Solar Energy 258 (2023) 203–219

Contents lists available at ScienceDirect

Solar Energy

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

Progress of PV cell technology: Feasibility of building materials, cost, performance, and stability

M.A. Fazal [a,*], Saeed Rubaiee [a,b]

[a] Department of Mechanical and Materials Engineering, University of Jeddah, Kingdom of Saudi Arabia
[b] Department of Industrial and Systems Engineering, University of Jeddah, Kingdom of Saudi Arabia

ARTICLE INFO

Keywords:
PV technology
Feasibility
Materials
Efficiency
Cost
Performance
Stability

ABSTRACT

Recently, the demand for PV technology by various sectors, including the public domain, industry, and space technology, has significantly increased. The feasibilities of existing PV technologies largely depend on building materials, efficiency, stability, cost, and performance. However, very nominal studies are dedicated to exploring current PV technologies' feasibility. Therefore, the progress of various PV technology should be reviewed systemically, specially to promote their practical applications. The present work attempts to sort out the current achievements, summarize the limitations, and point out the necessary research directions for future applications. It reveals that utilization of some PV technologies is technically feasible but economically it still seems unfeasible. Si-based PV is the most dominant technology with substantial advantages and is expected to maintain the best price competitiveness among all other potential PV technologies for the next decades. The traditional Al-BSF is gradually replaced by PERC and going to be outdated by 2026. The other c-Si based PV technologies including SHJ, TOPCon and IBC are expected to be mainstream in the latest 2/3 years due to their improved efficiency and reduced cost. However, the maximum c-Si based PV efficiency (26.1%) is approaching its theoretical Auger efficiency limit of 29.43% and therefore, some innovative strategies like tandem solar cells receive greater acceptances. Laboratory tests and data from actual services have suggested that III–V/Si and PVK/Si tandem cells are the most promising candidates to compete with c-Si-based technology in near future due to their specific properties. However, their practical uses are limited owing to some challenges. Similarly, mainstream thin film technologies including CdTe, CIGS, and GaAs play a crucial role in the PV market. This comprehensive review presents the significant shortcomings of each PV-technology and the possible solutions if any.

1. Introduction

Growing energy demand, environmental degradation, and depletion of conventional energy sources have accelerated the need for an alternative, renewable, low-cost, safe, and omnipresent energy source. One of the most potent ways to resolve this foreseeable world's energy crisis is to use solar radiation [1,2]. In this regard, photovoltaic (PV) solar technologies have attracted considerable attentions because of their easy installation, low maintenance cost, and sustainable energy source [3,4]. They can convert solar radiation into electricity economically. By the end of 2019, the total cumulative installed power capacity with a solar PV system globally reached 627 GW, sufficient to meet approximately 3% of the global electricity demand and contribute 5% reduction in worldwide electricity-related CO_2 emission [5]. This installed capacity can be increased to as large as 2.1 TW by the end of 2025 compared with 773.2 GW in 2020 [6]. At present, various PV technologies are being explored with an interest in increasing cell efficiency, enhancing durability, and reducing cost. Therefore, current PV cell

Abbreviations: Al-BSF, Aluminum back surface field; CdTe, Cadmium Telluride; CIGS, Copper Indium Gallium Selenide; DSSC, Dye-sensitized solar cell; DLIT, Dark lock-in thermography; DR, Degradation rate; EL, Electroluminescence; EDS, Electrodynamic screen; GaAs, Gallium arsenide; HIT, Heterojunction intrinsic thin layer; HJT, Heterojunction technology; IBC, Interdigitated back contact; ITO, Indium -tin oxide; LIT, Lock-in thermography; LCOE, Lower levelized cost of energy; LETID, Light and elevated temperature induced degradation; MSP, Minimum sustainable price; mc-Si, Multi-crystalline silicon; NREL, National Renewable Energy Laboratory; OSC, Organic solar cell; PVK/Si, Perovskite/silicon tandem cell; PV, Photovoltaic; PR, Performance ratio; PERC, Passivated emitter and rear cell; sc-Si, Single crystalline silicon; SHJ, Silicon heterojunction; STC, Standard test conditions; TCO, Transparent conductive oxide; TOPCon, Tunneling-oxide passivating contact; TSC, Tandem solar cell; UV, Ultraviolet; III–V/Si, Tandem solar cell on Si substrate.

* Corresponding author.
E-mail addresses: fazal@uj.edu.sa (M.A. Fazal), salrubaiee@uj.edu.sa (S. Rubaiee).

https://doi.org/10.1016/j.solener.2023.04.066
Received 3 December 2022; Received in revised form 4 April 2023; Accepted 30 April 2023
Available online 11 May 2023

technologies should be analyzed to achieve high reliability, performance, and minimum manufacturing cost.

Recently, the PV-based industries are experiencing remarkable growth because of increased interest in green energy, PV cost reduction, and efficiency enhancement. To date, crystalline silicon (c-Si) PV cells dominate large-scale electricity generation because of mass production, reduced prices, easy installation, and low maintenance cost [7,8]. Apart from c-Si PV technologies, many innovative PV cell technologies including thin film [9,10], dye-sensitized [11], organic [12], perovskite [13,14] and tandem multijunction cells [15,16] are currently under intensive research and development. Concerns on building materials [17,18], performance [19,20] cost [8,21], and stability [22,23] of various PV technologies have widely been reported in literatures. It appears that several research points must be discussed systematically to understand the feasibility of existing PV technologies. However, the scattered literature studies hardly allow to understand how competing technologies affect conversion efficiency, operating stability, cost, and performance to meet the future needs. Most often common people are unaware of the feasibility of existing PV technologies. Therefore, current achievements should be systematically explored, and potential research directions for future applications should be presented.

The commercially available Si-based PV modules are mostly either single- (sc-Si) or multi-crystalline silicon (mc-Si). To date, silicon is the most widely used semiconductor material employed in manufacturing PV modules. Crystalline silicon-based aluminum back surface field (Al-BSF) was the most popular PV technology till 2018. In recent times, various high-efficiency silicon based crystalline cells such as passivated emitter rear cell (PERC), silicon heterojunction (SHJ), interdigitated back contact (IBC), tunnel oxide passivated contact (TOPCon) solar cells are gaining more interest [24]. However, silicon-based PV has some drawbacks, including energy-intensive high-temperature processing, fragility [25], and limited module efficiency [26]. In addition, the record efficiency of crystalline silicon-based technology (26.1%) [27] is approaching its theoretical Auger efficiency limit of 29.4% [28]. As an alternative to conventional silicon-based PV modules, various technologies using new materials, different designs, and assembly techniques have been developed to address the downsides mentioned above. Among others, gallium arsenide (GaAs), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and mineral perovskite (CaTiO) are the most popularly used compound materials [29]. Some of these technologies are becoming more and more attractive because of their reliability and higher electric efficiency under various climatic conditions [26]. Manufacturing cost, band gap control, junction multiplications, stability etc. [30] are the significant limitations for many of these compound materials. In recent times, organic–inorganic metal halide with wider band gap have been recognized as a highly promising light absorbing material that improved drastically in the last couple of years. These materials having different band gaps are potentially used in the multijunction structure. There are currently PV modules in development expecting maximum efficiency of nearly 50%, which may hit the market sometime in the near future as an emerging PV technology. Table 1 demonstrates the chronological development of PV materials, efficiency, and current challenges. Till 2018, Al-BSF was the mainstream PV technology and later it was replaced by PERC. In 2018, the average efficiency of silicon-based PV was around 20%, but it reaches up to approximately 24–32% in 2021–23 with the advancement of PV technology and is expected to be increased further in near future. Assuming rapid and dynamic development of PV technologies in the near future, fundamental scientific queries arise on the feasibility of both existing and the emerging technologies. Therefore, the strength, weakness, performance, and future outlook of these PV technologies should be comprehensively understood.

Table 1**:**

The availability of various cell technologies is observed in the market, and some of them have been widely accepted by consumers, and some are in small-scale or pilot production. As matured technology, c-Si has been widely explored to achieve the trust of reliable energy efficiency and durability. Over recent years, c-Si cell industries have been in mass production, and it consolidates the role as the dominant solar technology accounting for over 90% of the market [7]. Any competitive solar cell technology must meet all economic, technological, and social criteria to reach the final mass production stage or achieve commercial acceptance. Although different solar technologies have been proposed and investigated, only c-Si, CIGS, and CdTe have overcome the threshold of commercialization and mass production [49]. The existence of any established PV technology, which is in mass production and market entry of any new PV technology, which are proposed and under investigation, largely depend on efficiency, stability, cost, environment friendliness of constituent materials, and overall performance of a particular cell technology. The development of technologies with high efficiency and minimum cost is one of the key objectives to attain a lower levelized cost of energy (LCOE) [50]. However, there is minimal study on comparative cost, efficiency, and performances for different existing and expected PV technologies. Particularly, the recent update on comparative strengths and weaknesses for various PV technologies is

Table 1
PV material types, chronological development, efficiency, and current challenges.

PV material types	Year and efficiency for specific PV materials	Current challenges
Silicon	1954: 6% was achieved by silicon p-n junction [31]. 1980–2018: 11–12% in 1980 and nearly 20% in 2018 were achieved by Al-BSF [32], 18% in 1984 [33]. Al-BSF was the mainstream PV technology till 2018. 2022–2023: 22.8–24.7% in 2022 was achieved by PERC [34,35]; 24.24% by TOPCon [36], 23.1% by SHJ [37], 29.15% in 2021 [38] and 32.5% in 2023 [39] was achieved by tandem PV solar cell. PERC becomes mainstream since 2016.	Manufacturing, quality improvement, efficiency limitation, fragility [25], Light and elevated temperature induced degradation [40]
Compound (thin film)	2010: 10.1% by a-Si, 16.7% by CdTe, and 19.6% by CIGS, 8.3% by organic tandem [41]. 2015: 13.6% by a-Si, 21.5% by CdTe, 21.7% by CIGS, and 12% by organic tandem [41]. 2023:14% by a-Si, 21.1% by CdTe, and 23.4% by CIGS [39], 32.9% was achieved by tandem cell with strain-balanced GaInP/GaAs-QW under one sun [42].	Manufacturing cost, bandgap control, junction multiplications, and stability [30].
Emerging (Organic, Inorganic or mix)	2009: 3% by perovskite-based dye-sensitized solar cell [43]. 2011: 6.5% by perovskite quantum-dot-sensitized solar cell [44]. 2015: >15% for perovskite with heavily doped charge extraction layer and it maintained 90% of its efficiency after 1000 h operation. [45]. 2021–2023: 18.2% by OSC, 13% by DSSC, 25.5% by perovskite in 2023 [39], 20.71% by modified PSC in 2022 [46].	Structure, materials processing, junction multiplications, materials toxicity [47], degradation [48], stability [41].

unknown. To fill this knowledge gap, an attempt has been made to sort out the current achievements on some critical aspects, including building materials, efficiency, cost, and performance of existing technologies, summarize the limitations, and point out the important research directions for future applications. Focus has also been given to highlighting the technological feasibility of different PV technologies for industrial production and solar energy generation. Finally, the prospects, challenges, and future outlook of varying PV technologies are summarized through a systematic approach.

2. PV cell technology and building materials

Commercially available PV modules are mostly made of single-crystalline silicon (sc-Si) or multi-crystalline Si (mc-Si). The mc-Si PV was the dominant technology until 2015 when the price of sc-Si drastically reduced [51]. In addition to Si-based PV cells, many innovative PV cells are still being developed and continuously improved with interest in their enhanced power efficiency and reduced manufacturing, operating, and maintenance costs. The existing PV technologies can be classified into four groups (known as generations) depending on the materials used, adapted manufacturing process, and PV cell performance. Fig. 1 presents the four generations of existing PV technologies.

2.1. Generation I: Crystalline silicon cell

First-generation technology includes sc-Si- and mc-Si-based PV cells. Currently, it dominates the market share by more than 90% [7]. The bulk material producing crystalline silicon is plentiful (making up 28% of the earth's crust). The sc-Si PV cells are produced from pseudo-square silicon wafer substrates, cut from column ingots grown via a Czochralski (Cz) technique. This technique is used to produce sc-Si from mc-Si. The entire technology in producing sc-Si is expensive. The maximum sc-Si cell efficiency reported by NREL is 26.1% [39]. However, mc-Si cells are made of square silicon substrates cut from polycrystalline ingots grown in quartz crucibles. They are less expensive than single-crystalline silicon cells. The maximum mc-Si cell efficiency reported by NREL is 23.3% [39]. At present, Si-based PV-cells are the most promising technology with strong advantages, including abundant supply, matured structure, rapidly decreasing material cost, and good semiconductor quality [52]. PV industries are shifting from aluminum back surface field (Al-BSF) c-Si to passivated emitter and rear cell (PERC) and silicon heterojunction (SHJ) to increase efficiency further [32].

Fig. 2 illustrates the cell structure of traditional c-Si, PERC, and SHJ. A traditional c-Si cell as shown in Fig. 2(a) has a PN-junction consisting of p- and n-doped layers. At the back of the PERC cells presented in Fig. 2 (b), there is an additional passivation layer for capturing more sunlight and making PERC more efficient in producing electricity. The silicon nitride (SiN_x) layer on top of a PN-junction in PERC serves as an anti-reflecting coating to reduce the reflection of solar radiation. PERC cells offered reduced rear-surface recombination and improved higher infrared light absorption, which enables in achieving up to 1% more efficiency than the traditional c-Si cells [53]. The record efficiency of PERC was 25% [54] in 2019 and it is going to be around 27% in 2023 [55]. However, this p-type PERC cell efficiency is approaching its limit, and cell manufacturing cost reduction is also slowed. With the rapid development of technology, n-type cells are appearing as a potential alternative to p-type cells for the next generation of mainstream technology. P-type cells are traditionally boron-doped silicon substrates subjected to light-induced degradation by forming boron-oxygen pair. In contrast, n-type cell silicon wafer substrates are usually doped with phosphorus which greatly decreases the tendency of light-induced degradation.

