy into Direct Current (DC) electricity which then using an inverter is converted to alternating current (AC) [11] as depicted in Fig. 2a. The basic structure of solar PVC is elaborated in Fig. 2b.

2.1.1 Specification of a Polycrystalline Solar PV Module

A typical Silicon (Si) PV module shown in Fig. 2 compromises various layer; the top most layer of glass sheet is used for mechanical support and protection [12]. To protect it from moisture and ultraviolet (UV) radiations it is overlay with an encapsulated layer of ethylene vinyl acetate (EVA). A solar module consists of approx. 60 to 72 individual 6-inch-square (15-cm-square) solar PVCs, arranged in series or parallel. A single cell under peak illumination is capable of producing 4–5 watts; at the back it is protected by a fluoropolymer sheet; and an aluminium frame is used for mounting purpose. Standard Si PV module facet parameters are 1 m/1.5 m/4 cm, with output power ratings approx. ranging from 260 to 440 W [12].

2.2 Solar PVC Parameters

While selecting solar PVC for a particular application its performance metrics should be known. To understand the performance metrics of a Solar PVC [13] its output parameters (discussed in detail in Table 1), current and voltage characteristics should be known. The short circuit current in solar PVC depends upon the surface area which is illuminated and thereby is termed as short circuit *current density* (J_{sc}). The open circuit voltage (V_{oc}) and short circuit current (I_{sc}) are measured between the $(+)^{ve}$ and $(-)^{ve}$ terminals of the solar PVC as shown in Fig. 3a.

The positive and negative terminal connection in solar PVC and its load connection can be understood by Fig. 3a. The solar PVC parameters can also be determined from the dark and illuminated I–V characteristics as shown in Fig. 3b. These characteristics vary in accordance to the material used in active layer and thus affecting its output efficiency. Considering voltage V is applied across the terminals (Fig. 3a), SQ's p–n junction theory [16] reveals exponential increase in the carrier concentration with qV/kT close to the junction (with kT/q, the thermal voltage $V_T = 26.692$ mV at ideal 25 °C) [10].

$$I_T = I_0\left(e^{\frac{qV}{kT}} - 1\right) - I_L$$

The Solar PVC has proved itself to be one of the most upcoming renewable source energy technologies. The photo voltaic material used faces some technical challenges which need to be organized. The stratification of solar PVC established in 2001 structures this technology in four "generations" on the basis of PCE and cost [10]. According to this organization the "Third generation" will always be better than the "first generation."

The next section reviews current solar PVC technologies categorized generation wise and the subsequent sections explore various performance metrics and materials implemented in that generation. The goal of the four generation of solar PVC is to make solar energy more productive over a broad band of solar spectrum (e.g., including infrared), cost effective so that it can reach more and more people, and more and more applications can be developed.

3 Solar PVC Generation

Solar PVC technologies have crossed three generations; lot of research work is still going on in its fourth generation [17]. The four generations shown in Fig. 4 depending upon the fabrication technology used and light absorbing material, can be further categorized depending upon substrate in the form of:

- Crystalline Silicon (Wafer based)
- Thin Film
- Emerging thin films

The sections below is a detailed study on various generations of solar cell and the technology and research associated with various output parameters like efficiency, cost and size.

3.1 First Generation of Solar PVC–Crystalline Silicon

First generation of solar PVC was developed in 1958 [18]. This was made up of Si with band gap of 1.1 eV [18]. In a Crystalline Silicon(C-Si) solar PVC or also termed as first generation of solar PVC, basic structure subsists of an n-type Si semiconductor layer (which acts as emitter layer) and p-type semiconductor layer (which acts as base layer). The p–n junction is thus formed by sandwiching these two layers [18, 19]. To avoid loss of incident light energy due

Table 1 Parameters effecting performance metrics of Solar cell

Parameter	Definition	Expected value	Factors affecting the parameter
Short circuit current (I_{sc})	Considering the electrodes of the solar PVC short circuited, the current flows through the external circuit called I_{sc}	For ideal PVC with average resistive losses, I_{sc} and the light-generated current are identical [14]	The I_{sc} is affected due to recombination which results in loss of photo-generated charge carriers [14] Lower band gap materials are efficient to absorb large part of the spectrum and thereby yield higher output current [14] Thickness of material
Open circuit voltage(V_{oc})	When zero current flows through the external circuit at a certain voltage, is called open circuit voltage [16] $V_{OC} = \frac{nkT}{q} \ln\left(\frac{I_{SC}}{I_O} + 1\right)$ (Eq. 2) where I_o = dark saturation current, I_{sc} = short circuit current, q = charge, N = Ideality factor, K = Boltzmann constant, T = Temperature	The higher PCE in solar PVC photoactive materials like germanium, Si and gallium arsenide with V_{oc} 245, 706 and 1020 mV, with their respective band-gaps of 0.67, 1.12 and 1.43 eV are considered [15]	Temperature Doping concentration
Fill factor(FF)	It is the ratio between the maximum power generated P_{max} and the product of V_{oc} and I_{sc} [14] $FF = \frac{P_{max}}{V_{oc} I_{sc}}$ Where $P_{max} = V_{max} * I_{max}$	The FF has a value around 80% for a normal Si PVC [15]	The series resistance (R_s) of the solar PV diode The parallel or shunt resistance (R_{sh}) of the solar PV diode The recombination rate in the space charge region of the PVC The reverse saturation current (J_o) of the p–n junction
Conversion efficiency	It is the ratio between P_{max} and the incident power (P_{in}) [14, 15]	Using an AM 1.5 solar spectrum: Shockley Quisser (SQ) limit defines maximum PCE of solar PVC as 33.7% considering a single p-n [8–15] junction (band gap of 1.34 eV) [15]	Temperature Thickness of material I_{sc} V_{oc} FF

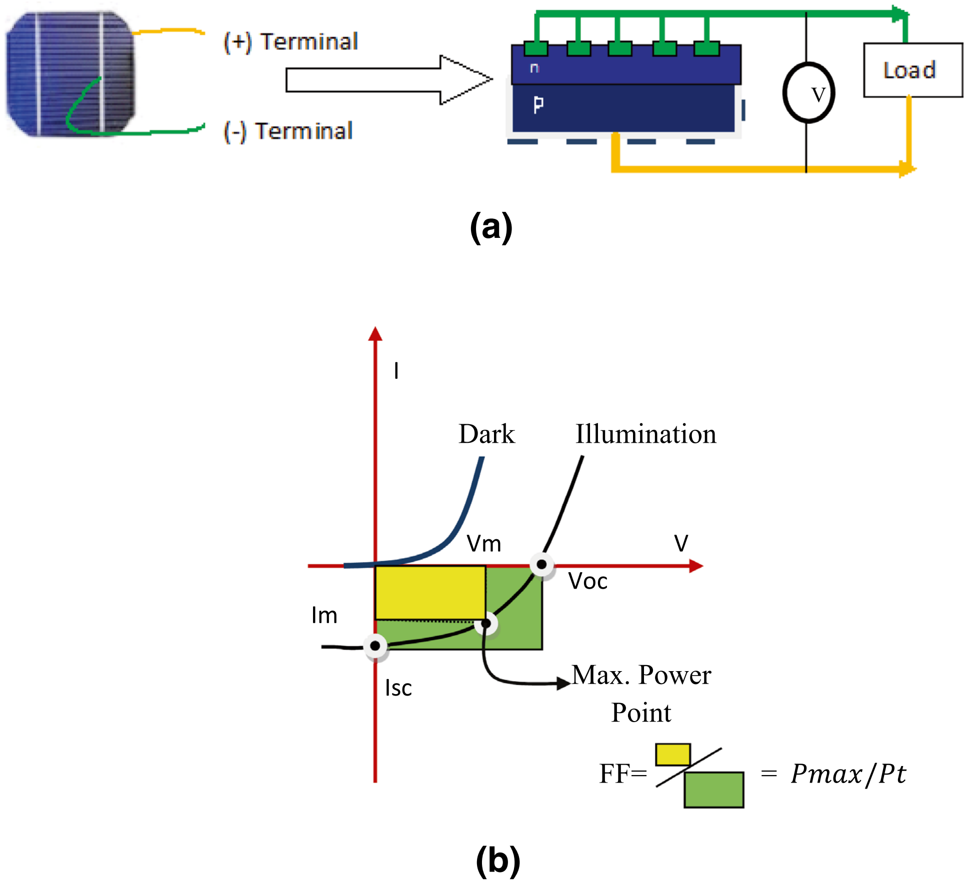

Fig. 3 **a** Open circuit voltage and short circuit current are measurement between the positive and negative terminals of the solar PVC. **b** I-V characteristics of Solar PVC in dark and light conditions

to reflection the uppermost surface of solar PVC is coated with thin anti-reflection coating. This loss of energy is due to reflection of light radiations. This is the oldest and the most popular technology due to its high PCE [19]. The industry product of C-Si modules began long back in 1963 by Japan Corporation which installed a 242 W PV [20] module on a light house, one of the world's largest commercial PV installations during that time. C-Si solar PVC accounted for about 90% of global PV sales in 2017 [20]. It can be further divided into two main categories:

- Mono-crystalline silicon solar PVC
- Poly-crystalline silicon solar PVC

3.1.1 Mono-crystalline Silicon Solar PVC

The mono-crystalline solar PVCs are sliced from a large single crystal which is then grown under carefully controlled conditions. They are also for the same reason called single C-Si. These cells are manufactured by czochralski process. In this process, boron is uniformly diffused to silicon wafer to form the p-type semiconductor. Then phosphorous is uniformly doped into this semiconducting material to form a p–n junction. Due to this uniform deposition of layers to each other this PV device has come