A heterojunction is an interface between two regions or layers of dissimilar semiconductors. SHJ, variously known as heterojunction technology (HJT) or heterojunction with intrinsic thin layer (HIT) is considered next technological step of PERC. It is one of the latest c-Si PV hybrid technologies that receives tremendous attentions by the top manufacturers. This technology sandwiches a crystalline silicon cell between two layers of amorphous thin film. As shown in Fig. 2(c), both sides of n-doped c-Si in SHJ structure are attached to an intrinsic and doped amorphous silicon (a-Si:H) layer followed by a transparent conductive oxide (TCO) layer. Indium -tin oxide (ITO) is commonly employed as TCO which improves lateral conduction and light absorption [56]. SHJ allows an increased efficiency when compared to conventional c-Si PV. The record efficiency achieved by interdigitated back contact (IBC) SHJ and c-Si PVs are approximately 26.7% [54] and 26.1%

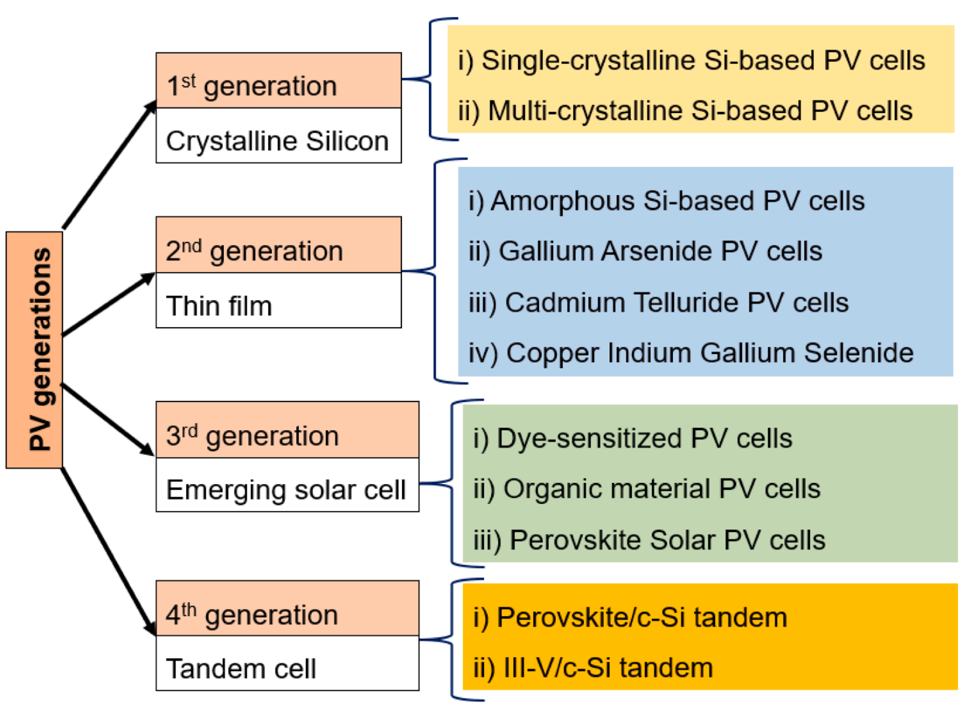

Fig. 1. Generations of existing PV cell technologies.

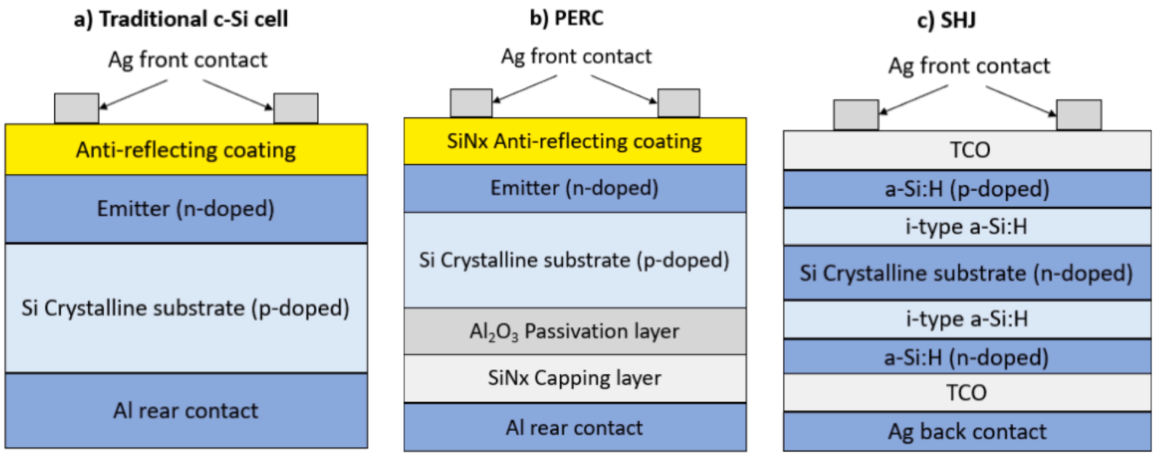

Fig. 2. Schematic of a) traditional crystalline silicon cell (a) passivated emitter and rear cell (PERC) and silicon heterojunction (SHJ) cell structures.

[27] respectively. During operation, the deposited amorphous silicon thin layer on its front and back surfaces absorbs some extra irradiance before it hits the middle c-Si cell. The main advantages of SHJ over c-Si cells include i) high efficiency, ii) low temperature coefficients close to −0.21%/°C indicating less performance loss over their cycles, and iii) bifacial as both front and back consist of thin film amorphous solar cells [57]. It is predicted that the SHJ cells by the end of this decade could achieve around 28% efficiency which is close to the theoretical c-Si PV cell efficiency. In 2023–2024, SHJ cell is expected to overcome Al-BSF in market share to become the second-most commercial PV technology after PERC/TOPCon, increasing to approximately 16% by 2029 [58]. This technology seems much mature and can compete with PERC particularly in terms of cost and compatibility with hot/humid environments. The challenges currently faced by SHJ are metallization [59], silver and indium free processing [56], quality of Si thin film, ultraviolet (UV) light stability [60], manufacturing process complexity [61] and so on.

Fig. 3 presents the projected world market share for different silicon-based PV technologies [58]. In the near future, multijunction silicon or silicon tandem, IBC cells are expected to be potentially increased. Their future progresses could also be much more rapid than originally anticipated. As per Fig. 3, the current Si-based PV market is covered by approximately 15% by Al-BSF, 70% by PERC, 8.5% by SHJ, and 7% by IBC, 1.5% by Si-tandem, while in 2029, the market coverage could be 70% by PERC, 16% by SHJ, 9% by IBC, and 5% by Tandem PV. It is noted that the traditional Al-BSF is predicted to be outdated in 2026, while PERC, SHJ, IBC, and Si-tandem will be increased in the future. Most of the recombination loss of traditional Si solar cells is due to metal contact and therefore, passivation is preferred to avoid this efficiency loss. SunPower Corporation in 2015, fabricated IBC using passivating contacts instead of metal contact [62]. In recent times, TOPCon, SHJ, and POLO (poly-Si on oxide)-IBC are gaining much interest. The reported efficiencies of TOPCon and POLO-IBC are 25.8% [63,64] and 26.1% [65] respectively. Like PERC, the TOPCon [24,66] and HJS [58] in the upcoming two/three years are expected to be in mainstream PV technology as these technologies show a clear edge in cost control, raw materials availability, easy processing sequence, high-efficiency potential and market share. The energy yield performances of SHJ and TOPCon modules in 2022 are experimentally observed to be respectively 8.79% and 5.55% higher than that of PERC modules [67]. As per the market estimation performed by ITRPV (2021) [58], the market share in 2031 is expected to be covered 80% by PERC/TOPCon PV cells and 15% by SHJ cells.

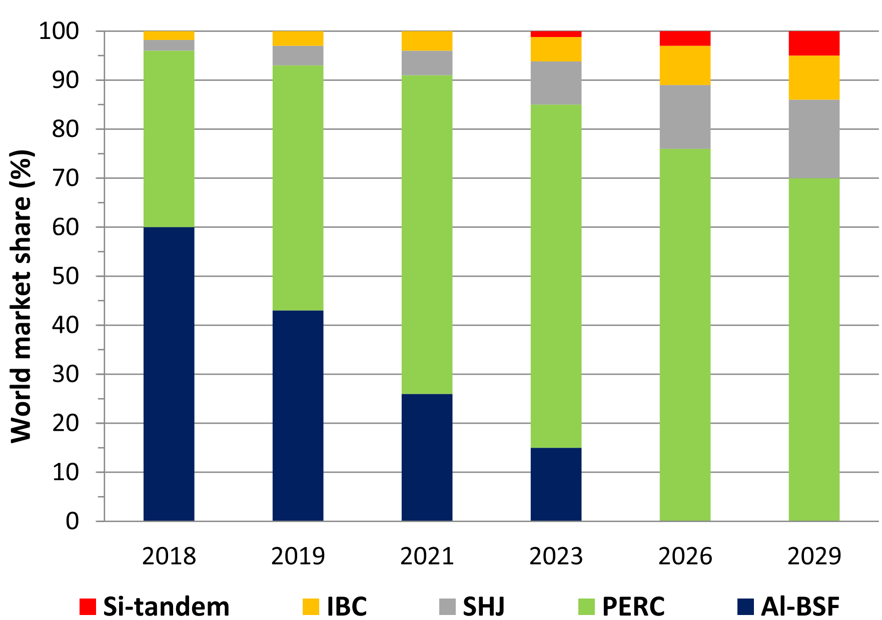

Fig. 3. Projected world market share for different silicon-based PV technologies [58].

2.2. Generation II: Thin film solar cells

Thin film PV cells occupy approximately 10% share of the total market. It is a second-generation technology of binary or quaternary semiconductor materials. The major thin-film technologies include a-Si, CdTe, CIGS, and GaAs (Fig. 4). Thin films absorb solar radiation at sufficient levels in the form of photons and converts them into electricity. The light-absorbing thickness in first-generation technology is 200–300 μm, while it is reduced to 10 μm in second-generation thin film technology [17]. Compared with first-generation technology, they are usually made of fewer materials with a simple manufacturing process, but they provide a slightly lower efficiency [68]. The largest advantage is that the cost of photo-absorbing semiconductors is reduced by replacing costly c-Si cells. It uses direct band gap semiconductor materials instead of indirect band gap silicon. However, the commercial use of second-generation PV technology is still limited because of some unresolved issues and challenges regarding reasonable efficiency levels on a competitive price.

The common thin-film PV technologies currently available are a-Si, CdTe, and CIGS, which offer cell efficacies of 14%, 22.1%, and 23.4%, respectively [39]. Among them, a-Si is the cheapest technology, and it needs less silicon. It has the superiority to operate at medium temperature level [69] and can be wrapped around a curved surface. The structure of a-Si cells, as shown in Fig. 4(a), is a typical p-i-n, where charge separation is driven by the drift field in an i-layer [70]. The major challenge of a-Si cells is related to their low efficiency, slow improvement, and shorter service life. However, one notable exception is CdTe modules, which have much potential to compete with c-Si in the near future. Along with technological advancement, CdTe cells and module efficiencies are recorded to be 22.1% and 18.6%, respectively [17]. The prime challenge of CdTe cells is related to toxicity and environmental concerns because of the use of toxic cadmium. CIGS has a high absorption coefficient with a flexible thin layer, allowing a simple deposition of a flexible substrate. However, the module efficiency is still lower because of less developed upscaling. Limited indium reservation is another downside of this CIGS cell technology [71]. Researchers are now trying to find alternative materials for replacing a CdS window layer from CdTe (Fig. 4b) and CGIS (Fig. 4c) because of cadmium toxicity [72].

It is worth mentioning that III–V compounds, including GaAs, InP, AlGaAs, and InGaP are currently receiving considerable research attention in the domain of thin film technology. The efficiencies of these compound single-junction solar cells are reported at 29.1%, 24.1%, 16.6%, and 22%, respectively [73,74]. In fact, GaAs (Fig. 4d) emerged as one of the most popular III–V semiconductor thin film cells having some advantages of high electron mobility, direct band gap and heat resistant properties, high efficiency, and performance. However, gallium, arsenic, bismuth, and selenium are reported to be on a short supply in all scenarios. In addition, several loss mechanisms should be resolved to achieve high-efficiency III–V compound solar cells. They include surface recombination loss, bulk recombination loss, interface recombination loss, voltage loss, fill factor loss, optical loss, and insufficient energy photon loss [75].

2.3. Generation III: Emerging solar cells

Third-generation PV technologies, including dye-sensitized, organic, and perovskite cells, are still under intensive research and development [76] in laboratories. Fig. 5 shows the schematic of dye-sensitized, organic, and perovskite cells. The concept of DSSC resembles natural photosynthesis [29]. The main components of DSSC as shown in Fig. 5 (a) include photoanodes (e.g., mesoporous nanostructured TiO_2), organic sensitizers (dye), electrolytes containing an iodide/triiodide redox couple and a counter electrode (e.g., Pt or carbon-based

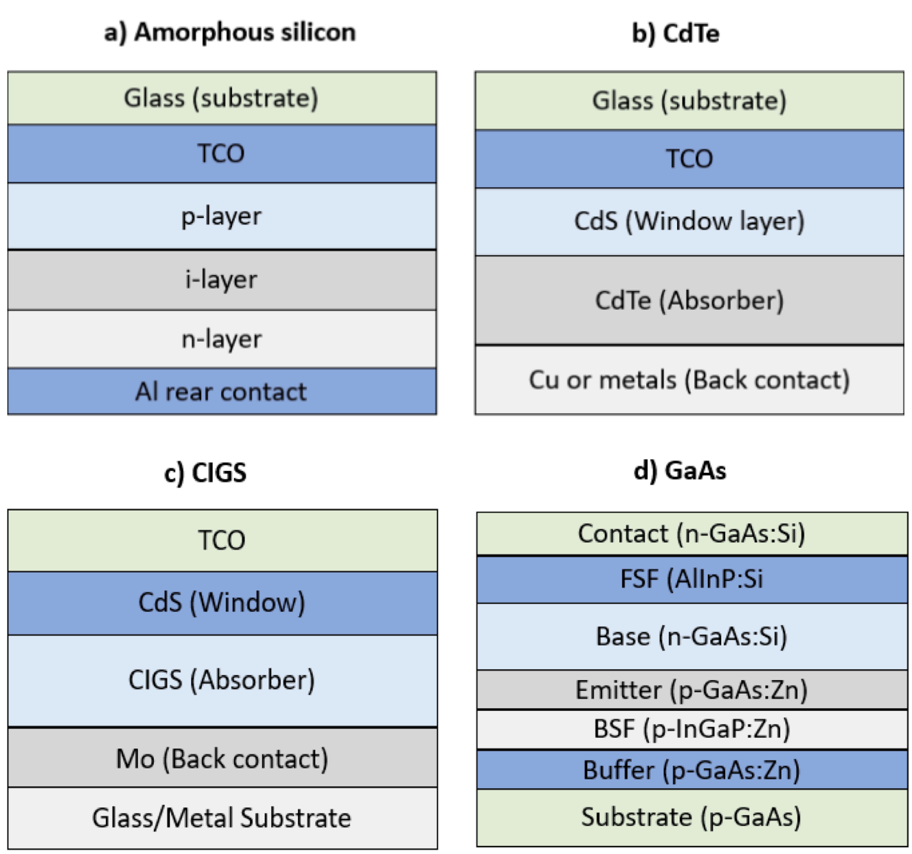

Fig. 4. Schematic of a) amorphous silicon (a-Si), b) cadmium telluride (CdTe), c) copper indium gallium selenide (CIGS), and d) gallium arsenide (GaAs) cell structures.

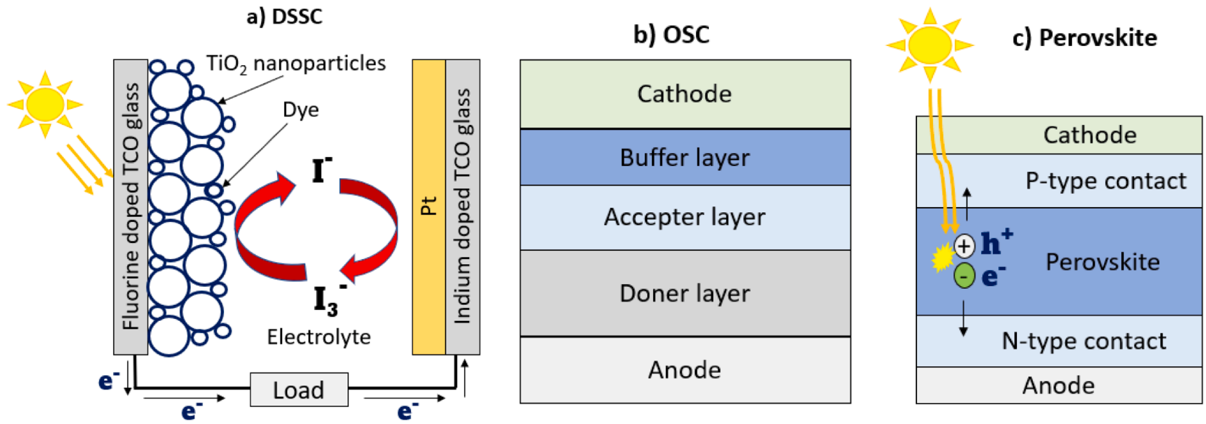

Fig. 5. Schematic view of a) dye-sensitized solar cells (DSSCs), b) organic solar cells (OSCs), and c) perovskite cells.

materials). Thus far, the efficiency of existing DSSCs has been increased to 12%, which is still much lower than that of first- and second-generation PV cells [77]. Their commercial uses are limited because of liquid electrolytes, low stability and related issues [78]. Unlike DSSCs, organic solar cells (OSCs) have a planar device architecture, as shown in Fig. 5(b). The operational steps of polymer/organic solar PV cell include photogeneration of excited ions, dissociation, charge separation of exited ions and transportation of the carriers to the reverse electrode [17]. The main advantages of OSCs include the low cost and use of flexible electrode substrates, semitransparency, large-scale fabrication, and solution-processibility [79] while the major disadvantage is low-carrier mobility. The efficiency of OSCs still falls behind the inorganic devices.

Currently, perovskite solar cells having perovskite-structured organometal halide compounds have become increasingly popular. The schematic of thin-film perovskite cells is shown in Fig. 5(c). CH_3NH_3I and $PbCl_2$ (or PbI_2) are commonly used perovskite precursors in preparing planar cell structures [80]. During a short span of time, the efficiency of perovskite cells has increased to 25.5% [39]. However, the major challenge of perovskite is its instability and toxic lead content [32]. Researchers are potentially working on using Sn [81] and Bi [82] instead of Pb for making lead-free perovskite cells. Though the instability of perovskite cells is another major concern until now [83], this issue can be overcome, and other properties can be improved. This emerging technology aims to make solar PV systems more efficient and less expensive by using various new materials, such as [84]. However, remarkable progress is observed in this third-generation PV technology; as such, it is expected to arrive and capture the market soon [17].

2.4. Generation IV: Tandem PV technology

A vast majority of PV cells available in the market have an efficiency limit of 20–25%. In fact, the efficiency achieved by a single junction c-Si approaches towards its theoretical limit (29.4%) [28]; as such, innovative strategies, such as multijunction or tandem solar cells (TSC), are being potentially investigated. It basically comprises two or more photovoltaic absorbers each with different bandgap properties in order to use the sun's spectrum more efficiently. Recently, tandem cells including III-V/Si, and perovskite/Si (PVK/Si) [30] are considered promising candidate to suppress Si efficiency records. Several analyses show its limiting efficiency up to 69.9% for an infinite number of subcells under 1 sun illumination [85–87]. Tandem cells could be referred to as fourth-generation solar cells, which have already been successfully commercialized at a smaller scale. It is usually manufactured by stacking several PN junctions of different bandgap semiconductor materials to overcome the fundamental limitation of single junction c-Si [49]. Each layer of multijunction tandem cells having a specific band gap energy allows the cell to absorb solar radiation in a particular spectral region. Usually, the top layer uses a large band gap to absorb most visible spectra up to the bottom layer with low bandgap energy for absorbing radiation in the infrared region [88]. In this case, the non-absorbed solar radiation with broader wavelengths is transmitted to the next subcells for further absorption.

Despite the high fabrication cost, III-V tandem solar cell on silicon (III-V/Si) has already been proven as a reliable and high-efficiency technology potentially used in space and concentration PV applications [7,89]. At the initial stage, the III-V tandem devices have been exclusively used for space applications since the late 1990 s. The GaInP/GaAs double junction (2 J) and GaInP/GaAs/Ge triple junction (3 J) throughout 1990 s achieved 21–22% and 24% efficiency respectively [90,91]. The most commercially successful tandem cell developed in the space industry during that time was Ga0.5In0.5/Ga0.99In0.01As/Ge which achieved 32% efficiency under 1 Sun [92]. A TSC fabricated by direct epitaxial growth of III-V materials on Si has been reported in the current year, 2023 to achieve 35.9% conversion efficiency [93]. In another study, mechanically stacked GaInP/GaAs III-V cell on silicon is also reported to achieve an efficiency of 35.9% [54]. Recently, a six-junction tandem cell achieved an efficiency of 39.2% and 47.1% under 1 and 143 suns, respectively [94]. However, due to high fabrication cost, the III-V based tandem cells have not yet got the popularity in PV market. In addition, the current mismatch in subcells still causes difficulties in improving efficiency further [95]. New structure with various fabrication methods such as mechanical stack [96], metamorphic growth [97], water bonding technology [98], etc. have recently been proposed to overcome these problems.

In tandem PVs, perovskite also shows great potential as an alternative to the III-V top cell. Recently, PVK/Si tandem solar cells have been reported with efficiency records of 32.5% [39]. Recently, this tandem cell has received alarming attentions because of its low cost and remarkable progress in achieving efficiency in a short span of time. For easier fabrication and reduced cost, two terminals (2 T, also known as monolithic) perovskite/Si TSC as shown in Fig. 6(a) is preferred. In 2 T perovskite/Si TSC, the perovskite top cell is fabricated directly on the top of the Si bottom cell where current matching is essential. While in three- or four-terminal (3 T or 4 T) configuration (Fig. 6b and c), the perovskite top cells and Si bottom cells are fabricated separately where both subcells are electrically independent.

Table 2 shows the chronological development of 2 T and 4 T TSCs with materials and efficiency since 2015 to 2023. Researchers around the world uses different perovskite compositions to get better efficiency. Various organic–inorganic metal halides such as formamidinium-cesium (FACs)-, methylammonium (MA)-, Cesium (Cs)- lead iodide (PbI_3) and mixed halide-based perovskites have widely been recognized as potential light-absorbing materials that give better conversion efficiency. These materials are identified the best partner for Si cells due to their low excitation bonging energies, sharp optical absorption edge, long carrier diffusion lengths, and excellent defect tolerance [99]. Regardless

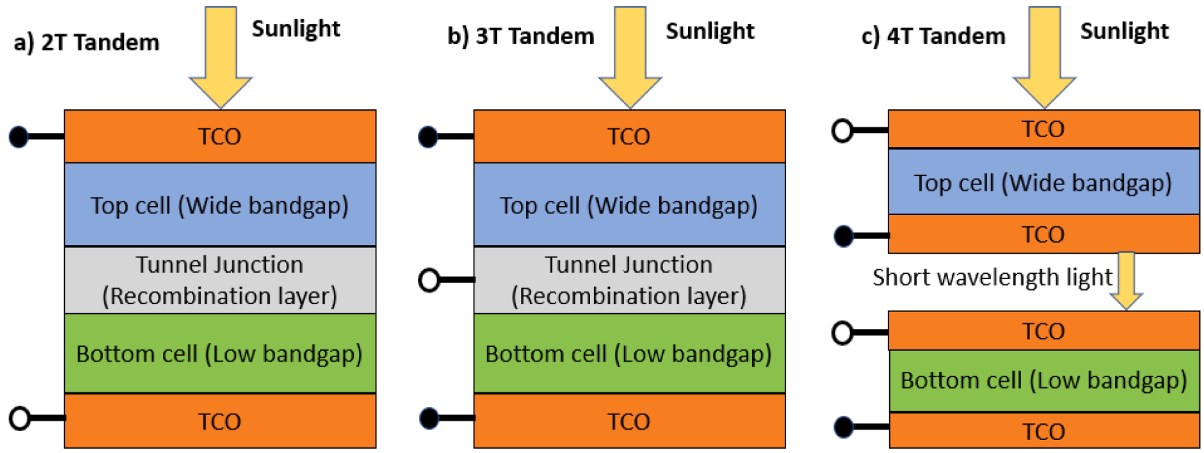

Fig. 6. Schematic view of a) 2 terminal (2 T), b) 3 terminal (3 T) and c) 4 terminal (4 T) tandem cells.

Table 2
Efficiency of 2 T and 4 T perovskite/Si tandem solar cell (TSC) reported since 2015 to 2023.