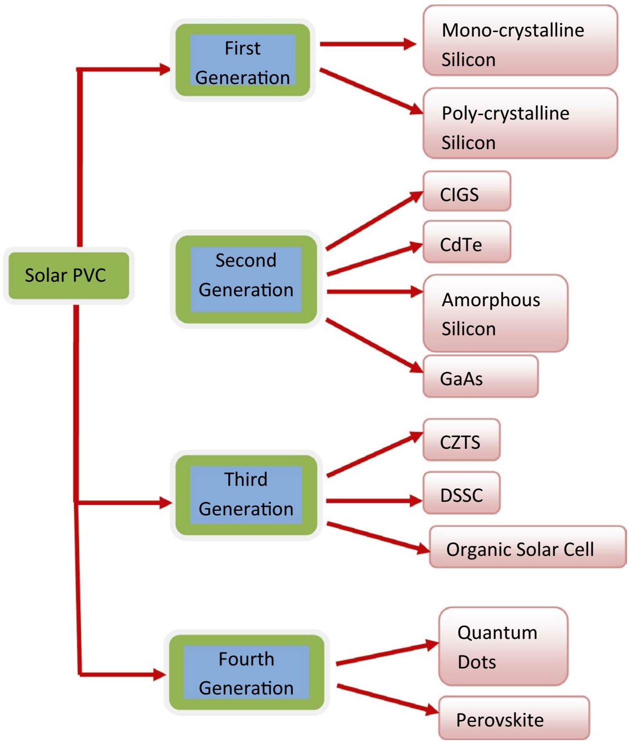

Fig. 4 Four generations of solar PVC

closer to theoretical PCE around 33.16% [21]. The top surface of the cell needs an Anti-reflective Coating (ARC) due to shiny property of Si which can result in light reflection. To avoid loss of incident light the surface needs to be covered with thin (micron size) pyramid shape structures (textured surface) to reduce reflection losses. The solar PV commercial module on textured surface uses an ARC of silicon nitride (SiNx) or titanium oxide (TiOx) to further reduce reflection losses [22]. The expected lifespan of these cells is typically 25–30 years [21–24]. The C-Si single junction(rear junction) terrestrial cell recently have shown 26.3 ± 0.5% efficiency on designated illuminated area of 180.43 cm^2 as tested in Fraunhofer Germany Institute for Solar Energy Systems (FhG-ISE) lab on July 2016 [24]. The C-Si terrestrial module (108 cells) with 24.4 ± 0.5% efficiency on 13,177 cm^2 designated illuminated area was confirmed by Advanced Industrial Science and Technology (AIST) on September 2016 under the global AM 1.5 spectrum (1000 W/M^2) [24]. The temperature of the solar PVC module and single junction cell was optimized at 25 °C.

3.1.2 Poly-crystalline Silicon Solar PVC

Polycrystalline solar PVCs are made by coupling of large number of crystals called crystallites resulting in a metal flake effect. As such poly-Si and multi-Si are synonyms, but multi C-Si usually refers to crystals bigger than 1 mm. Si wafer from multiple Si crystal is used rather than Si wafer from a single Si crystal under tightly controlled growth conditions; this results in a cheaper production mechanism in comparison to mono-crystalline solar PVC. They are constructed from square Si substrates which are cut from polycrystalline ingots and are grown in quartz crucibles. The production of these cells is more economical in comparison to mono-crystalline solar PVC but cannot compete with the PCE. The low efficiency is the result of defects which occur on surface due to crystal structures formed as a result of hardening. These defects reduce the efficiency [24], the lab efficiency of 18% to 27% have been reported for this cell. A requirement of five tons poly-Si is needed in manufacturing conventional solar PVC modules with 1 megawatt (MW) output [25].

The multi C-Si single junction terrestrial cell recently have shown 21.3 ± 0.4% efficiency on total area of 242.74 cm^2 as tested in FhG-ISE lab on July Nov 2015 [26]. The multi C-Si terrestrial module (120 PVCs) with 19.9 ± 0.4% efficiency on 15,143 cm^2 designated illuminated area was confirmed by FhG-ISE on October 2016 under the global AM 1.5 spectrum (1000 W/M^2) [27]. The temperature of the solar PVC module and single junction cell was optimized at 25 °C.

3.1.3 Passivated Emitter Rear Contact (PERC) Solar PVC

The Passivated Emitter Rear Contact (PERC) solar PVC was first developed in University of New South Wales around 1980s by Martin Green and his research team [28, 29]. Under this technology addition of extra layer at rear side of solar PVC was proposed as a twostep procedure to back surface field [30]: Step (i) application of rear surface passivation film; Step (ii) usage of lasers/chemicals for creation of tiny pockets by opening rear passivation stack so that more solar light can be absorbed. Although the addition of these steps is an extra effort but output efficiency is stipulated threefold as the recombination rate gets considerably reduced, photon absorption is high and increase in internal reflectivity is observed. The passivation layer at the rare side of solar PVC turned to be an efficacious methodology to capture unabsorbed light by reflecting it back for second absorption attempt resulting in optimum output yield. The PERC solar PVC from top to rear layers can be consolidated as below:

- Contacts: silver screen printed paste
- Anti-Reflective Coating (ARC) layer
- Photovoltaic material: Si wafers with phosphorous diffused, boron doped to form the P–N junction
- Back Surface Field: aluminium back surface field
- Protective Layer: screen printed aluminium paste

Table 2 below enlists merits and demerits of first generation Solar PVC and a comparison of different materials used in first generation.

The first generation which still covers the highest global market till now, with its good outdoor performance and lifetime; faces a drawback in terms of cost and size. These drawbacks were one of the main working grail for second generation solar cell. The second generation is discussed in the subsequent section.

3.2 Second Generation Solar PVC: Thin films

First generation solar cell comes up with high efficiency and the disadvantage of increased cost. This results in the need of removing unnecessary material especially in active layer which generated the idea of thin film second generation solar cells. This generation used less material while maintaining the appropriate efficiency of cell. The thin film solar PVC technology uses 1–10 µm [31] of photo active layer and is more efficient than C-Si in absorbing the solar energy. The production of thin films based second generation solar PVC involves vacuum processes which requires high temperature that leads to the high energy consumption. This generation of solar cells discourages the use of Si. These provide the typical

Table 2 Comparative study of first generation Solar PVC [CHECK7]

Material	Mono-crystalline	Poly-crystalline
Substrate thickness	160–240 µm [22]	160–240 µm [22]
Manufacturing process	Czochralski process float-zone Bridgman techniques	By metallurgical grade Si via a chemical purification process, called the Siemens process By pyrolysis method in which silane (SiH_4) is chemically decomposed at very high temperatures (580 to 650 °C) [24]
Max Absorption range	Indirect band gap Si-1.12 eV or 1107 nm (infrared spectrum of light) Crystalline silicon has a direct transition of 3.4 eV or 364 nm (blue spectrum of light) [23]	Depending upon crystallization structure
Efficiency in Lab [9]	27.6% [24]	23.4% [25]
Merits and demerits	Highest efficiency Material (Si) used for fabrication is abundant Highly standardized process for production Highly expensive Lot of Si wastage—as wafers are sawed from Si ingots	Less time for production Lower costs Material (Si) used for fabrication is abundant Highly standardized process for production Probability of defects is more Less efficient than mono-crystalline as recombination takes place at defect sites

performance range of 10–15% [31]. These cells use scarce elements which act as limiting factor in cost (Table 3). Materials used in thin film solar cells are:

- Cadmium Telluride(CdTe)
- Copper Indium Gallium Selenide(CIGS)
- Amorphous-Si (a-Si)
- Gallium Arsenide (GaAs)

3.2.1 Cadmium Telluride

In CdTe thin film solar PVC tellurium and cadmium are combined, to produce cadmium telluride (CdTe) and is predominant in thin film technology [32]. They are able to absorb large amount of light i.e. almost 90% of solar spectrum [32, 33]. They are cheap to produce but are less reliable than a-Si solar cell. Polycrystalline thin film CdTe is the leading material in the solar cell market [33]. The CdTe cells provide ideal band gap of 1.5 eV for good conversion efficiency. Although cadmium is a low toxic material but rarity of tellurium of which telluride is an anionic form is the key drawback in use of CdTe in solar industry [34, 35]. The CdTe solar PVC terrestrial cell recently have shown 21.0 ± 0.4% efficiency on aperture area of 1.0623 cm^2 as tested in Newport lab on August 2014 [36]. The CdTe terrestrial module (thin film) with 18.6 ± 0.4% efficiency on 7038.8 cm^2 aperture area was confirmed by NREL on April 2015 under the global AM 1.5 spectrums (1000 W/M^2) [37]. The temperature of the solar PVC module and single junction cell was optimized at 25 °C.

3.2.2 Copper Indium Gallium Selenide

The CIGS thin film solar PVC is a combination of copper, indium, gallium, selenide. These are manufactured by the deposition of thin layer of copper, indium, gallium and selenide on a glass substrate along with two electrodes. Sputtering, electrochemical coating, electron beam deposition are some of the processing techniques for CIGS because these materials have high sunlight absorption capacity [38]. CIGS provide long life with minimum degradation. The efficiency for CIGS solar cell is above 15% and a share 2% in overall PV market [38, 39]. It is among the most promising semiconductors materials in thin film technologies which provide high efficiency and low cost. Furthermore, CIGS thin film solar cells also provide excellent outdoor stability and power. Although it is less expensive and light weight but its poor indoor performance and emission of toxic material [40, 41] hinders its application in large scale in PV cell industry. The CIGS mini module terrestrial PVC have shown 18.7 ± 0.6% efficiency on total area of 15.892 cm^2 as tested in FhG-ISE lab on September 2013 [42]. The CIGS (Cd free) terrestrial module with 17.5 ± 0.5% efficiency on 808 cm^2 designated illuminated area was confirmed by AIST on June 2014 under the global AM 1.5 spectrum (1000 W/M^2) [43]. The temperature of the solar PVC module and single junction cell was optimized at 25 °C.