Year	2 T Tandem Configuration (PVK/c-Si)		4 T Tandem Configuration (PVK/c-Si)	
	Perovskite composition /bandgap (eV)	Efficiency	Perovskite composition /bandgap (eV)	Efficiency
2015	$MAPbI_3$ (1.58 eV)	13.7% [106]	$MAPbI_3$	18.2% [107]
2016	$MAPbI_3$ (1.58 eV)	20.5% [108]	$MAPbI_3$ (1.58 eV)	23% [109]
2017	$FAMACsPbI_{3-x}Br_x$ (1.69 eV)	20.57% [110]	$RbFAMAPbI_{3-x}Br_x$ (1.73 eV)	26.6% [111]
2018	$FAMACsPbI_{3-x}Br_x$ (1.69 eV)	22.22% [112]	$CsFAPbI_{3-x}Br_x$ (1.77 eV)	27.1% [113]
2019	$CsFAMAPbI_{3-x}Br_x$ (1.63 eV)	25.2% [114]	$MAPbI_3$ (1.58 eV)	25.5% [115]
2020	$CsFAMAPbI_{3-x}Br_x$ (1.68 eV)	25.7% [116]	$CsFAPbI_{3-x}Br_x$ (1.65 eV)	25.7% [117]
2021	$CsFAMAPbI_{3-x}Br_x$ (1.68 eV) plus carbazole additive	28.2% [101]	$FACsPbI_3$ (1.46 eV)	28.3% [118]
2022	Perovskite (stain modulated)	26.95% [119]	$Cs_{0.05}FA_{0.82}MA_{0.13}Pb(I_{2.86}Br_{0.14})$ (~1.6 eV) plus sodium fluoride (NaF) as stabilizer	23.82% [102]
2023	Perovskite	32.5% [39]	$Cs_x(FA_{0.4}MA_{0.6})_{1-x}PbI_{2.8}Br_{0.2}$ (1.6 eV)	28% [120]

of the terminal, PVK/Si tandem cells still suffer from optical losses. Short service life, as well as toxic lead in perovskite have also limited its commercial applications. Researchers around the globe are putting tremendous effort in overcoming these problems. The addition of nanotextured interfaces [100], potassium passivation [99] with top cell, carbazole (nitrogen-containing heterocyclic molecule) [101], and a small amount of sodium fluoride (NaF) [102] in perovskite as stabilizer has been reported to reduce the optical loses and thus, improve TSC efficiency. Recently, a two-terminal TSC with wide bandgap perovskite ($MAPbI_3$) as top cell (1.61 eV) and low bandgap copper indium diselenide ($CuInSe_2$, CIS) as bottom sub-cell (1.04 eV) has been reported to produce conversion efficiency of 30.21% [103]. Similarly, antimony sulfide on thing crystalline silicon (Sb_3S_3 – on – c-Si) TSC with an efficiency of 23.5% shows much potential due to their natural abundance, complementary bandgaps, cost-competitiveness, and non-toxicity [104]. However, the prime challenge to be addressed during transitioning these new technologies from laboratory research to outdoor applications is light and elevated temperature induced degradation (LETID). For maximizing energy yield, subcell current matching during operation is important. Considering change in temperature, radiation, and dust level during operation, TSCs will often operate in a current limiting subcell configuration. Despite these challenges, Babics et al., [105] reported a PVK/Si tandem that shows high power output and retains 80% of its original power output after 1 year exposure under harshest weather. In general, tandem PV cells are expected to be a promising technology for next-generation mainstream solar cells as it shows clear edge of cost control, process simplicity, and very high efficiency.

Table 2**:**

2.5. PV cell efficiencies and building materials

The efficiencies of PV cells for various technologies obtained from different sources have been presented in the above sections. In this section, the highest cell efficiencies and building materials for different technologies have been illustrated. In 2023, National Renewable Energy Laboratory (NREL) reported the highest cell efficiencies for different technologies. The graphical presentation of the data reported NREL is presented in Fig. 7. The highest cell efficiencies of sc-Si and mc-Si PV technologies are 26.1% and 23.3%, respectively. For second-generation technology as seen in Fig. 6b, the maximum and minimum cell efficiencies are observed for GaAs and a-Si are 29.1% and 14%, respectively. The cell efficiency in emerging (third generation) cell technology is maximum for perovskite (25.7%) and minimum for DSSC (13%). The first-generation and some second-generation cells having good efficiency and performance are in mass production and commercially used for different applications. In recent times, the multijunction cells (fourth generation) are receiving greater importance. The highest efficiencies of two, three and four junction cells reported by NREL in 2023 (Fig. 6b) are 32.9, 39.5, and 39.2% respectively. The efficiencies of these technologies under concentrated conditions are reported by 35.5, 44.4, and 47.6% accordingly. Researchers across the globe are still optimistic about the improved performance and commercialization of new-generation PV cells. To predict the technological move in the future and the required materials and cost, Gervais et al., [7] conducted an in-depth study considering two pathways, namely, scenario A (Moderate roadmap) and scenario B (Innovative roadmap). Scenario A depicts the conservative evolution of PV technologies and their exitance in the coming decades. Scenario B presents the market entry of new generations and the fall of noncompetitive PV cell technologies. Besides, Fig. 8 illustrates the development of PV market until 2050, considering the moderate roadmap with scenario A and the innovative roadmap with scenario B [7].

In both scenarios, market share for PERC decreases with time, while it increases for III–V/Si technology. Scenario B presents its favorable

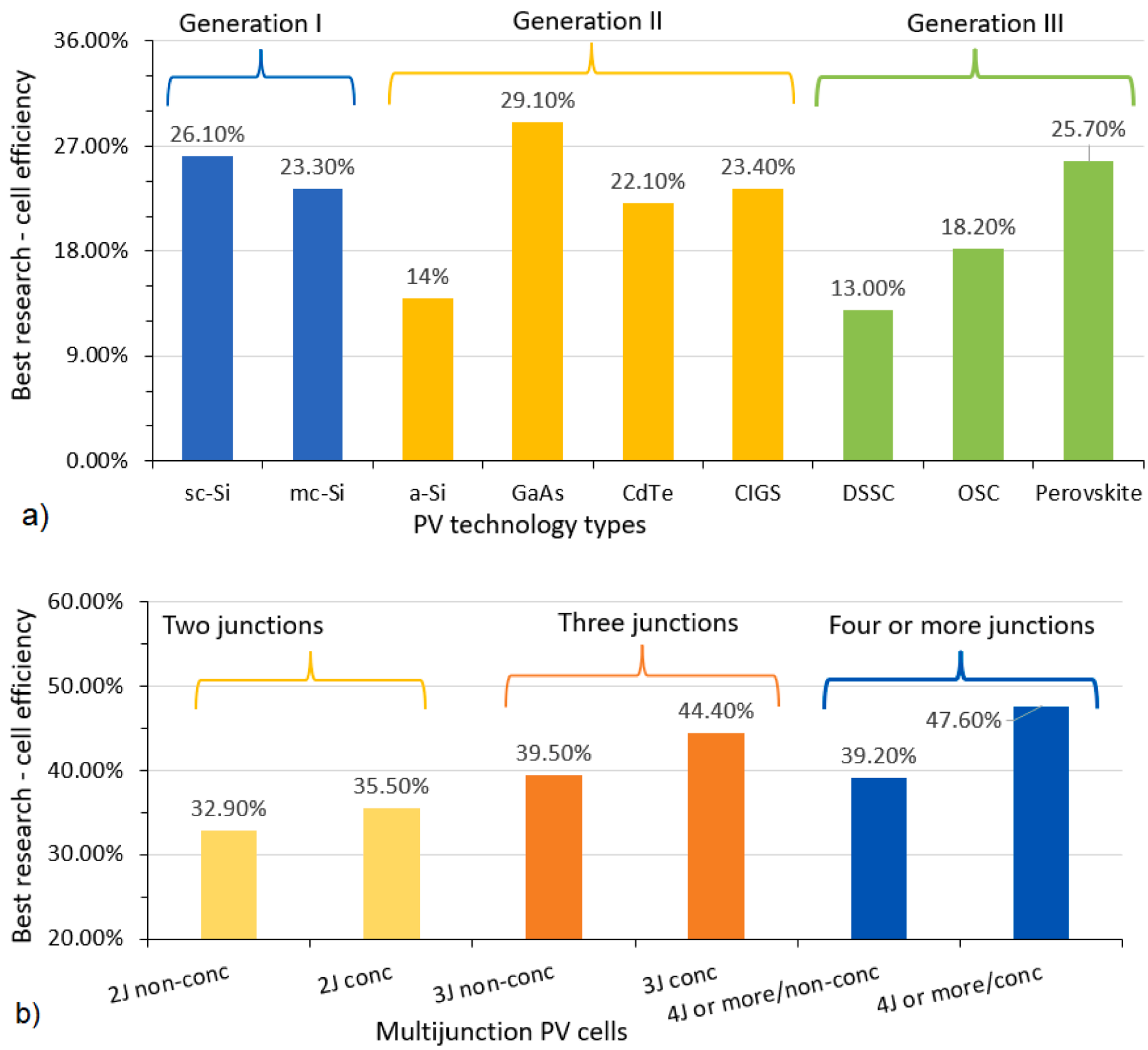

Fig. 7. Efficiencies of a) different PV cell technologies and b) multijunction cells (concentrator and non-concentrator) cells obtained from the best research. Adapted from Ref. [39].

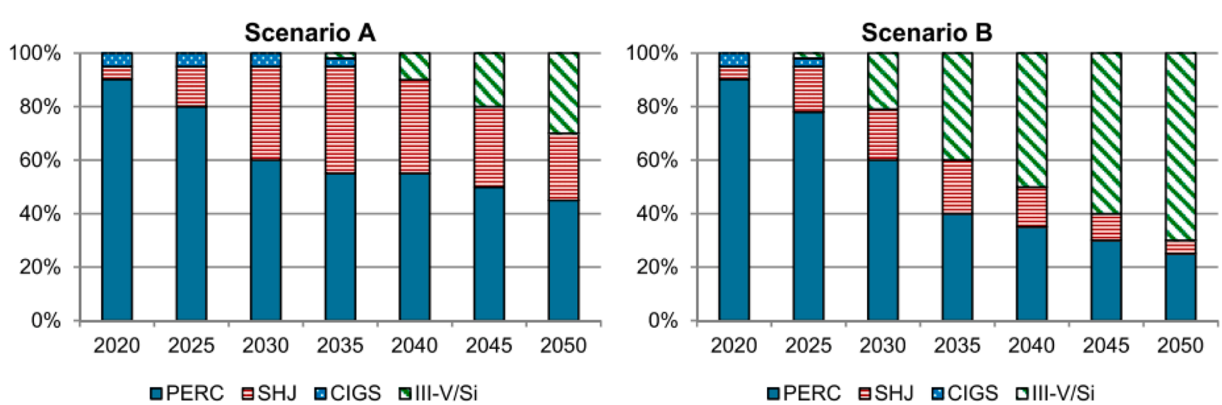

Fig. 8. Development of the PV market until 2050 considering a moderate roadmap with scenario A and an innovative roadmap with scenario B [Adapted from Ref. 7].

context starting from 2035 and dominates the market share of 70% by 2050. In scenario A, 40% of the market share will be achieved by SHJ in 2035, and it will decrease with time. According to Smith et al., [17], SHJ is predicted to grow from 5% market share in 2019 to 13% by 2025. The major materials required for PERC, SHJ, CIGS, and III–V/Si modules are Si, Al, and others, including Ag, In, Ga, Bi, and Pb [7]. Aluminum is mainly used in a module frame, while Si and other materials are used in metallic elements in different PV modules. Currently, the cost of c-Si represented by Al-BSF or PERC has already fallen to approximately \$0.25–0.27/watt [8]. It will decrease continuously soon by reducing the required silicon amount and wafer thickness and increasing power generation.

3. Cost of PV cell technologies

PV technologies, PV markets and the PV industries have changed drastically over the past few years. New opportunities and challenges have emerged as the PV technologies become much more affordable, and reliable. Cost analysis and performance of PV mainly represents its affordability and reliability respectively which ultimately reflect the feasibility of the technology. This section presents the history of price reduction for different energy producing technologies, and then focusses on the cost analysis of various PV technologies. The cost for various energy generation technologies is compared with an established metric, namely, levelized cost of energy (LCOE). It accounts for the accumulated energy and associated costs over the lifetime of a production process. In the last decade, the development of PV is increased by decreasing the related cost significantly. Fig. 9(a) presents the estimated LCOE of energy generation from various sources in 2009 and 2019 [121]. The energy price of PV in 2019 is 40 USD/MWh which is lower than that of wind (41 USD/MWh), gas (56 USD/MWh), coal (109 USD/MWh) and nuclear (155 USD/MWh). The cost of PV solar energy in 2009 was highest and it reduced to lowest in 2019. It is also observed that the PV cost in 2019 was reduced by around 89% as compared to that in 2009. A similar finding was also reported by IEA in 2020, where it stated that solar PV costs have reduced around 80% in the last 10 years [5]. The energy price for PV was the highest in 2009, but it was reduced to the lowest level in 2019 compared with those of wind, gas coal, and nuclear sources. The energy price of wind, gas, and coal in 2009 was reduced by 69.63%, 32.53%, and 1.8% as compared to those in 2009. Among all energy sources, PV has demonstrated the most potential energy technology in recent times due to its lowest energy price (40 USD/MWh) and highest cost reduction (89%) with time. Many researchers [122,123] conducted simulation and experimentations to identify the technical and cost-effective configuration for different PV technologies. In most cases, c-Si PV is reported as the most feasible technology. Currently, 90% of the PV market is dominated by c-Si, and 10% of the market is represented by thin-film PV modules and a low extent with different categories. The PV technologies currently available in mass production include c-Si, CdTe, and CIGS while lab or pilot scales include III-Vs and perovskites. Fig. 9(b) shows the estimated minimum sustainable price (MSP) and projected MSP for different PV technologies available in the market.

The cost analysis of PV technologies as shown in Fig. 9(b) presents

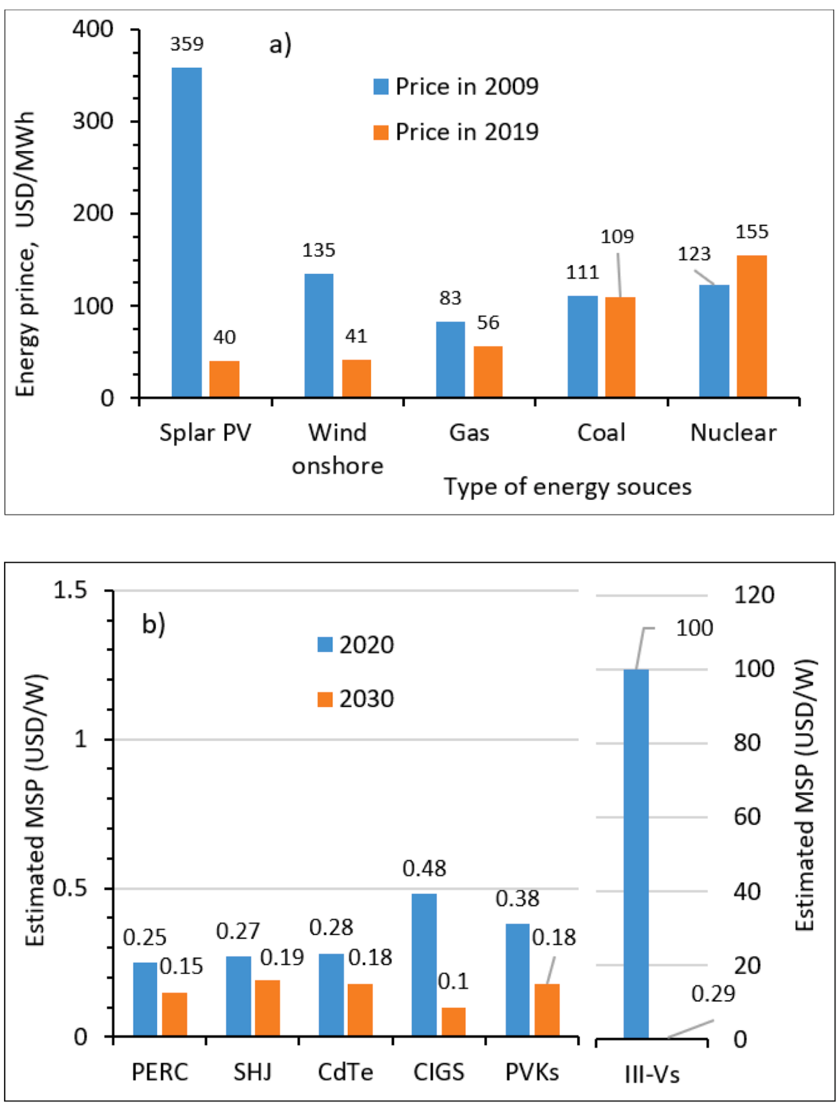

Fig. 9. A) estimated lcoe for new-generation resource applications in 2009 and 2019. adapted from ref. roser, [121], b) Estimated MSP for different established PV technologies, assuming 15% gross margin, Data source: Ref. Smith et al., [8].

that the estimated module prices of PERC, SHJ, CdTe, CIGS, perovskites and III–V in 2020 were approximately 0.25, 0.27, 0.28, 0.48, 0.38 and $100%/W respectively and are expected to be reduced to 0.15, 0.19, 0.18, 0.1, 0.18 and $0.29/W accordingly by 2030 [8]. The PERC cell technology is expected to maintain the best price competitiveness among all other promising PV technologies in the future. The CdTe and CIGS modules presented slightly higher MSPs while III-V showed extremely high price in 2020. The module prices of PERC, SHJ, CdTe, CIGS, perovskites and III–V are expected to be reduced by 2030 due to the developing technology and increased capacity of PV electricity generation. The 2030 projection assumes thinner wafers, reduces Ag paste use (drop to 50 mg/cell), increases throughputs, and enhances the module efficiency to 23%. PV modules with other materials have been developed in recent years because of remarkable research progress globally on this aspect. Therefore, these PV technologies are considered promising technology in recent and near-future time. In addition to these technologies, the III–V and perovskite PVs are currently in small-scale or pilot production [8]. As per Fig. 9(b), the estimated MSPs in 2020 for III–V and perovskite technology are $100/watt and $0.38/watt respectively. Because of the extremely high price of III-V PV technology, it is kept in niche markets such as terrestrial concentrator or space applications. On the other hand, perovskite has reasonable price, but its application is still limited due to its short life. Both III-Vs and perovskite PV technologies are under considerable research and their prices are expected to be decreased further to $0.29/watt and $0.18/watt, respectively by 2030. In recent times, perovskite on silicon tandem has received much popularity due to its high efficiency and low production cost. The estimated MSP of PVK/c-Si in 2020 is around $0.31/watt [8]. However, most of the new PV technologies are not feasible yet in their practical applications. As discussed above, utilization of some PV technologies is reported as technically feasible but economically it still seems unfeasible.

4. PV cell performance

The rapid development of PV building materials has introduced different potential cell technologies with interest to ensure quality products with high performance and reliability at a minimal cost. This section presents the performance of different PV cell technologies in terms of power output, power degradation, annual performance ratio (PR), merits and demerits of individual PV technologies. In the previous section, it was concluded that c-Si, CdTe, and CIGS cells among others are becoming increasingly attractive because of their improved power conversion efficiency with a lower MSP. The maximum power production capacity of c-Si or thin film (CdTe and CIGS) PV module available in markets is usually rated under standard test conditions (STC: 1000 W/m^2, 25 °C, and 1.5 AM). However, the resulted module surface temperature under actual operating conditions is significantly higher than that under STC, and it significantly reduces the PV output power. The decrease in the power output of a PV module due to the increase in operating temperature is presented by the percentage of a negative number of γ. Virtuani et al. [124] investigated the temperature coefficients and various operating temperature responses on power, open circuit voltage, and short circuit current for different commonly used PV modules (Fig. 10). All thin film technologies except thin film Si modules have lower γ for power compared with a c-Si module. The ascending

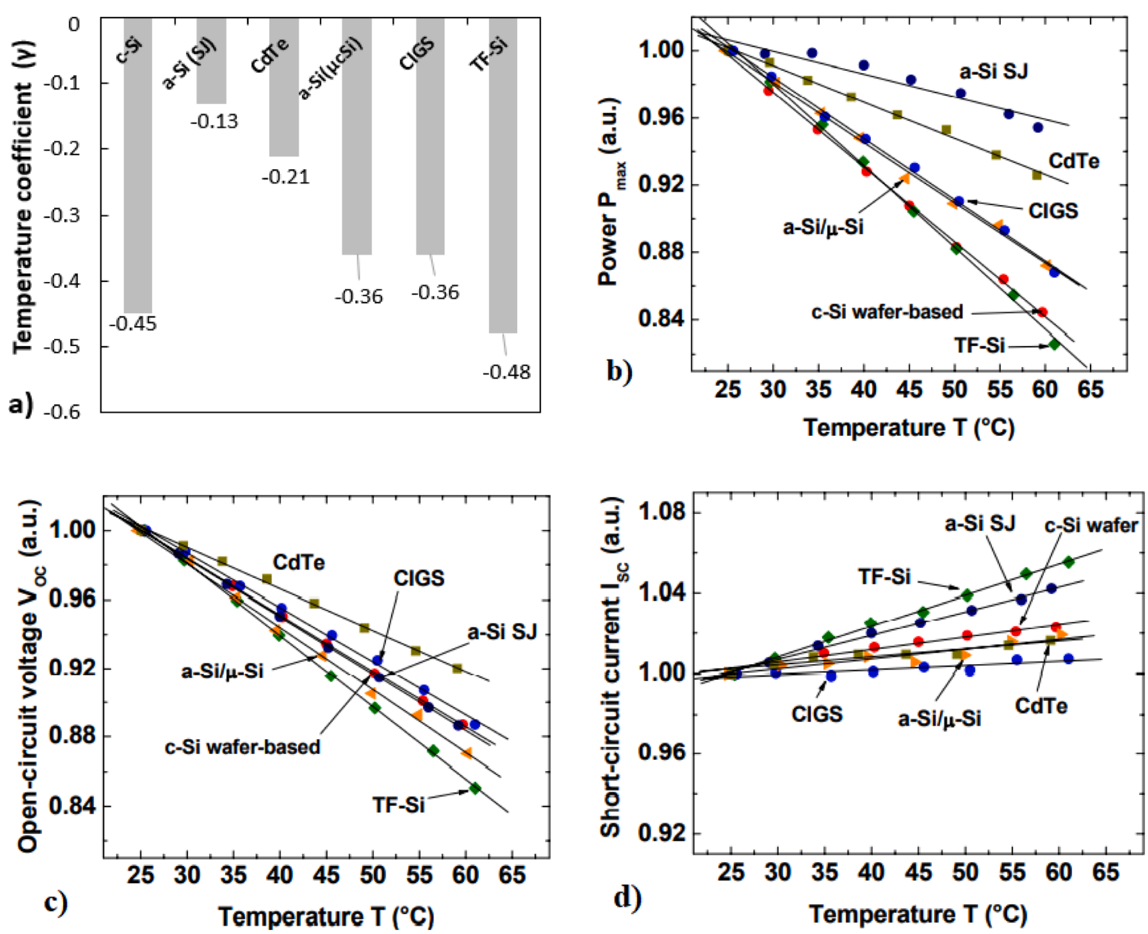

Fig. 10. A) temperature coefficient for power (γ) of single junction amorphous silicon (a-si sj), tandem micrograph (a-si/µc-si), cdte, cigs, and thin film c-si (tf-si); effect of temperature on b) module's maximum power (p_{max}), c) module's open circuit voltage (V_{oc}), and d) module's short circuit current (I_{sc}). Adapted from Ref. Virtuani et al., [124].

order of cell technologies in terms of temperature coefficients is TF-Si (−0.48%/°C) > c-Si (−0.45%/°C) > CIGS (−0.36%/°C) > CdTe (−0.21%/°C) > a-Si (−0.48%/°C). They added that the magnitudes of the temperature coefficient could strongly be correlated with the bad gap energy for the corresponding cell material. The approximate bad gap energies of these cell materials are 1.1 eV (c-Si), 1.8 eV (a-Si), ~1.2 eV (CIGS) and ~ 1.44 eV (CdTe). In Fig. 10, as the operating module temperature increases, the maximum power (P_{max}) and open circuit voltage (V_{oc}) decrease, whereas the short circuit current (I_{sc}) slightly increases. The PV efficiency decreases as the module surface temperature increases mainly because of the decrease in V_{oc} [126,148]. Thin film c-Si and c-Si cells are more sensitive to temperature than other cell technologies.

The percentage of efficiency loss due to an increase in module surface temperature is usually determined by γ (T_s −25 °C), where T_s is module surface temperature subjected to irradiation, and γ is a temperature coefficient (negative number) expressed as %/1 °C [127]. The value of γ depends on used cell materials and the module surface temperature is influenced by solar radiation, location and weather. Thus, the efficiency losses are particularly driven by PV materials, geographical location, solar radiation, weather, and corresponding module surface temperature. The actual solar energy yield per year for a particular PV material can vary depending on locations and operating conditions as well. The annual performance ratio (PR) representing the performance of various PV materials is derived by taking the ratio of the actual yield to the expected yield. According to Chandra and Yadav, [128], the PR of various technologies, such as mono-c-Si, m-c-Si, a-Si, CIGS, CdTe, and HIT, having the same kind of distribution sites and natural resources are 79.17%, 72.15%, 41.02%, 65.56%, 56.45%, and 97.27%, respectively (Fig. 11). They also added that PR could be influenced by solar irradiance, panel back side temperature, panel shading instruments used, inverter selection, losses present in panel, and period for data recording. As the PR offered by a PV module approaches 100%, the efficiency of the respective solar module increases. Practically, 100% cannot be achieved because of unavoidable losses during operation (e.g., thermal loss due to increased surface temperature). In Fig. 11, the maximum PR (97.27%) is observed in HIT technology, whereas the minimum PR (41.02%) is found in a-Si technology. HIT technology is becoming increasingly popular because of its good efficiency. It consists of an intrinsic a-Si layer followed by a p-type a-Si layer deposited on a randomly textured n-type Cz c-Si wafer to form a PN heterojunction. The PV industry has experienced tremendous growth because of increasing interest in green and sustainable energy, advances in PV performance, and PV cost reduction.

Table 3 summarizes the current scenario of different PV technologies in terms of merits and demerits. Until now, c-Si, CdTe, and CIGS cells have overcome the threshold of industrial production and commercial usage. However, CIGS is expected to be outdated by 2030 as noncompetitive PV cell technologies. According to Smith et al., [8], c-Si and CdTe technologies will likely achieve higher efficiency by 2030 because they can increase the annual energy yield and alleviate the system cost. The efficiency achieved for single junction c-Si approaches the theoretical value and therefore, multijunction or tandem cells have recently received greater attention as next-generation solar cells. Tandem cells have already been successfully commercialized. However, each multijunction TSC technology faces some difficulties including unsatisfactory performance, ease of fabrication, cost minimization, compatibility, instability and short service life or toxicity of the constituent subcells. The key issues to be explored in the development of super-high-efficiency MJ solar cells include the selection of subcell materials, the tunnel junction of subcell interconnection, carrier confinement, photon confinement, lattice matching, antireflection in a broader wavelength region, and so on [75]. The long-term stability TSC under the current mismatch is yet to be explored and discussed.