3.2.3 Amorphous Silicon

The two above mentioned thin film technologies CdTe and CIGS are chalcogenide-based thin films cells. They can be successfully fabricated in labs but still industry of PV

Table 3 Comparative study of second generation Solar PVC

	CdTe	CIGS	a-Si	GaAs	HJ
Material	Compound of Tellurium and cadmium	Compound of copper, indium, Gallium and Tin	Silicon	Compound of gallium and arsenide	Silicon
Layer thickness	1 Âμm [36]	Less than 1 micrometre [42]	0.2–0.5 micrometre [48]	0.1 micrometre [57]	165 micrometre [57]
Manufacturing process	Fast film deposition and evaporation methods [32–34]	Sputtering [38–40]	Sputtering or chemical vapour deposition [44, 45]	Epitaxial lift-off (ELO) [54–57]	Deposition of a-Si:H and/or μc-Si:H layers by PECVD process at a temperature below 250 °C
Max Absorption range	Direct band gap material with Photon absorption frequency 1.02–1.68 eV [37]	Direct band gap material with Photon absorption frequency 1.45 eV [39]	Indirect band gap material with Photon absorption frequency 1.1–1.7 eV [44]	Direct band gap material with Photon absorption frequency 1.42 eV [54]	Dependent on material
Efficiency in Lab	20–23% [39, 40]	17.5% [42, 43]	11–15% [48, 49]	28.8% [54]	26% [59]
Advantages and disadvantages	No Staebler-Wronski effect, stability is good Shortage of Cd and Te will be a problem for mass production Te and Cd are toxic and pose a problem for household applications	No Staebler-Wronski effect, stability is good Shortage of Sn and In will be a problem for mass production Cd buffer layer is toxic and is a problem for household applications	Staebler-Wronski effect and poor stability No shortage of silicon Absorption of light can be improved by using tandem cell structure	No Staebler-Wronski effect, stability is good High efficiency	Low cost and low temperature requirement

looks forward to silicon-based thin film cells as it shows less issues than their countervail thin film in terms of toxicity and humidity and low manufacturing yields [44].

Amorphous Silicon (a-Si) is a nontoxic material used in making of non-crystalline solar cell where atoms of silicon are randomly distributed within the structure. Catalytic Chemical Vapor Deposition (CVD), Plasma-Enhanced Chemical Vapour Deposition (PECVD), sputtering are some of the processing techniques [21] used for a-Si solar cell. An a-Si solar PVC is fabricated by using the continuous vapor deposition technique over a silicon substrate keeping temperature critically low and can be easily deposited on very large glass substrates (up to 5.7 m^2) making process cost effective [44–47]. These cells consist of p-i-n layers which degrade the cell performance when exposed to sunlight. In order to achieve better stability, thinner layers must be used. Ensuing its properties of light weight and flexibility there are many companies that have focused on development of a-Si modules which are apt product for flat and curved surfaces. The module efficiencies of a-Si module are in the range 4% to 10% [42]. Very small cells at laboratory level may reach PCE of 13.2% [45]. The a-Si microcrystalline solar PVC recently have shown 11.8 ± 0.3% efficiency on total area of 1.044 cm^2 as tested in AIST lab on October 2014 [46, 47].

The fabrication techniques employed to improve existing PCE of a-Si are:

- *Tandem Cells*: It employs combination of various layers of Si allotropes with a-Si layer resulting in multi-junction solar PVC. Further these tandem cells can be stacked with multi crystalline silicon (*μc-Si*) *or* proto-crystalline silicon (*pc-Si*) to yield better results. The a-Si tandem solar PVC recently have shown 12.3 ± 0.3% efficiency on total area of 14.322 cm^2 as tested in FSTI lab on September 2014 [48]

Using a-Si/μc-Si: As a solution to above mentioned stumbling blocks faced by thin film, tandem or multi-junction micromorph solar PVC has emerged as a panacea. Micromorph solar PVCs are based on a multi-junction architecture and incorporate two solar PVCs which are stacked on top of each other. While the thin a-Si top cell efficiently absorbs the blue light of solar spectrum, red and near-infrared light gets absorbed by the thicker microcrystalline silicon (μc-Si) bottom cell improving the overall cell's PCE [49]. Since the photoactive material in all layers is Si PECVD can be used; it result in the production of micromorph thin-films up to 1.4 m^2 [49].

Using a-Si/pc-Si: a-Si can also be stacked with pc-Si for tandem-cell. The use pc-Si layer with a low volume fraction of nano-crystalline Si is preferred for high V_{oc}. These types of silicon present dangling and twisted bonds, which results in deep defects (energy levels in the band gap) [50] as well as deformation of the valence and conduction bands (band tails) [50, 51].

- *Thin-film Polycrystalline Silicon (poly-Si) on glass*: This technology aims to blends the merits of bulk Si with thin-film devices considering glass as the base resulting in low cost high quality photovoltaic material. The fabrication methodology with electron beam evaporation is used as a deposition technique which is cheaper than PECVD [52] to produce these modules. The electron beam deposition technique results in non-conformal uneven surface deposition due to which textured substrate becomes a necessity and is not an easy task. The methodology involves deposition of antireflection coating (reducing light reflection from the solar PVC) and doped Si onto textured glass substrates (e.g.: patterned Indium tin oxide). The texturing of the glass increases the light trapping thereby effectively enhancing the PCE of the solar PVC [53]. Another reason for low cost poly-Si solar modules is the absence of a Transparent Conducting Oxide (TCO) layer. Its absence not only benefits the production process as it is bypassed, but the absence of this layer enhances the contact mechanism making direct contacts. Not with standing with the advantages, poly-Si has still lot of scope for research in this field.

3.2.4 Gallium Arsenide Thin Film PVCs

The other photoactive semiconductor alternative for single-crystalline thin film solar PVC is gallium arsenide (GaAs). This single junction solar PVC device has a record efficiency of 28.8% but with the drawback of high cost [54]. GaAs based solar PVC possess n (emitter)-on-p (base) or p-on-n structural organization. The later faces low PCE in comparison to former; as in case of n on p fabrication electron penetrates deep resulting in low recombination rate and high diffusion length as it goes through p-type base region whereas p on n endure low diffusion length [54–57]. The fabrication cost is the hindrance in fabrication of n on p Ga As solar PVC. GaAs based multi-junction solar PVC modules have wide area of applications like spacecraft's and concentrator photovoltaic. Most common solar PVC configuration used solar panels on spacecraft's is (InGaP/(In)GaAs/Ge cells) with high PCE and cost [61]. Their application in concentrator photovoltaics' (GaAs concentrator solar cell), uses lenses to focus solar radiations and reduces cost. The GaAs thin film solar PVC have shown 28.8 ± 0.9% efficiency on aperture area of 0.9927 cm^2 as tested in NREL lab on May 2012 [57].

3.2.5 Heterojunction (HJ) Solar PVCs

The wafer based crystalline solar PVC has influenced PV market from 2008 featuring good efficiency and long life time. However, expensive wafers and high temperature requirement remains the main stumbling block for wafer-based c-Si solar PVCs. As a solution to the aforementioned predicaments HJ solar PVC has proved to be a promising low cost, low temperature and low material consumption solution. The output efficiency reported of heterojunction solar cell at industrial production level is above 20% [58]. Some researchers have claimed output efficiency over 26% designated area of 180.4 cm^2 []. The explication in output yield is due to highly recombination active metal contacts and diffused junction cells that are electronically isolated from absorber with the insertion of wider bandgap material layer. This enhances open circuit voltage in the heterojunction devices without employing any patterning technique.

In order to provide effective light trapping this technique employs random patterning of n-type c-Si wafer. The passivation steps involve deposition of a-Si:H on both sides of c-Si wafer, with deposition of P-type a-Si:H as emitter on one side and n-type a-Si:H on the other side to form the Back-Surface Field (BSF). To improve the carrier transport to the contacts in a cell TCO layer is added [59]. The fabrication steps involve deposition of a-Si:H and/or µc-Si:H layers in a PECVD (plasma enhanced chemical vapor deposition) process at a temperature below 250 °C [58–60].

In consideration of the second generation solar PVCs which aims at low material consumption excessive use of Si wafers is avoided. This reduces production costs of these types of solar PVCs in comparison to the first generation. However, the industry still rely on first generation as the production of second generation solar PVCs still include vacuum processes and high temperature treatments, which results in large energy consumption. Further, the second thin film generation solar PVCs are based on scarce elements which limit its usage in terms of cost. These drawbacks led to the introduction of third generation of cell.

3.3 Third Generation Photovoltaic Cells: Emerging Thin Films

The evolution of third-generation solar cells was a great development in this field as they came up with a drastically high efficiency when compared with the second generation solar PVC's. This generation solar PVC's provide an alternative to its countervail made up of p–n junctions and thin cells respectively as these cells surpass the Shockley Queisser limit of 33.7% PCE [9] for single band-gap solar PVCs. This solar generation uses organic materials such as small molecules or polymers as photoactive material and also includes highly efficient and expensive multi-junction solar PVCs. Their high production cost limits its commercial application. Polymer solar cells or plastic solar cells, has emerged as a simple, quick and inexpensive large-scale organic option; as the use of polymer photoactive materials makes it readily available and potentially inexpensive. In comparison to first and second generation the third generation solar PVCs usage is limited; but researchers believe in its great potential and more devices are still in progress.

An a-Si or GaAs contribute as the layers of the multi-layered structure of common third-generation systems; many researchers have proposed frequency conversion in solar cell. The wavelength conversion enables usage of light that the solar cell cannot absorb to light spectra that it can utilize, these results in more output power. The use of hot-carrier effects and other multiple-carrier ejection techniques are also used to enhance PCE.