Table 3**:**

5. PV cell stability

This section presents the importance of PV cell stability, the degradation efficiency, environmental factors that deteriorate energy yield, defects in cells, defect identification techniques, and remedial measures. The stability of PV modules is vital for its different stockholders, including manufactures, project investors, and consumers. The reliable service life of PV modules helps manufacturers, project investors, and consumers provide more realistic warranties, make better financial decisions, and increase trust in PV energy accordingly [22]. However, predicting the reliable lifetime of PV a module is still quite challenging. A reliable PV system is mainly represented by lower degradation rate and longer service lifetimes. These are affected by building materials, processing technology, environment (e.g., cold and hot weather, humidity, snow, dust, and temperature), and operating conditions. The service life of a PV module usually lasts 25–30 years. However, PV

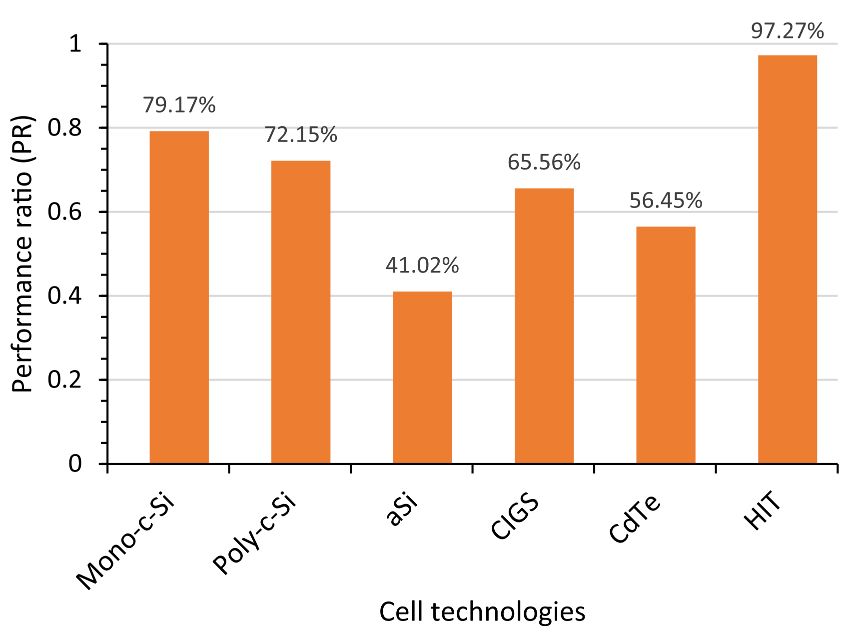

Fig. 11. Annual variation in the mean percentage of performance ratio (PR) of various technologies. Adapted from Ref. [128].

Table 3
The merits and demerits of different PV cell technologies.

PV cell technologies	Merits	Demerits
c-Si PV Single crystalline silicon (sc-Si) and Multi-crystalline silicon (mc-Si)	- Has plentiful bulk materials - Cell cost is drastically reduced - Reliable and degradation rate is less - Long service life and good stability	- Fragile and has limited efficiency - Indirect and low bandgap energy - Efficiency decreases as temp increases - Manufacturing process is complex
PERC	- Absorbs more irradiance - Reduced surface recombination - Less reflection due to having SiN_x	- Cell efficiency is approaching to limit - Cost reduction is slowed - Light induced degradation
Silicon heterojunction (SHJ)	- Has high efficiency - Low temperature coefficient - Bifacial harvesting at lower cost	- Major challenge – Ag and In free SHJ - Metallization and poor thin film - UV light stability & process complexity
Thin film PV		
Amorphous silicon	- Light, cheap and less silicon is needed. - It can be wrapped around a curve surface	- Has less efficiency and short life - It requires relatively larger area
Gallium arsenide (GaAs) thin film	- Higher conversion rate than c-Si - Has good temperature resistance	- High cost, package complexity - Highly toxic; it causes health hazards
Cadmium telluride (CdTe)	- Has potential to compete with c-Si in future - High solar absorption	- Toxic - Rare elements
Copper indium gallium selenide (CIGS)	- Direct bandgap materials - High solar absorption - Tandem CIGS devices	- Rare elements; to be outdated in 2030 - High growth temperature - Use of expensive vacuum equipment
Emerging PV		
Dye-sensitized cells	- Large spectral range and low cost. - It captures a large fraction of light - It works in low light conditions - High-temperature performance	- It uses of liquid electrolyte - Freezing, expansion, sealing problems - Instable - Danger with evaporation
Organic cells	- Lightweight nature, large area coverage - Low-cost of manufacturing - Semi-transparent and environment friendly - Easy integration with other products	- Low efficiency, stability, and strength - Electricity cannot flow very easily - Its efficiency is limited
Perovskite cells	- Cn absorb light of wider wavelength - It produces more electricity - Lightweight, flexible, semitransparent	- Poor film quality - Toxic in nature, less stability - Performance is degraded over time
Tandem PV III-V/Si and PVK/Si tandem cells	- Highly increased efficiency - Materials compatibility, wider bandgap - Control of manufacturing cost - Minimization of thermalization loses	- Major challenges with structure, material processing, junction multiplications, stability, carrier confinement, LETID, lattice matching etc.

modules over their service time slowly degrade and produce reduced electricity.

Sharma et al., [129] investigated the degradation behavior of a-Si, mc-Si and HIT modules upon outdoor exposure for 28 months in India. They observed that the average peak power was reduced by 6.4%, 0.5% and 0.36% for a-Si, mc-Si and HIT modules respectively. Oxidation of antireflecting coating, soiling of glass, and wavy pattern at the back of PV module was the frequent defects reported by them. However, no visual defects were identified in the HIT module except soling of glass. The efficiency degradation rate (% per year) of different cell technologies, including PERC, SHJ, CdTe, CIGS, and III–V observed by Smith et al., [8] under the standard test condition, is presented in Fig. 12. Perovskite cells showed the highest degradation rate of 80%/year in 2010, which is expected to be reduced to 0.5%/year by 2030. According to Wu et al., [130], the instability of organic–inorganic hybrid halide lead perovskite can be attributed to humidity, phase instability, thermal instability, and ion migration. They added that the possible solution could be additive engineering, surface passivation engineering, and perovskite composition engineering. The efficiency degradation rates of PERC, SHJ, CdTe, CIGS, and III–V (Fig. 12, inset) were 0.5, 0.7, 0.45, 0.45 and 0.4%/year respectively in 2020 and are expected to be reduced to 0.4%/year or below by 2030. The mean power degradation rates of sc-Si, mc-Si, and a-Si cells in Ghana reported by Aboagye et al., [18] are 1.37%/year, 1.44%/year, and 1.67%/year, respectively. The degradation rate basically helps assess the stability, service lifetime, and warranties of this technology.

The service lifetime and warranties of PV modules were only 10–15 years around four decades before [131], but in recent years, they increased to more than 25–30 years [128,132]. However, service life and energy-yielding performance are also influenced by operating conditions, locations, and environments. Santhakumari and Sagar, [133] comprehensively reviewed various atmospheric parameters responsible for deteriorating the module/cell efficiency, and failure categories that occur in a PV module over time during operation. All sorts of PV cells/modules can be subjected to different environmental factors, including dust, temperature, wind velocity, humidity, hailstorms, snowfalls, and sandstorms, and deteriorate the PV performance by reducing energy yield. These factors may create different defects in PV, including discoloration, anti-reflecting coating deterioration, corrosion, snails, glass breakage and cracking, delamination, and hotspot. The possible degradation mechanism with required explanation [23,134,135] and the inspection techniques [136–138] of these defects have been reported by multiple researchers from different parts of the globe. Table 4 summarizes the inspection techniques used and defects identified for different PV modules under outdoor exposures. As seen from Table 3, the faults in cells/modules can comprise electrical (poor soldering, shunts, short-circuited cells, shading, broken interconnection ribbons, and cell cracks), optical (delamination, encapsulant discoloration, bubble formation, and front glass copper breakage) or some other types of problems, including defective bypass diode, potentially induced degradation, and open circuited submodule. These degradations can be initiated and further aggravated during operation because of different environmental factors mentioned above and thus adversely affect cell performance. The close monitoring and analysis of degradation and its remedial measures are important to enhance the service life of PV cells. The common techniques to be employed for detecting the degradation of cells or modules include visual inspection, IR imaging, I–V characterization, electroluminescence (El) imaging, lock-in thermography (LIT), and UV fluorescence imaging. The awareness of enhancing performance by reducing environmental impacts is essential. In this case, several mitigation techniques reported by Santhakumari and Sagar, [133] include active and passive cooling, lightening protection, dust cleaning through mechanical cleaning, manual cleaning, natural, hydraulic surface, hydrophilic surface, water cleaning, electrodynamic screen (EDS), and so on. They added that these mitigation techniques are essential to enhance PV performance stability, especially for positioning it in desert,

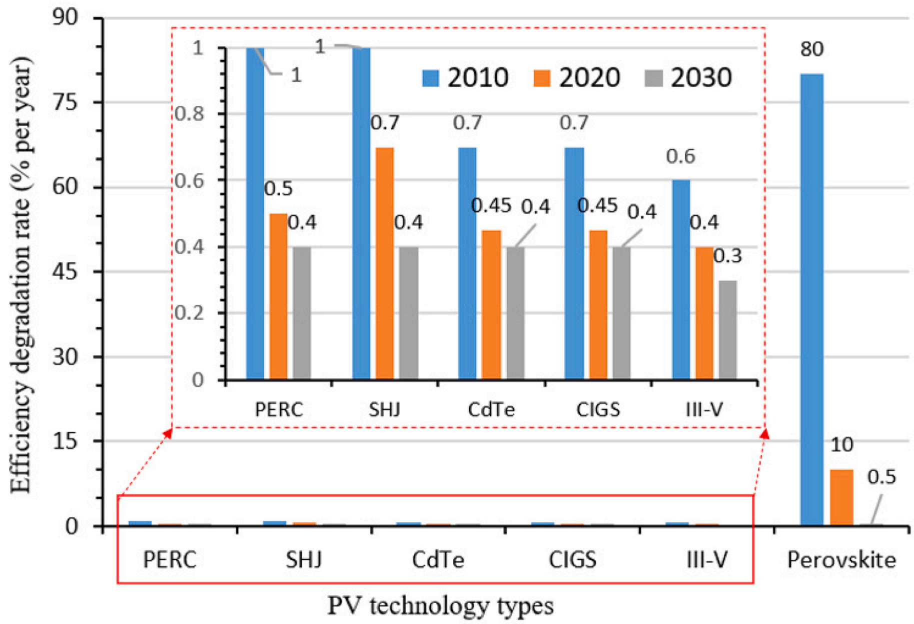

Fig. 12. Efficiency degradation rate (% per year) for different PV technologies. Adapted from Ref. [8].

Table 4
Summary of inspection techniques used, and defects identified for different PV modules under outdoor exposures (DR: Degradation rate of maximum power or mean power).

Country	Cell types	Period (y)	DR (%/y)	Defects reported and inspection techniques		Ref.
				Flaws	Inspection techniques	
Spain	mc-Si	22	1.4 (P_{mean})	Browning, milky pattern, and oxidation of the metallization grid	Visual inspection, IR thermography, EL, and electrical performance	[137]
Italy	2 Sc-Si	20	0.24, 0.84–2.75 (P_{max})	Broken fingers, cell disconnection, and corrosion	Visual inspection, infrared (IR), and electroluminescence (EL)	[138]
Malaysia	p-type mc-Si	9	–	Crack, power loss, and leakage current	EL imaging, dark I–V measurement, leakage current, and P_{max} measurement	[139]
Algeria	6 mc-Si	20–25	3.33–4.64 (P_{avg})	Busbar damage, cracks, ARE discoloration, and EVA degradation	Visual inspection, I–V, and P–V measurements	[140]
India	90 Sc-Si modules	22	0.3–4.1 (P_{avg})	Chalking of back sheet, corrosion, finger discoloration, and ribbon disconnection	Visual inspection, I–V, thermal imaging, and insulation registration Measurement	[134]
Italy	c-Si	20	0.22 (P_{max})	Discoloration, delamination, corrosion, finger discoloration, and ribbon disconnection	Visual inspection, I–V, IR thermography, and insulation resistance	[141]
Algeria	sc-Si	>12	4.16–7.87 (P_{max})	Delamination, EVA discoloration, corrosion, glass breakage, crack, solder bond, and ARC degradation	Visual inspection, I–V, and P–V	[142]
India	sc-Si	28	1.4 (P_{avg})	Delamination, glass breakage, bubbles formation, discoloration, grid and ARC degradation, soiling, hotspot, and crack	Visual inspection, Thermal imaging, and indoor I–V measurements	[143]
Algeria	sc-Si	0.75 to 32	0.26–4.75 (P_{max})	Delamination, discoloration, corrosion, cracks, broken glass, snails, soiling, and ARC degradation	Visual inspection, I–V, and P–V measurements	[144]
India	sc- and mc-Si	2.5	0.51 (P_{max})	Snails, discoloration, hotspot, and ribbon weakening	Visual inspection, thermal imaging, and indoor I–V	[145]
Italy	mc-Si	3	–	Snail trails, microcracks in cells, and fingers blackened	Visual inspection, dielectric withstand, I–V, wet leakage current, and EL	[146]
India	mc-Si	20	–	EVA discoloration, busbar and finger gridlines, and corrosion	Visual inspection, electroluminescence, and dark lock-in thermography	[147]

dusty, remote, and high-speed wind areas.