Emerging third generation Solar PVC includes:

- Copper zinc tin sulfide solar PVC (CZTS), and derivate CZTSe and CZTSSe
- Dye-sensitized solar PVC, also known as "Grätzel cell"
- Organic solar PVC

3.3.1 Copper Zinc Tin Sulfide (CZTS)

CZTS are basically thin film based solar cells. The other thin film solar PVC's GaAs and CdTe contain toxic elements (cadmium and arsenic) and CIGS system contains rare indium elements. Thus, these two types of solar cells cannot meet the future commercialization aspects. CZTS is the direct band gap photoactive material with a high absorption coefficient and a multilayer structure; thus, it can be employed in the absorption layer of thin film solar cells and it provides a band gap of 1.50 eV which is very close to the best band gap required by semiconductors devices which is 1.35 eV [60, 61]. CZTS is expected to become the ideal absorption layer [61] material of next generation thin film solar PVCs due to its abundant component elements in the earth crust, nontoxic and environmentally friendly properties which are not exhibited by CdTe and CIGS if compared.

In 1977, the Cu_2CdSnS_4 based monocrystalline solar cells were successfully fabricated and reached the efficiency of 1.6% in Bell Lab [61]. Ito and Nakazawa in Japan Shinshu University utilized the synthesized Cu_2CdSnS_4 monocrystal to achieve V_{oc} of 165 mV in 1988 [62, 63]. In 1997, Katagiri et al. synthesized p-type conductivity with a band gap of 1.45 eV and the absorption coefficient over 10^4 cm^{-1} and obtained the conversion efficiency of 0.66% [63]. However, the existence range of single-phase based CZTS is small and quaternary synthesis is difficult, so it is no new breakthrough for quite a long time, such as the band structure, defect type, and so on. It is still under investigation. The CZTS solar PVC terrestrial cell recently have shown 7.6 ± 0.1% efficiency on aperture area of 1.067 cm^2 as tested in NREL on April 2016 [64]. The temperature of the solar PVC module and single junction cell was optimized at 25 °C.

3.3.2 Dye Sensitized Solar Cell

Dye Sensitized Solar Cells (DSSC), are categorized in third generation thin film based solar PVC. DSSC provide a very good alternative to the present p–n junction based solar cells both technically and economically [65]. The special feature of these solar PVC's which make them different from the conventional ones is that both the task of light absorption and charge carrier transport the two functions are separated here. Main constituents of DSSC device are:

- Semiconductor electrode n-type TiO_2 and p-type NiO.
- Dye sensitizer (organic dye molecule), which is sandwiched between the electrodes.
- Redox mediator
- A counter electrode

As broad band-gap photo-voltaic material is used wide range of solar spectra get absorbed by the sensitizer. With the harvesting of photons the separation of low charge mobility carriers at interface is accomplished using light-induced electron injection mechanism from the dye into the conduction band to collector of the semiconductor. In contrast with conventional PV architecture design that uses solid-state photo-voltaic for exciton generation and electricity conversion, DSSCs uses electrolyte solution for transporting ions to metal electrodes (viz. platinum) [66]. The fringe benefit of sensitizers (viz. ruthenium compounds) comprising absorption of wide spectrum band in concomitance with transparent conducting oxide films (viz. titanium oxide films-nanoporus) of nano-crystalline results in high absorption coefficient. DSSC cover quantitative conversion of incident power radiation into electricity over a large spectral range extending from the UV to the near IR region. DSSC has achieved over 10% of conversion efficiency in AM1.5 with high flexibility, low price and easy assembling [65–67]. There are good prospects to produce these cells at lower cost than conventional solar PVCs. The drawback which they face is the reliability factor as degradation occurs at high temperatures [36–40]. The Dye sensitized PVC terrestrial cell recently have shown 11.9 ± 0.4% efficiency on aperture area of 1.005 cm^2 as tested in AIST on September 2012 [67]. The Dye sensitized terrestrial mini module with 10.7 ± 0.4% efficiency on 26.55 cm^2 designated illuminated area was confirmed by AIST on Feb 2015 under the global AM 1.5 spectrum (1000 W/M^2) [67]. The temperature of the solar PVC module and single junction cell was optimized at 25 °C.

3.3.3 Organic Solar PVC (OSC)

An OSC or plastic solar PVC is made up of the polymers or the organic materials. Polymers are basically long chained organic compounds which have carbon as their main components. Conductive polymers which absorb the light and convert it into electrical energy are used for making these types of solar cells [68]. Advantage of organic solar PVC is that they are flexible and they can be customized in terms of band gap as it can be changed by molecular engineering i.e. changing length and the functional group of the polymers. The harvesting of photons in OSC's is high due to better optical absorption coefficient, so wide range of solar spectra can be absorbed with a little amount of photovoltaic material (usually in nano-meters scale). The key challenges that cognate with OSC's are low output efficiency, high degradation factor and low strength in analogy with Si based solar PVC [69]. The OSC terrestrial cell have shown 11.2 ± 0.3% efficiency on designated illuminated area of 0.922 cm^2 as tested in AIST lab in 2015 [70]. The OSC mini module with 9.7 ± 0.3% efficiency on 26.14 cm^2 designated illuminated area was confirmed AIST lab in 2015 under the global AM 1.5 spectrums (1000 W/M^2) [70]. The temperature of the solar PVC module and single junction cell was optimized at 25 °C.

In comparison to Si based PVCs, OSC are less costly to fabricate, lightweight and environmental friendly. But the major drawback is less efficiency i.e. 1/3 of the hard material efficiency [70]. The complete comparison of third generation is shown in Table 4.

3.4 Fourth Generation Solar PVC

The technical exigency globally with variegated applications has become a key challenge impacting R&D work toward the evolution of substitute solar PVC technologies called "fourth-gen". Heretofore, most of the effort on fourth generation solar PVC's is a part of research in the laboratory and still far from industry approach. The fourth generation of solar cell employs two enlisted mechanism:

- Quantum Dots
- Concentrated solar cells

3.4.1 Quantum Dots: Nano-crystal Based Solar PVCs

Quantum dots (QD) solar PVCs are recognized as nano-crystal solar PVCs as they are made up of nano-crystal range of transition metal groups called quantum dots and are a promising technology. The solution-processed QD's play a key role in high and efficient absorption of solar spectra. The Nano-crystals are first mixed into anise bath and then coated over the Si substrate [71]. QD has the capability to

Table 4 Comparative study of third generation Solar PVC

	DSSC	OPV	CZTS
Material	Nano-crystals [65]	Polymer or organic materials like graphene [68]	Copper Zinc Tin Sulfide
Current Cell efficiency	High efficiency—single junction cells > 12% efficiency, and tandem cells > 12% efficiency (liquid BHJ design) [66, 67]	Low efficiencies—Single layer about 9.7% efficiency [70]	CZTS solar PVC with a 7.6% PCE [64]
Manufacturing/Cost	Conventional roll-printing techniques/Offers the lowest cost of all printed solar cells and short energy payback time < 1 year [67]	Roll-to-roll printing and deposition methods/Low cost fabrication for large area devices [69]	Vacuum and non-vacuum techniques. Use of alloys like (Zn and SnS) that evaporates undergoing while fabrication and is a challenge/High-price manufacturing process involved [63]
Merits and Demerits	Non-silicon based technology—sheltered from silicon supply and prising issues Lightweight, flexible, transparent and colouring options Maintains efficiency in low light—Indoor and outdoor. Enable R2R standard printing Uniform output over a range of light levels Commercially available during 2009 from G24 Innovations for low power small application and later for large area roofing applications from Corus Group and Pecell Technologies Degradation has been observed in lab when exposed to UV rays and heat, PVC sheathing is strenuous to seal due to solvents and corrosion	Non-silicon based technology—sheltered from silicon supply and prising issues Lightweight, flexible, transparent and colouring options Maintains efficiency in low light—Indoor and outdoor. Enable R2R standard printing Enabler for applications where mechanical flexibility and disposability are valued Commercially available only from 3G solar, Konarka Technologies, Plextronics and solarmer Material instability over the long term, making it unsuitable for roof applications	It proffers to reduce the material gridlocks found in CIGS It is non-toxic Non-silicon based technology—sheltered from silicon supply and prising issues Material cost and availableness are key challenges faced

tune bad-gap with change in QD size hence modulating the absorption of solar spectra. QD solar PVC have shown continuous up gradation, with a lab record solar PVC efficiency of 9.2% [72]. These solar PVC's are cheaper to manufacture and have lot of potential in research and practical applications. But QD intrinsic disorder impedes its commercial usage as it not only impacts on carrier mobility but also decreases V_{oc}.

3.4.2 Concentrated Solar PVCs (CSC)

Lots of research and development in the field of solar PVC's has come up with the most recent technology which is CSC. This works on the principle of optics where a high amount of solar energy is concerted over a compact cell area with the help of lens arrangement. Depending upon the power of the lens CSC is classified as low, medium and high solar PVCs. These solar cells have various advantages such as no thermal mass, no prompt reaction and are available in wide range of sizes. The lab conversion efficiency of this solar PVC is claimed more than 40% [73]. These cells provide stable and high energy output throughout the day. These can be implemented in smaller areas and lot of accuracy and stability is required for their installation. The chances of optical losses are major drawback it faces [73, 74].

This new generation of solar cells exploits usage of various new materials besides Si, and includes nano carbon tubes, Si wires and solar inks using organic dyes and conductive plastics conventional printing press technologies [75].

The ultimate aim of research in this fields is to enhance on the solar PVCs efficiency already commercially accessible, to develop new technology—basically by making solar energy conversion more effective over a wider band of solar energy (e.g. including infrared), economically good so it can be used by more and more people, and to develop more and different applications [76].

At present, the research work on third and fourth generation solar cells is still a work in laboratory and is not commercially available. The next section gives an overview on latest recent advances and developments in field of Solar PVC.

4 Performance Metrics

The performance metrics are the parameters that are used to evaluate and compare the performance of the device. In this paper the evaluation and comparison generation wise is done on following performance metrics:

- Efficiency
- Cost
- Environmental Impact
- Material Complexity

4.1 Efficiency

Solar PVC conversion efficiency is the most important performance metrics. It refers to how much portion of energy incident on cell form the sunlight can be transformed via photovoltaic into electricity. The efficiency of the solar PVCs, in combination with temperature, pollution, latitude and climate determines the annual energy output of the photo-voltaic system. With sunlight impinging from the zenith on a sunny day, a surface perpendicular to the light receives about 1 kW/m^2. When converted by a solar cell of 10% efficiency, 100 W/m^2 electrical energy can be harvested. The greater the PCE of solar cell, lesser surface area will be entailed to meet solar panels energy requirements.

4.2 Cost

While the solar cell market has shown healthy growth of > 20%, the cost of solar cell energy is still considerably higher than other forms of energy. Polysilicon is still the key raw photovoltaic material used by industry to make silicon wafers. This material rational 30% or more to the overall PVC cost and so it has been pegged as a major cost contributor to the overall solar PV manufacturing market. If the overall cost of solar PVC is considered the total wafer cost more than 60%. The research development of non-Si-based solar PV photovoltaic materials has changed the PV landscape entirely, offering exciting near-term cost reductions for material systems.

4.3 Environment Impact

The fabrication of solar panels enmesh use of electricity and water which results in emission of greenhouse gasses and leads to global warming. As many caustic chemical viz. sodium hydroxide and hydrofluoric acid are also used in fabrication of solar panels which creates waste. These predicaments have lot of environmental impact and also undercut solar PVC ability to fight climate change and reduction in environmental toxics.

4.4 Material Complexity (Structure)

The material complexity here is referred to the degree of disorder in a photoactive material used in solar PVC. It is an important parameter to evaluate performance metrics as cell efficiency varies inversely with complexity. The maximum efficiency can be achieved with minimum material complexity. Therefore c-Si based solar PVC has better efficiency that a-Si as amorphous materials atomic positions are not defined whereas it is less defined in polycrystalline films and are well defined in crystals. This results in more complex structure for a-Si solar PVC than their crystalline correlatives.

5 Results

The indicators to clinch on the performance evaluation for solar PVC as mentioned in Sect. 4 are efficiency, cost, environmental impact and material complexity. The research data considered for comparisons of these metrics in this review is taken from various sources, such as research papers, business journals and industry associations. The complete effort is made to corroborate the data enlisted, which is comparable as it is considered for same system boundary.

5.1 Efficiency

The efficiency metrics evaluation of solar PVC (Fig. 5) measures a panel's ability to convert the sunlight directly into DC electricity. The higher will be the efficiency, lesser will be the area needed to generate a given amount of electricity. The efficiency of panel will judge the physical size of the system to be build making it an important criterion. With an angle of environmental impact also, the more efficient the panels will be, there will be less manufacturing waste. The C-Si based solar PVC technology with the lab record PCE of 27% has no subdue in terms of reliability and life span. Undoubtedly the PCE of emerging nanomaterial-based thin film technologies in many research papers have claimed lab records < 30%. Another advantage being that the deposition of nano-photovoltaic materials instead on conventional option glass has the proficiency to be deposited on plastic, paper or any other flexible alternative. This property avoids the use of heavy piece of glass for mechanical support. The property of engineering these complex nano-photoactive materials for maximum solar spectra absorption with nano scale orders for magnitude of material make them a competitive with Si solar cells but durability of this emerging technology is still in research frame.

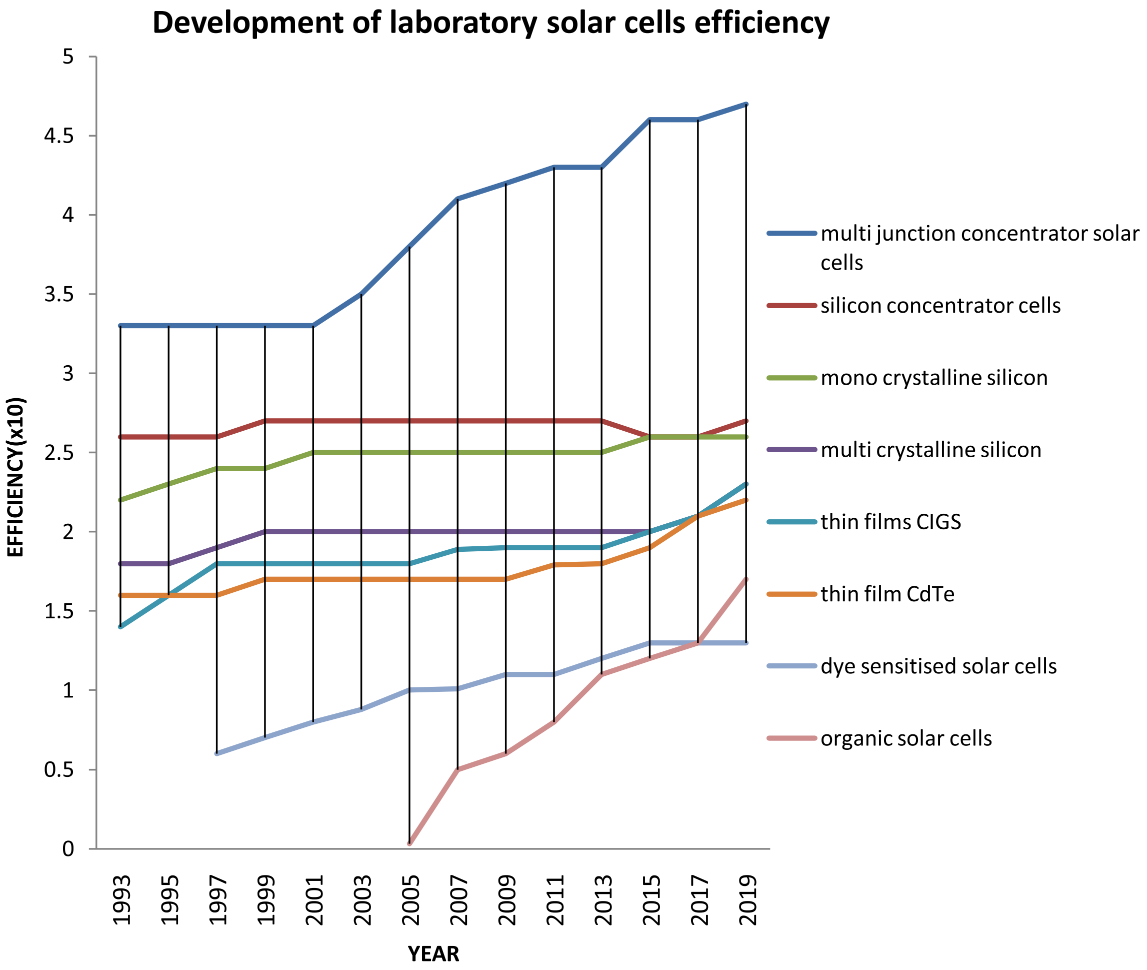

Fig. 5 Graph representing development of Solar PVC in terms of efficiency [77]

5.2 Cost

The capitalized cost of Solar PVC can be defined on the equivalent present value of the system lasting for n years irrespective of any other damage consideration. The Fig. 6 delineates the comparison of three generations of solar PVC in terms of cost/Watt. The first generation solar PVC rely on high-price Si wafers and cover > 90% of the present commercial solar market. As such material complexity of Si as a photovoltaic material is simple but it's processing in transforming it into wafers is not only complex but is high-budgeted too. The nano-photovoltaic material makes the process less energy intensive, easier and cheaper. Therefore, second-generation cells are based on thin films of materials such as a-Si, mono-crystalline Si, CdTe or CIGS. Third-generation cells are emerging research goals and there is rapid increase in the cell PCE yet cost remains a main hurdle as the processing techniques are quite expensive.

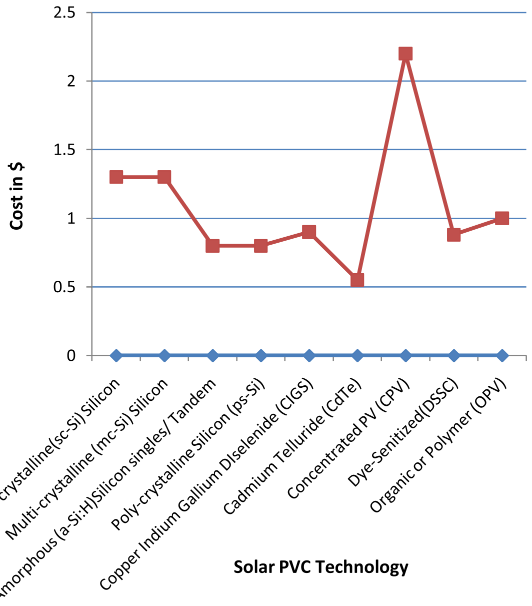

Fig. 6 Graph representing development of Solar PVC in terms of cost [78]

5.2.1 Environment Impact

Solar PVC technologies have, in general, lesser negative environmental impacts in comparison to non-renewable resourses viz. conventional electricity production powered by fossil fuels. At present, most of the solar PV manufacturers meet or even exceed protocols set globally for handling and alleviating hazardous materials [79]. Solar PVC manufacturing companies use small amounts of heavy metals and other chemicals such as cadmium and lead for production of PVC, toxic gases used in production of c-Si are made environment friendly before releasing. Table 5 gives a brief on toxic gases produced during manufacturing of PVC and its effect on human body.