Table 4**:**

6. Summary and conclusions

In an attempt to promote solar energy utilization, this comprehensive review highlights the trends and advances of various PV cell technologies. The feasibility of PV cell technologies is accomplished by extending the discussion on generations of PV technology, PV building materials, efficiency, stability, cost analysis, and performance. The main purpose of this feasibility study is to highlight the current energy conversion efficiency, strength, and weakness of different PV cell technologies. Based on the literature study, the in-depth findings on these aspects are listed below:

i) The entire PV market is currently covered by two generations, namely, c-Si (90%) and thin film (10%) technologies. The c-Si PV includes approximately 15% Al-BSF, 70% PERC, 8.5% SHJ, 5% IBC and 1.5% Si-tandem. Al-BSF is expected to be outdated in 2026 and the use of PERC and SHJ will increase with time. The thin film PV technology is broadly covered by CdTe, CIGS, and CIGS. Recently, TOPCon, and tandem PV are considered promising technologies for the next generation mainstream PV solar system.
ii) The module costs of PERC, SHJ, CdTe, and CIGS are approximate \$0.25/watt, \$0.27/watt, \$0.28/watt, and \$0.48/watt, respectively. They are expected to be reduced further to \$0.15/watt, \$0.19/watt, \$0.18/watt, and \$0.1/watt accordingly by 2030. Some existing PV production is covered by III–Vs and perovskite technologies, which cost \$100/watt and \$0.38/watt in 2020 and are expected to be reduced to \$0.29/watt and \$0.18/watt, respectively by 2030.
iii) The three-mainstream thin-film PV technologies are a-Si, CdTe, and CIGS, which in 2023 offer cell efficacies of 14%, 22.1%, and 23.4%, respectively. The III–V compound solar cells, including GaAs, InP, AlGaAs, and InGaP are also considered potential thin film technology. The efficiencies of GaAs (29.1%), InP (24.1%), AlGaAs (16.6%), and InGaP (22%) are found to be quite good. However, the supply of gallium, indium, bismuth, arsenic, and selenium is short. Some of the materials used in thin films, such as cadmium and arsenic, are highly toxic and cause occupational health hazards, and some of them are rare and expensive.
iv) The emerging cell technologies (DSSC, OSC, and perovskite) are less expensive, but still not commercially used because of their short service life. Recently, PVK/Si TSC cell has been reported with a remarkable efficiency of 32.5%. However, the major challenges of TSCs during transitioning from lab to field are LETID, instability and subcell current matching. Researchers are potentially working to resolve these issues. They are focusing on Sn and Bi instead of using toxic Pb for making lead-free perovskite TSC.
v) c-Si, CdTe, and CIGS cells have overcome the threshold of industrial production and commercial usage. However, CIGS is expected to be commercially outdated in 2035, whereas c-Si and CdTe are expected to maintain the best competitiveness among other technologies in the future. The practical efficiency of c-Si approaches its theoretical limit; thus, some innovative strategies, such as III-Vs, III–V/Si and PVK/Si, might lead the technological progress in the near future.
vi) The most common faults in cells/modules are electrical (poor soldering, shunts, short-circuited cells, broken interconnection ribbons, and cell cracks), optical (delamination, encapsulant discoloration, bubble formation, and front glass copper breakage), or some other problems including defective bypass diode, potentially induced degradation, and open circuited submodule. These degradations can be initiated and further aggravated during operation because of different materials, environmental factors and adversely affect cell performance. The close monitoring and analysis of degradation and its remedial measures are important to enhance the service life of PV cells.

7. Future outlooks and prospects

i) Currently, tremendous research efforts are dedicated to PERC, SHJ, Si-tandem, IBC, and TOPCon to further enhance the performance, stability, and technology upscaling. However, the operational challenges, projected cost, and techno-economic analysis of these new technologies under the same environmental conditions and natural resources are not well documented in the scientific literatures.
ii) Development of TSC should be inclusive and address the outdoor operational challenges. The key issues to be explored in developing super-high-efficiency TSC include subcell material selection, ease of subcell interconnection, carrier confinement, lattice matching and so on.
iii) Currently, most of the thin-film technologies are involved with various losses (bulk, surface, interface, recombination, voltage, fill factor, and optical loses). They face different critical challenges including choice of materials, structural and material designs, coating, absorbers, performance monitoring, system optimization, control, reliability, stability and so forth.
iv) The behavior of new PV technologies is less straightforward owing to the variation of building materials and processing methods. Therefore, there is a pressing need to identify, characterize and mitigate the possible failure modes in practical field for avoiding the major delays in commercialization.

Declaration of Competing Interest

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

Acknowledgment

This work was funded by the Deanship of Scientific Research (DSR), the University of Jeddah, Jeddah (Grant No. UJ-02-004-ICGR). The authors gratefully acknowledge the technical and financial support of DSR.

References

[1] Agrawal, K., Jha, S., Mittal, R., Vashishtha, S., 2022. Assessment of floating solar PV (FSPV) potential and water conservation: Case study on Rajghat Dam in Uttar Pradesh, India. Energy Sustain. Dev. 66, 287–295. https://doi.org/10.1016/j.esd.2021.12.007.
[2] Madsen, D., Hansen, J., 2019. Outlook of solar energy in Europe based on economic growth characteristics. Renew. Sustain. Energy Rev. 114, 109306 https://doi.org/10.1016/j.rser.2019.109306.
[3] Guo, X., Dong, Y., Ren, D., 2023. CO2 emission reduction effect of photovoltaic industry through 2060 in China. Energy 269, 126692. https://doi.org/10.1016/j.energy.2023.126692.
[4] Ghaleb, B., Asif, M., 2022. Assessment of solar PV potential in commercial buildings. Renew. Energy 187, 618–630. https://doi.org/10.1016/j.renene.2022.01.013.
[5] IEA-PVPS, Task 1 Strategic PV Analysis and Outreach: 2020 Snapshot of Global PV Markets, Report IEA-PVPS T1-37: 2020. 2020.
[6] Spasić, V, *Global solar power to cross 200 GW annual installation threshold in 2022*. 2021.
[7] Gervais, E., Shammugam, S., Friedrich, L., Schlegl, T., 2021. Raw material needs for the large-scale deployment of photovoltaics – Effects of innovation-driven roadmaps on material constraints until 2050. Renew. Sustain. Energy Rev. 137, 110589 https://doi.org/10.1016/j.rser.2020.110589.
[8] Smith, B, Woodhouse, M, Horowitz, K, Silverman, T, Zuboy, J, Margolis, R, Photovoltaic (PV) Module Technologies: 2020 Benchmark Costs and Technology Evolution Framework Results, Technical Report NREL/TP-7A40-78173, November 2021. 2021.
[9] Abdelhameed, M., Abdelbar, M., Esmat, M., Jevasuwan, W., Fukata, N., 2022. Hole-injection role of solution-processed thermally treated VOx thin films in Si nanowire-based solar cells. Nano Energy 99, 107373. https://doi.org/10.1016/j.nanoen.2022.107373.
[10] Preeti, K., S., 2023. Extraction and analysis of TCO coated glass from waste amorphous silicon thin film solar module. Sol. Energy Mater. Sol. Cells 253, 112227. https://doi.org/10.1016/j.solmat.2023.112227.
[11] Kabir, F., Manir, S., Bhuiyan, M., Aftab, S., Ghanbari, H., Hasani, A., Fawzy, M., Silva, M., Mohammadzadeh, M., Ahmadi, R., Abnavi, A., Askar, A., Adachi, M., 2022. Instability of dye-sensitized solar cells using natural dyes and approaches to improving stability – An overview. Sustainable Energy Technol. Assess. 52, 102196 https://doi.org/10.1016/j.seta.2022.102196.
[12] Fan, Z., Wang, Y., Xu, S., Hou, S., Zhuang, C., Wang, B., 2022. Versatile third components in organic ternary solar cells. Sol. Energy 231, 732–757. https://doi.org/10.1016/j.solener.2021.12.009.
[13] Iqbal, M., Manzoor, M., Noor, N., Rehman, I., Mushahid, N., Aftab, S., Alanazi, Y., Ullah, H., Afzal, A., 2022. Tuning of the electronic bandgap of lead-free double perovskites K2AgBiX6 (X = Cl, Br) for solar cells applications and their