5.3 PV Technology Classification Based on Material Complexity

The PV technology can also be classified on the basis of photovoltaic material complexity employed. Figure 7 shows the arrangement in terms of material complexity employed starting from wafer based technology which utilizes single

Table 5 Representation of different Solar PVC materials used in photovoltaic cell on the basis of intoxicating materials or substances that can harm environment [79]

Solar PVC materials	Environmentally friendly	Toxic gases produced [77]	Hazards
C-Si	No	Silicon dust called kerf Trichlorosilane ($HSiCl_3$) Toxic phosphine (PH_3)	Respiratory Problem Headache, nausea, vomiting, diarrhea and abdominal pain Serious exposure to these gases may cause shock, convulsions, coma, irregular heartbeat, and liver and kidney damage
Poly-crystalline	No	Chloro-Silanes	Bad effect on eyes
a-Si	No	Diborane	Get mixed with air forming explosive mixtures
CdTe	No	Cadmium compounds	It affects the kidneys and bones
CIGS	No	Hydrogen sulfide Hydrogen selenide	The effects of hydrogen sulfide depend on the amount you breathe in and for how long. Exposure to very high concentrations of this gas can lead to death in no time It can irritate the lungs causing coughing and/or shortness of breath
Polymer Solar PVC	Yes	–	–
Dye Sensitized Solar PVC	Yes	–	–
Nano crystal Solar PVC	Yes	–	–
Concentrated Solar PVC	Yes	–	–

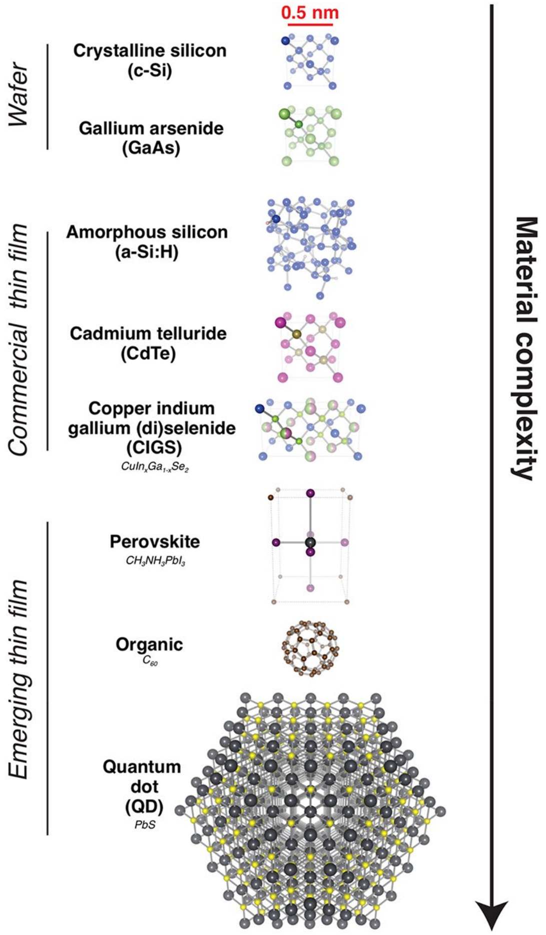

Fig. 7 Material complexity of various materials in solar PVC [80]

or few atoms building blocks to complex thin-film technologies. These emerging thin film technologies are then arranged in order of increasing complexity, ranging from amorphous elemental materials such as a-Si, through polycrystalline thin films such as CdTe, to complex nanomaterials such as quantum dots, which contain thousands of lead and sulphur atoms [80].

6 Future Expectation

The renewable, low-carbon energy option that can escalate and fulfil global energy demand is Solar Energy. At present c-Si based Solar PVC are considered to be the most reliable and business-like choice. But the fabrication process of these cells is highly complex and need of thick Si wafer (for high intrinsic light absorption) leads to a rigid and heavy weight glass-enclosed c-Si modules contributing to higher cost. There is lot of research going on to enhance solar PVC output efficiency either by (i) working on outdoor practical issues [78, 79] or by (ii) developing a novel Solar PVC technology based on nano-materials; which can prove itself to be easier, cheaper and efficient solution.

These nanomaterial based design will have unique attributes like lightweight, ultra-thin, transparent and much more that will open up doors for new applications [80]. The advancement in research leads to the pragmatic use of new technologies resulting in improvement in PCE or reducing the cost of current devices capitalizing on existing manufacturing plant and proven mass-production capacity. Recent trends have exhibited better revolutionary solution that might result in new device concepts viz. DSSC and polymer based solar PVCs (including organic/inorganic hybrids). Undeniably these new emerging solar PVC have shown promising outcomes but none has succeeded in out paring c-Si solar PVC in cost or efficiency, but there is every chance that these devices might still demonstrate step-change improvements or those new types of device may yet emerge. Advancement in solar PVC is Quantum Dot Solar PVC in which the absorbing photovoltaic material used is quantum dot. These photoactive materials will supplant conventional bulk materials such as Si, CIGS or CdTe with quantum dots. The advantage of using this concept is that with change in the size of quantum dots, the band-gap can be easily modulated across a wide range of energy levels and hence resulting in increase in wider solar spectrum absorption [81–83]. This makes modulation of the band-gap with quantum dots propitious for solar PVCs.

There is lot of development in defining new materials for Solar PVC. The perovskite solar cell has a potential to expeditiously capture the market. But one of the biggest disadvantages it faces when compared to its countervail Si based solar PVCs is stability and their relatively short lifespan [84, 85]. A pervasive problem that research in lab beset is its inability to scale up experiments compatible for use in industry. As such it is not difficult to make perovskite films on a small scale in the research laboratory, but it is arduous to replicate the same on the large scale needed for mass production.

7 Conclusion

Solar PVC is a low-carbon photovoltaic technology which is not only scalable but technical matured too and has a potential to meet global energy demands. It has a competence to generate electricity at terawatt scale with the viable strategy to extenuate climate change peril. The creative residential and commercial business models, furtherance in conversion efficiency and reduce cost in photo-voltaic technology have resulted in the credible rise in installation of solar panels. This paper compare various technologies used in solar PVC's from generation to generation on the basis

Table 6 Overall comparison table of different materials [24, 25, 34, 43, 49, 57, 64, 67, 70, 72, 73, 77, 78]

Technology	Units	1st Generation		2nd Generation				3rd Generation			4th Generation	
		Single or Mono-crystalline(c-Si) Silicon	Multi-crystalline (mc-Si) Silicon	Amorphous (a-Si:H) Silicon singles/Tandem	Poly-crystalline Silicon (ps-Si)	Copper indium gallium selenide (CIGS)	Cadmium telluride (CdTe)	III-V Compound multi-junction, concentrated PV (CPV)	Dye-sensitized (DSSC)	Organic or polymer (OPV)	Quantum dot	Perovskite
Best research solar cell efficiency	%	26.33	21.3	10.5/13.6	11.0	22.6	22.1	46.0	11.9	11.5	11.3	22.1
Confirmed solar cell efficiency	%	20–26	14–20	6–9	9.0–11.0	10–16	8–11	38–43	8–11	6–10	1–9	5–17
Commercial PV module efficiency	%	16–21	13–15	8–11	9.0–10.5	14–16	8–11	26–32	5–10	2–4	–	–
Confirmed maximum PV module efficiency	%	24.4	19.9	7.2/10.0	10.5	18.7	11.2	38.9	10.7	9.7	–	12.1
Current PV module cost	$/W	<1.3	<1.3	~0.8	~0.8	~0.9	~0.55	~2.2	0.88	~1.0	–	–
Market share in 2016	%	35%	55%	2	1	2	5	–	–	–	–	–
Maximum PV module output power	W_p	320	320	300	120	120	120	120	–	–	–	–
PV module size	m^2	2.0	1.4–2.5	1.4	1.0	0.6–1.0	0.72	–	–	–	–	–
Status of commercialisation		Mature/Large Scale Production	Mature/Large Scale Production	Medium Scale Production	Medium Scale Production	Medium Scale Production	Medium Scale Production	Small Scale Production	R&D Phase	R&D Phase	R&D Phase	R&D Phase
Cost per watt per efficiency	$/kWh	0.060	0.087	0.112/0.080	0.076	0.074	0.049	0.060	0.10	0.10		

of performance metrics of efficiency, cost, environmental impact and material complexity.

The generations report various Solar PVC technologies on the basis of photovoltaic material employed to absorb solar spectra and collect electric charge. These materials in this paper are categorized into three general categories (i) Wafer-based solar PVC which includes traditional c-Si (ii) commercial thin-film solar PVCs which includes a-Si (non-crystalline silicon), CdTe, and CIGS (iii) emerging thin-film technologies which includes quantum dots, organic and concentrated solar PVCs. This study deduces that still lot of focused effort needs to be made in terms of better PCE, reducing manufacturing complexity, decreasing material thickness and cost for which research work should continue on all the technologies. The prediction on how these technologies will evolve is inexpedient; as for now none covenants to be best on all three measures. For example, if emerging thin film technologies are considered and find application in windows or mobile phone displays or curtains, to cover the demand manufacturers will need to work through production issues, resulting in lower-cost and larger-scale production in the future. Table 6 shows an overall comparison of all the materials generation wise. Advancement on these generations will not only confer in reduction of greenhouse-gas emissions but will also aid in providing electricity to the areas which are still deprived of light. Howbeit, more research progress and contribution are required to strengthen a substantial rise in the solar PVC at industry acceptable PCE and price.

References

1. A. Damiano, G. Gatto, I. Marongiu, M. Porru, A. Serpi, Real-time control strategy of energy storage systems for renewable energy sources exploitation. IEEE Trans. Sustain. Energy **5**(2), 567–576 (2014)
2. J. Yi, P.F. Lyon, P.J. Davison, P. Wang, P.C. Taylor, Robust scheduling scheme for energy storage to facilitate high penetration of renewables. IEEE Trans. Sustain. Energy **7**(2), 797–807 (2016)
3. U. Wurfel, A. Cuevas, P. Wurfel, Charge carrier separation in solar cells. IEEE J. Photovolt. **5**(1), 461–469 (2015)
4. J.C. Pla et al., Short circuit current vs cell thickness in solar cells under rear illumination: a direct evaluation of the diffusion length. J. Solid-State Electron. **44**(4), 719–724 (2000)
5. R. Chawla, P. Singhal, A.K. Garg, Design and analysis of multi junction solar photovoltaic cell with graphene as an intermediate layer. J. Nanosci. Nanotechnol. **20**(6), 3693–3702 (2020)
6. R. Chawla, P. Singhal, A.K. Garg, Performance comparison of Si and InGaN p-n junction Solar Cell. Int. J. Sci. Eng. Res. **8**(4), 176–181 (2017)
7. G.L. Araújo, A. Martí, Absolute limiting efficiencies for photovoltaic energy conversion. Sol. Energ. Mater. Sol. C **33**, 213–240 (1994)
8. J.J. Loferski, Theoretical considerations governing the choice of the optimum semiconductor for photovoltaic solar energy conversion. J. Appl. Phys. **27**, 777–784 (1956)
9. W. Shockley, The theory of p–n junctions in semiconductors and p–n junction transistors. Bell Syst. Technol. J. **28**, 435–489 (1949)
10. S. Ruhle et al., Tabulated values of the Shockley–Queisser limit for single junction solar cells. J. Solar Energy **130**, 139–147 (2016)
11. M.A. Green, Radiative efficiency of state-of-the-art photovoltaic cells. Prog. Photovolt. **20**, 472–476 (2012)
12. M.A. Green, K. Emery, Y. Hishikawa, W. Warta, E.D. Dunlop, Solar cell efficiency tables (version 47). Prog. Photovolt. **24**, 3–11 (2016)
13. A. Richter, M. Hermle, W. Glunz, Reassessment of the limiting efficiency for crystalline silicon solar cells. IEEE J. Photovol. **3**, 1184–1191 (2013)
14. J. Mattheis, J.H. Werner, U. Rau, Finite mobility effects on the radiative efficiency limit of pn-junction solar cells'. Phys. Rev. B **77**, 085203 (2008)
15. M.Y. Levy, C.B. Honsberg, Rapid and precise calculations of energy and particle flux for detailed-balance photovoltaic applications. J. Solid-State Electron. **50**, 1400–1405 (2006)
16. M.A. Green, S.P. Bremner, Energy conversion approaches and materials for high-efficiency photovoltaics. J. Nat. Mater. **16**, 23–34 (2016)
17. A.K. Shukla, K. Sudhakar, P. Baredar, Recent advancement in BIPV product technologies: a review. Energy Build. **140**, 188–195 (2017). https://doi.org/10.1016/j.enbuild.2017
18. R.M. Swanson, Approaching the 29% limit efficiency of silicon solar cells, in *Conference Record of the Thirty-first IEEE Photovoltaic Specialists Conference*, pp. 889–94 (2005)
19. Article-"The new silicon valley – Polysilicon". 2 February 2015. Archived from the original on 30 April 2015
20. M.A. Green, A.W. Blakers, J. Shi, E.M. Keller, S.R. Wenham, 19.1% efficient silicon solar cell. Appl. Phys. Lett. **44**(12), 1163–1164 (1984)
21. Crystalline Silicon PV Market by Type (Mono-Crystalline and Multi-Crystalline) and End-User (Residential and Commercial, Utility-Scale) - Global Opportunity Analysis and Industry Forecasts 2014–2022
22. D.D. Smith, P. Cousins, S. Westerberg, R. De Jesus-Tabajonda, G. Aniero, and Y.-C. Shen, Toward the practical limits of silicon solar cells, in *40th IEEE Photovoltaic Specialists Conference*, pp. 1465–1469 (2014)
23. M.A. Green, K. Emery, Y. Hishikawa, W. Warta, E.D. Dunlop, Solar cell efficiency tables (Version38). J. Prog. Photovolt. Res. Appl. **19**(5), 84–92 (2011)
24. B.M. Kayes et al., 27.6% Conversion efficiency, a new record for single-junction solar cells under 1 sun illumination, in *2011 37th IEEE Photovoltaic Specialists Conference (PVSC)*, pp. 4–8 (2011)
25. M.A. Green, K. Emery, Y. Hishikawa, W. Warta, E.D. Dunlop, Solar cell efficiency tables (Version 49). J. Prog. Photovolt. Res. Appl. **25**(1), 3–13 (2017)
26. H. Park, Y. Lee, J. Park et al., Front and back TCO research review of a-Si/c-Si heterojunction with intrinsic thin layer (HIT) solar cell. Trans. Electr. Electron. Mater. **19**, 165–172 (2018)
27. S. Zhang, X. Pan, H. Jiao, W. Deng, J. Xu, Y. Chen, P.P. Altermatt, Z. Feng, P.J. Verlinden, 335 watt world record p-type monocrystalline module with 20.6% efficient PERC solar cells. IEEE J. Photovoltaics (to be published)
28. A.W. Blakers, A. Wang, A.M. Milne, J. Zhao, M.A. Green, 22.8% efficient silicon solar cell. Appl. Phys. Lett. **55**, 1363–1365 (1989)
29. J. Zhao, A. Wang, M.J. Keevers, M.A. Green, High efficiency PERT cells on SEH p-type Si substrates and PERT cells on SHE n-type Si substrates (2000)
30. M.A. Green, The passivated emitter and rear cell (PERC): from conception to mass production. Sol. Energy Mater. Sol. Cells **143**, 190–197 (2015)

31. J. Jean, P.R. Brown, R.L. Jaffe, T. Buonassisi, V. Bulović, Pathways for solar photovoltaics. Energy Environ. Sci. **8**, 1200–1219 (2015)
32. R.M. Geisthardt, M. Topic, J.R. Sites, Status and potential of CdTe solar-cell efficiency. IEEE J. Photovolt. **5**(4), 1217–1221 (2015)
33. N.R. Paudel, K.A. Wieland, A.D. Compaan, Ultrathin CdS/CdTe solar cells by sputtering. Sol. Energy Mat. Sol. C **105**, 109–112 (2012)
34. J.L. Peñaa, O. Arésa, V. Rejóna, A. Rios-Floresa, J.M. Camachoa, N. Romeob, A. Bosiob, A detailed study of the series resistance effect on CdS/CdTe solar cells with Cu/Mo back contact. Thin Solid Films **520**(2), 680–683 (2011)
35. E. Colegrove, R. Banai, C. Blissett, C. Buurma, J. Ellsworth, M. Morley, S. Barnes et al., High-efficiency polycrystalline CdS/CdTe solar cells on buffered commercial TCO-coated glass. J. Electron. Mater. **41**(10), 2833–2837 (2012)
36. First solar press release, First Solar builds the highest efficiency thin film PV cell on record, 5 August 2014
37. First solar press release. First Solar achieves world record 18.6% thin film module conversion efficiency, 15 June 2015
38. M. Topic, R. Geisthardt, J.R. Sites, Performance limits and status of ˇ single-junction solar cells with emphasis on CIGS. IEEE J. Photovolt. **5**(1), 360–365 (2015)
39. J. Ramanujam, U.P. Singh, Copper indium gallium selenide based solar cells—a review. Energy Environ. Sci. **10**(6), 1306–1319 (2017)
40. ZSW takes CIGS thin film cell to 22% conversion efficiency, https://www.pv-tech.org
41. P. Jackson, D. Hariskos, E. Lotter, S. Paetel, R. Wuerz, R. Menner, W. Wischmann, M. Powalla, New world record efficiency for Cu(In, Ga)Se2 thin-film solar cells beyond 20%. Prog. Photovolt Res. Appl. **19**, 894–897 (2011)
42. E. Wallin, U. Malm, T. Jarmar, O. Lundberg, M. Edoff, L. Stolt, World-record Cu(In, Ga)Se2-based thin-film sub-module with 17.4% efficiency. Prog. Photovolt. Res. Appl. **20**, 851–854 (2012)
43. H. Sugimoto, High efficiency and large volume production of CIS-based modules, in *40th IEEE Photovoltaic Specialists Conference*, Denver, June 2014
44. M. Faryad, A. Lakhtakia, Enhancement of light absorption efficiency of amorphous-silicon thin-film tandem solar cell due to multiple surface-plasmon-polariton waves in the near-infrared spectral regime. J. Opt. Eng. **52**(8), 087106 (2013)
45. L. Fang, S.J. Baik, S. Lim, S. Yoo, K.S. Lim, Amorphous Si rear Schottky junction solar cell with a LiF/Al back electrode. IEEE Trans. Electron. Devices **58**(9), 3048–3052 (2011)
46. T. Matsui, H. Sai, T. Suezaki, M. Matsumoto, K. Saito, I. Yoshida, M. Kondo, Development of highly stable and efficient amorphous silicon based solar cells, in *Proceedings of the 28th European Photovoltaic Solar Energy Conference* pp. 2213–2217 (2013)
47. H. Sai, K. Maejima, T. Matsui, T. Koida, M. Kondo, S. Nakao, Y. Takeuchi, H. Katayama, I. Yoshida, High efficiency microcrystalline silicon solar cells on honeycomb textured substrates grown with high-rate VHF plasma-enhanced chemical vapor deposition. Jpn. J. Appl. Phys. **54**, 08KB05 (2015)
48. J.S. Cashmore, M. Apolloni, A. Braga, O. Caglar, V. Cervetto, Y. Fenner, S. Goldbach-Aschemann, C. Goury, J.E. Hötzel, T. Iwahashi, J. Kalas, M. Kitamura, M. Klindworth, M. Kupich, G.F. Leu, J. Lin, M.H. Lindic, P.A. Losio, T. Mates, D. Matsunaga, B. Mereu, X.V. Nguyen, I. Psimoulis, S. Ristau, T. Roschek, A. Salabas, E.L. Salabas, I. Sinicco, Improved conversion efficiencies of thin-film silicon tandem (MICROMORPH™) photovoltaic modules. Sol. Energy Mater. Sol. Cells **144**, 84–95 (2016). https://doi.org/10.1016/j.solmat.2015.08.022
49. R. Chawla, P. Singhal, A.K. Garg, Int. J. Inf. Technol. (2017). https://doi.org/10.1007/s41870-017-0043-6
50. B.M. Kayes, L. Zhang, R. Twist, I.K. Ding, G.S. Higashi, Flexible thin-film tandem solar cells with > 30% efficiency. IEEE J. Photovolt. **4**, 729–733 (2014)
51. F. Meillaud, C. Battaglia et al., Latest developments of high efficiency micromorph tandem silicon solar cells implementing innovative substrate materials and improved cell design. IEEE Photovoltaics Specialist Conference (PVSC) (2011). https://doi.org/10.1109/6185923
52. C. Becker, T. Sontheimer, S. Steffens, S. Scherf, B. Rech, Polycrystalline silicon thin films by high-rate electronbeam evaporation for photovoltaic applications—Influence of substrate texture and temperature. Energy Procedia **10**, 61–65 (2011)
53. G. Sozzi, S. Di Napoli, R. Menozzi, B. Bissig, S. Buecheler, A.N. Tiwari, Impact of front-side point contact/passivation geometry on thin-film solar cell performance. Sol. Energy Mater. Sol. Cells **165**, 94–102 (2017)
54. S. Moon et al., Highly efficient single-junction GaAs thin-film solar cell on flexible substrate. Sci. Rep. **6**, 30107 (2016)
55. E.D. Kosten, J.H. Atwater, J. Parsons, A. Polman, H.A. Atwater, Highly efficient GaAs solar cells by limiting light emission angle. Light Sci. Appl. **2**, e45 (2013)
56. G. Mariani, A.C. Scofield, C.-H. Hung, D.L. Huffaker, GaAs nanopillar-array solar cells employing in situ surface passivation. Nat. Commun. **4**, 1497 (2013)
57. B.M. Kayes, H. Nie, R. Twist, S.G. Spruytte, F. Reinhardt, I.C. Kizilyalli, G.S. Higashi, 27.6% conversion efficiency, a new record for single-junction solar cells under 1 sun illumination, in *Proceedings of the 37th IEEE Photovoltaic Specialists Conference*, 2011
58. T. Mishima, M. Taguchi, H. Sakata, E. Maruyama, Development status of highefficiency HIT solar cells. Sol. Energy Mater. Sol. **95**, 18 (2010)
59. M.Q. Khokhar, S.Q. Hussain, S. Kim et al., Review of rear emitter silicon heterojunction solar cells. Trans. Electr. Electron. Mater. **21**, 138–143 (2020)
60. K. Yoshikawa, H. Kawasaki, W. Yoshida et al., Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%. Nat Energy **2**, 17032 (2017)
61. K.U. Isah, J.A. Yabagi, U. Ahmadu, M.I. Kimpa, M.G.Z. Kana, A. Aghagbudutema, Effect of different copper precursor layer thickness on properties of Cu2ZnSnS4 (CZTS) thin films prepared by sulfurization of thermally deposited stacked metallic layers. IOSR J. Appl. Phys. **2**(6), 14–19 (2013)
62. C. Steinhagen, M.G. Panthani, V. Akhavan, B. Goodfellow, B. Koo, B.A. Korgel, Synthesis of Cu_2ZnSnS_4 nanocrystals for use in low-cost photovoltaics. J. Am. Chem. Soc. **131**(35), 12554–12555 (2009)
63. W. Wang, M.T. Winkler, O. Gunawan, T. Gokmen, T.K. Todorov, Y. Zhu, D.B. Mitzi, A 12.6% $Cu_2ZnSnS_xSe_{4-x}$ (CZTSSe) solar cell is presented with detailed device characteristics. Adv. Mater. **4**(7), 1301465 (2013)
64. K. Sun, C. Yan, F. Liu, J. Huang, F. Zhou, J.A. Stride, M. Green, X. Hao, Over 9% efficient kersterite Cu2ZnSnS4 solar cell fabricated by using Zn1-xCdxS buffer layer. Adv. Energy Mater. **6**, 1600046 (2016). https://doi.org/10.1002/aenm.201600046
65. L. Ciani, M. Catelani, L. Donati, M. Scaringella, E. Perrotta, and M. Bruzzi, Characterization of optical ageing effects on Ruthenium based dye-sensitized solar cells, in *2014 Proceedings of the IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, pp. 491–495 (2014)
66. M. Grätzel, B. O'Regan, A low-cost, high-efficiency solar cell based on dyesensitized colloidal TiO_2 films. Nature **353**, 737–740 (1991)
67. R. Komiya, A. Fukui, N. Murofushi, N. Koide, R. Yamanaka and H. Katayama, Improvement of the conversion efficiency of a monolithic type dyesensitized solar cell module, Technical Digest,

in *21st International Photovoltaic Science and Engineering Conference*, Fukuoka, November 2011; 2C-5O-08 (2011)

68. G. Scarpa, E. Martin, S. Locci, B. Fabel, P. Lugli, Organic thin-film phototransistors based on poly(3-hexylthiophene). J. Phys: Conf. Ser. **193**(1), 012114 (2009)
69. L.D. Menard, J.M. Ramsey, Fabrication of sub-5 nm nanochannels in insulating substrates using focused ion beam milling. Nano Lett. **11**(2), 512–517 (2011)
70. S. Mori, H. Oh-oka, H. Nakao, T. Gotanda, Y. Nakano, H. Jung, A. Iida, R. Hayase, N. Shida, M. Saito, K. Todori, T. Asakura, A. Matsui, M. Hosoya, Organic photovoltaic module development with inverted device structure. MRS Proc. **2015**, 1737 (2015). https://doi.org/10.1557/opl.2015.540
71. O.E. Semonin, J.M. Luther, S. Choi, H.-Y. Chen, J. Gao, A.J. Nozik, M.C. Beard, Peak external photocurrent quantum efficiency exceeding 100% via MEG in a quantum dot solar cell. J. Sci. **334**(6062), 1530–1533 (2011)
72. Z. Zheng et al., Recent progress towards quantum dot solar cells with enhanced optical absorption. Nano Sci. Lett. **11**, 266 (2016)
73. V.M. Andreev, V.A. Grilikhes, V.P. Khvostikov et al., Concentrator PV modules and solar cells for TPV systems. J. Solar Energy Mater. Solar Cells **84**(1–4), 3–17 (2004)
74. J.I. Rosell, X. Vallverdu, M.A. Lechon, M. Ibanez, Design and simulation of a low concentrating photovoltaic/thermal system. J. Energy Convers. Manag. **46**(18–19), 3034–3046 (2005)
75. F. Dimroth, T.N.D. Tibbits, M. Niemeyer, F. Predan, P. Beutel, C. Karcher, E. Oliva, G. Siefer, D. Lackner, P. Fuß-Kailuweit, A.W. Bett, R. Krause, C. Drazek, E. Guiot, J. Wasselin, A. Tauzin, T. Signamarcheix, Four-junction wafer-bonded concentrator solar cells. IEEE J. Photovolt. **6**(1), 343–349 (2016)
76. NREL, 2020, Best Research-Cell Efficiency Chart, https://www.nrel.gov/pv/cell-efficiency. Accessed 2 June 2020
77. NREL, 2020, Solar Technology Cost Analysis, https://www.nrel.gov/analysis/solar-cost-analysis Accessed 2 June 2020
78. A. Patra et al., Solar cell production release hazardous gases and requires toxic materials. Int. J. Sci. Technol. Manag. **2**(3), 25–31 (2013)
79. R. Chawla, P. Singhal, A.K. Garg, Internet of things driven framework for smart solar energy system. ASME J. Energy Resour. Technol. **142**(1), 011201 (2020). https://doi.org/10.1115/1.4044124
80. R. Chawla, P. Singal, A.K. Garg, A Mamdani fuzzy logic system to enhance solar cell micro-cracks image processing. Int. Res. **9**, 34 (2018). https://doi.org/10.1007/s13319-018-0186-7
81. MIT Energy Initiative. The Future of Solar Energy: An Interdisciplinary MIT Study, in *Chapter 2: Photovoltaic Technology*, pp. 21–45, (2015)
82. Current and Future Costs of Photovoltaics: Long-term Scenarios for Market Development, System Prices and LCOE of Utility-scale PV Systems (Fraunhofer Institute for Solar Energy Systems, 2015); http://go.nature.com/2aYJCgc
83. Sarkar, S., Rahman, M.M. A Novel Method for Optimizing Power Efficiency of a Solar Photovoltaic Device. Trans. Electr. Electron. Mater. (2020)
84. N. Park, High efficiency perovskite solar cells: materials and devices engineering. Trans. Electr. Electron. Mater. **21**, 1–15 (2020)
85. S. Albrecht et al., Monolithic perovskite/silicon-heterojunction tandem solar cells processed at low temperature. Energy Environ. Sci. **9**, 81–88 (2016)