thermoelectric characteristics. Sol. Energy 239, 234–241. https://doi.org/10.1016/j.solener.2022.05.018.
[14] Ahmad, K., Khan, M., Kim, H., 2022. Simulation and fabrication of all-inorganic antimony halide perovskite-like material based Pb-free perovskite solar cells. Opt. Mater. 128, 112374 https://doi.org/10.1016/j.optmat.2022.112374.
[15] Khan, F, Rezgui, B, Khan, M, Al-Sulaiman, F. Perovskite-based tandem solar cells: Device architecture, stability, and economic perspectives. Renewable and Sustainable Energy Reviews. 2022; In Press: 112553. 10.1016/j.rser.2022.112553.
[16] Yan, L., Qiu, S., Yu, B., Huang, J., Qiu, J., Zhang, C., Guo, F., Yang, Y., Mai, Y., 2022:. Synergistic Passivation of Perovskite Absorber Films for Efficient Four-Terminal Perovskite/Silicon Tandem Solar Cells. Adv. Energy Sustainability Res. 2100199. https://doi.org/10.1002/aesr.202100199.
[17] Singh, B., Goyal, S., Kumar, P., 2021. Solar PV cell materials and technologies: Analyzing the recent developments. Mater. Today:. Proc. 43, 2843–2849. https://doi.org/10.1016/j.matpr.2021.01.003.
[18] Aboagye, B., Gyamfi, S., Ofosu, E., Djordjevic, S., 2021. Degradation analysis of installed solar photovoltaic (PV) modules under outdoor conditions in Ghana. Energy Rep. 7, 6921–6931. https://doi.org/10.1016/j.egyr.2021.10.046.
[19] Ghosh, S., Singh, S.K., Yadav, V.K., 2023. Experimental investigation of hotspot phenomenon in PV arrays under mismatch conditions. Sol. Energy 253, 219–230. https://doi.org/10.1016/j.solener.2023.02.033.
[20] Carigiet, F., Brabec, C., Baumgartner, F., 2021. Long-term power degradation analysis of crystalline silicon PV modules using indoor and outdoor measurement techniques. Renew. Sustain. Energy Rev. 144, 111005 https://doi.org/10.1016/j.rser.2021.111005.
[21] Nieto-Díaz, B., Crossland, A., Groves, C., 2021. A levelized cost of energy approach to select and optimise emerging PV technologies: The relative impact of degradation, cost and initial efficiency. Appl. Energy 299, 117302. https://doi.org/10.1016/j.apenergy.2021.117302.
[22] Weib, K., Bruckman, L., French, R., Oreski, G., Tanahashi, T., 2021. Service Life Estimation for Photovoltaic Modules. Report IEA-PVPS T13–16, 2021.
[23] Kim, J., Rabelo, M., Padi, S.P., Yousuf, H., Cho, E., Yi, J., 2021. A review of the Degradation of Photovoltaic Modules for Life Expectancy. Energies 14, 4278. https://doi.org/10.3390/en14144278.
[24] Ghosh, D.K., Bose, S., Das, G., Acharyya, S., Nandi, A., Mukhopadhyay, S., Sengupta, A., 2022. Fundamentals, present status and future perspective of TOPCon solar cells: A comprehensive review. Surf. Interfaces 30, 101917. https://doi.org/10.1016/j.surfin.2022.101917.
[25] Techdirections, Techdirections, October 2019, New PV Cells Benefit Energy Harvesting. 2019.
[26] Brun, N, Wehrli, B, Fent, K. Ecotoxicological assessment of solar cell leachates: Copper indium gallium selenide (CIGS) cells show higher activity than organic photovoltaic (OPV) cells. Sci. Total Environ. 2016; 543: 703–14. 10.1016/ j.scitotenv.2015.11.074.
[27] Yoshikawa, K., Kawasaki, H., Yoshida, W., Irie, T., Konishi, K., Nakano, K., Uto, T., Adachi, D., Kanematsu, M., Uzu, H., Yamamoto, K., 2017. Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion e–ciency over 26%. Nat. Energy. 2, 17032. https://doi.org/10.1038/nenergy.2017.32.
[28] Richter, A., Hermle, M., Glunz, S., 2013. Reassessment of the Limiting Efficiency for Crystalline Silicon Solar Cells. IEEE J. Photovoltaics 3, 1184–1191. https://doi.org/10.1109/JPHOTOV.2013.2270351.
[29] Salameh, T., Zhang, D., Juaidi, A., Alami, A., Al-Hinti, I., Olabi, A., 2021. Review of solar photovoltaic cooling systems technologies with environmental and economical assessment. J. Clean. Prod. 326, 129421 https://doi.org/10.1016/j.jclepro.2021.129421.
[30] Khan, F., Rezgui, B.D., Khan, M.T., Al-Sulaiman, F., 2022. Perovskite-based tandem solar cells: Device architecture, stability, and economic perspectives. Renew. Sustain. Energy Rev. 165, 112553 https://doi.org/10.1016/j.rser.2022.112553.
[31] Chapin, D., Fuller, C., Pearson, G., 1954. A new siliconp-njunctionphotocell for converting solar radiation into electrical power. J Appl Phys. 25, 676. https://doi.org/10.1063/1.1721711.
[32] Green, M., 2019. Photovoltaic technology and visions for the future. Prog. Energy 1, 013001. https://doi.org/10.1088/2516-1083/ab0fa8.
[33] Blakers, A.W., Green, M.A., Jiqun, S., Keller, E.M., Wenham, S.R., Godfrey, R.B., Szpitalak, T., Willison, M.R., 1984. 18-percent efficient terrestrial silicon solar cells. IEEE Electron Device Lett. 5 (1), 12–13. https://doi.org/10.1109/EDL.1984.25813.
[34] Kashyap, S., Pandey, R., Madan, J., Sharma, R., 2022. Design and simulations of 24.7% efficient silicide on oxide-based electrostatically doped (SILO-ED) carrier selective contact PERC solar cell. Micro and Nanostructures. 165, 207200 https://doi.org/10.1016/j.micrna.2022.207200.
[35] Kashyap, S., Madan, J., Pandey, R., Ramanujam, J., 2022. 22.8% efficient ion implanted PERC solar cell with a roadmap to achieve 23.5% efficiency: A process and device simulation study. Opt. Mater. 128, 112399 https://doi.org/10.1016/j.optmat.2022.112399.
[36] Cheng, H., Liu, W., Liu, Z., Yang, Z., Ma, D., Du, H., Luo, J., Xing, H., Liao, M., Zeng, Y., Yan, B., Ye, J., 2022. Emitter formation with boron diffusion from PECVD deposited boron-doped silicon oxide for high-efficiency TOPCon solar cells. Sol. Energy Mater. Sol. Cells 240, 111713. https://doi.org/10.1016/j.solmat.2022.111713.
[37] Descoeudres, A., Allebé, C., Badel, N., Barraud, L., Champliaud, J., Christmann, G., Debrot, F., Faes, A., Geissbühler, J., Horzel, J., Lachowicz, A., Levrat, J., Martin de Nicolas, S., Nicolay, S., Paviet-Salomon, B., Senaud, L.L., Ballif, C., Despeisse, M., 2018. Low-temperature processes for passivation and metallization of high-efficiency crystalline silicon solar cells. Sol. Energy 175, 54–59. https://doi.org/10.1016/j.solener.2018.01.074.
[38] Hutchins, M, Tandem cells approaching 30% efficiency, 30.01; 2020. https://www.pv-magazine.com/2020/01/30/tandems-cells-approaching-30-efficiency/. 2020.
[39] NREL, Transforming energy, 2023, Photovoltaic research – The best research – cell efficiency, https://www.nrel.gov/pv/pvdpc/. 2023.
[40] Ning, L., Song, L., Zhang, J., 2022. Research progress of light and elevated temperature-induced degradation in silicon solar cells: A review. J. Alloy. Compd. 912, 165120 https://doi.org/10.1016/j.jallcom.2022.165120.
[41] Kazmerski, L., 2015. Best Research Solar Cell Efficiencies. National Renewable Energy Laboratory. Retrieved from www.nrel.gov/ncpv/images/efficiency_chart.jpg.
[42] Steiner, M.A., France, R.M., Buencuerpo, J., Geisz, J.F., Nielsen, M.P., Pusch, A., Olavarria, W.J., Young, M., Ekins-Daukes, N.J., 2021. 32.9% efficient tandem solar cell with strain-balanced GaInAs/GaAsP quantum wells. 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC).
[43] Kojima, A., Teshima, K., Shirai, Y., Miyasaka, T., 2009. Organometal halide perovskites as visible-light sensitizers for photovoltaic cells. J Am Chem Soc. 131 (17), 6050–6051. https://doi.org/10.1021/ja809598r.
[44] Im, J.H., Lee, C.R., Lee, J.W., Park, S.W., Park, N.G., 2011. 6.5% efficient perovskite quantum-dot-sensitized solar cell. Nanoscale 3 (10), 4088–4093. https://doi.org/10.1039/c1nr10867k.
[45] Chen, W., Wu, Y., Yue, Y., Liu, J., Zhang, W., Yang, X., Chen, H., Bi, E., Ashraful, I., Grätzel, M., Han, L., 2015. Efficient and stable large-area perovskite solar cells with inorganic charge extraction layers. Science 350 (6263), 944–948. https://doi.org/10.1126/science.aad1015.
[46] Zhang, P., Chen, J., Song, L., Gu, N., Du, P., Chen, X., Zha, L., Chen, W.-H., Xiong, J., 2022. Passivation of perovskite surfaces using 2-hydroxyacetophenone to fabricate solar cells with over 20.7% efficiency under air environment. Appl. Surf. Sci. 598, 153842 https://doi.org/10.1016/j.apsusc.2022.153842.
[47] Mat Yunin, M.Y.A., Mohd Adenam, N., Khairul, W.M., Yusoff, A.H., Adli, H.K., 2022. Effect of Stability of Two-Dimensional (2D) Aminoethyl Methacrylate Perovskite Using Lead-Based Materials for Ammonia Gas Sensor Application. Polymers (Basel) 14 (9). https://doi.org/10.3390/polym14091853.
[48] Svanström, S., García-Fernández, A., Jacobsson, T.J., Bidermane, I., Leitner, T., Sloboda, T., Man, G.J., Boschloo, G., Johansson, E.M.J., Rensmo, H., Cappel, U.B., 2022. The Complex Degradation Mechanism of Copper Electrodes on Lead Halide Perovskites. ACS Mater Au. 2 (3), 301–312. https://doi.org/10.1021/acsmaterialsau.1c00038.
[49] Kim, C., Jung, E., Noh, Y., Seo, S., Choi, Y., Park, H., Song, M., Choi, K., 2021. Strategy for large-scale monolithic Perovskite/Silicon tandem solar cell: A review of recent progress. EcoMat. 3, 12084. https://doi.org/10.1002/eom2.12084.
[50] Jain, N., Hudait, M., 2014. III–V multijunction solar cell integration with silicon: present status, challenges and future Outlook. Energy Harvesting and Systems 3–4. https://doi.org/10.1515/ehs-2014-0012.
[51] Feldman, D, Ramasamy, V, Margolis, R, *U*.S. Solar Photovoltaic BESS System Cost Benchmark Q1 2020 Report. National Renewable Energy Laboratory - Data (NREL-DATA), Golden, CO (United States); National Renewable Energy Laboratory (NREL), Golden, CO (United States). 2021.
[52] Philipps, S, Warmuth, W. Photovoltaics report. . Fraunhofer ISE. 2017: 1-43.
[53] Magazine, S, A Complete Guide to PERC Solar Panels (vs. Other Techs), 6th March, 2022, Solar Magazine, https://solarmagazine.com/solar-panels/perc-solar-panels/. 2022.
[54] Green, M., Hishikawa, Y., Dunlop, E., Levi, D., Hohl-Ebinger, J., Yoshita, M., HoBaillie, A., 2019. Solar cell efficiency tables (Version 53). Prog Photovoltaics Res Appl 27, 3–12.
[55] Cookson, C, Leap in efficiency of solar cells predicted by inventor, 7th Feruary, 2023, https://www.ft.com/content/031bacfe-80df-458c-a00c-25520a99505c. 2023.
[56] Yu, J., Bai, Y., Li, J., Qiu, Q., Chen, T., Huang, Y., Yu, J., Liao, J., 2023. Process challenges of high-performance silicon heterojunction solar cells with copper electrodes. Sol. Energy Mater. Sol. Cells 250, 112057. https://doi.org/10.1016/j.solmat.2022.112057.
[57] Magazine, S, Heterojunction solar panels: How they work & benefits, Solar Magazine, 23 March, 2023, https://solarmagazine.com/solar-panels/heterojunction-solar-panels. 2023.
[58] ITRPV, International Technology Roadmap for Photovoltaic (ITRPV) 2021,12th edition. 2021.
[59] Zeng, Y., Peng, C.-W., Hong, W., Wang, S., Yu, C., Zou, S., Su, X., 2022. Review on Metallization Approaches for High-Efficiency Silicon Heterojunction Solar Cells. Transactions of Tianjin University. 28 (5), 358–373. https://doi.org/10.1007/s12209-022-00336-9.
[60] Wu, C.-K., Zou, S., Peng, C.-W., Gu, S.-W., Ni, M.-F., Zeng, Y.-L., Sun, H., Zhang, X.-H., Su, X.-D., 2023. Improving the UV-light stability of silicon heterojunction solar cells through plasmon-enhanced luminescence downshifting of $YVO_4:Eu^{3+}$, Bi^{3+} nanophosphors decorated with Ag nanoparticles. Journal of Energy Chemistry. 81, 212–220. https://doi.org/10.1016/j.jechem.2023.01.050.
[61] Veirman, J., Caron, J.S., Jeronimo, P., Gageot, T., Kinfack Leoga, A.J., Ozanne, A. S., De Vecchi, S., Soulas, R., Favre, W., Ragonesi, A., Carbone, L., Sciuto, M., Voltan, A., 2022. Towards an industrial in-line solution for efficient post-treatment of silicon heterojunction solar cells. Sol. Energy Mater. Sol. Cells 245, 111867. https://doi.org/10.1016/j.solmat.2022.111867.

[62] Yousuf, E.H., Khokhar, M., Chowdhury, S., Pham, D.P., Kim, Y., Ju, M., Cho, Y., Cho, E., Yi, J., 2021. A Review on TOPCon Solar Cell Technology. Current Photovoltaic Research. 9, 75–83. https://doi.org/10.21218/CPR.2021.9.3.075.
[63] Richter, A., Benick, J., Feldmann, F., Fell, A., Hermle, M., Glunz, S.W., 2017. n-Type Si solar cells with passivating electron contact: Identifying sources for efficiency limitations by wafer thickness and resistivity variation. Sol. Energy Mater. Sol. Cells 173, 96–105. https://doi.org/10.1016/j.solmat.2017.05.042.
[64] Green, M., Hishikawa, Y., Dunlop, E., Levi, D., Hohl-Ebinger, J., Ho-Baillie, A., 2018. Solar cell efficiency tables (version 51). Prog. Photovoltaics Res. Appl. 26, 3–12. https://doi.org/10.1002/pip.2978.
[65] Haase, F., Hollemann, C., Schäfer, S., Merkle, A., Rienäcker, M., Krügener, J., Brendel, R., Peibst, R., 2018. Laser contact openings for local poly-Si-metal contacts enabling 26.1%-efficient POLO-IBC solar cells. Sol. Energy Mater. Sol. Cells 186, 184–193. https://doi.org/10.1016/j.solmat.2018.06.020.
[66] Liu, C., Chen, D., Chen, Y., Ling, Y., Zou, Y., Wang, Y., Gong, J., Feng, Z., Altermatt, P.P., Verlinden, P.J., 2020. Industrial TOPCon solar cells on n-type quasi-mono Si wafers with efficiencies above 23%. Sol. Energy Mater. Sol. Cells 215, 110690. https://doi.org/10.1016/j.solmat.2020.110690.
[67] Wang, L., Tang, Y., Zhang, S., Wang, F., Wang, J., 2022. Energy yield analysis of different bifacial PV (photovoltaic) technologies: TOPCon, HJT. PERC in Hainan. Solar Energy. 238, 258–263. https://doi.org/10.1016/j.solener.2022.03.038.
[68] Zhang, T., Wang, M., Yang, H., 2018. A Review of the Energy Performance and Life-Cycle Assessment of Building-Integrated Photovoltaic (BIPV). Systems Energies. 11, 3157. https://doi.org/10.3390/en11113157.
[69] Ren, X., Li, J., Jiao, D., Gao, D., Pei, G., 2020. Temperature-dependent performance of amorphous silicon photovoltaic/thermal systems in the long term operation. Appl. Energy 275, 115156. https://doi.org/10.1016/j.apenergy.2020.115156.
[70] Okamoto, H., Nitta, Y., Yamaguchi, T., Hamakawa, Y., 1980. Device physics and design of a-Si ITO/pin heteroface solar cells. Sol. Energy Mater. 2, 313–325.
[71] Andersson, B., 2000. Materials availability for large-scale thin film photovoltaics. Prog Photovoltaics Res Appl. 8, 61–76.
[72] Mertens, K., 2018. Photovoltaics: Fundamentals, Technology, and Practice. John Wiley & Sons Prog Photovoltaics Res Appl. 8 (1), 61–76.
[73] Kayes, B, Nie, H, Twist, R, Spruytte, S, Reinhardt, F, Kizilyalli, I, Higashi, G. 27.6% conversion efficiency, a new record for single junction solar cells under 1 sun illumination. Proceedings of the 37th IEEE Photovoltaic Specialists Conference, IEEE; 2011:4 2011. doi:DOI: 10.1109/ PVSC.2011.6185831.
[74] Green, M., Dunlop, E., HohlEbinger, J., Yoshita, M., Kopidakis, N., Hao, X., 2020. Solar cell efficiency tables (Version 56). Progr. Photovoltaics. 28, 629. https://doi.org/10.1002/pip.3303.
[75] Yamaguchi, M. High-Efficiency GaAs-Based Solar Cells. In Post-Transition Metals; IntechOpen: London, UK, 2020. 2020. 10.5772/intechopen.94365.
[76] Sampaio, P., Gonzalez, M., 2017. Photovoltaic solar energy: conceptual framework. Renew. Sustain. Energy Rev. 74, 590–601. https://doi.org/10.1016/j.rser.2017.02.081.
[77] Sharma, K., Sharma, V., Sharma, S., 2018. Dye-Sensitized Solar Cells: Fundamentals and Current Status. Nanoscale Res. Lett. 13, 381. https://doi.org/10.1186/s11671-018-2760-6.
[78] Kabir, F., Manir, S., Bhuiyan, M.M.H., Aftab, S., Ghanbari, H., Hasani, A., Fawzy, M., De Silva, G.L.T., Mohammadzadeh, M.R., Ahmadi, R., Abnavi, A., Askar, A.M., Adachi, M.M., 2022. Instability of dye-sensitized solar cells using natural dyes and approaches to improving stability – An overview. Sustainable Energy Technol. Assess. 52, 102196 https://doi.org/10.1016/j.seta.2022.102196.
[79] Liu, S., Sun, Y., Chen, L., Zhang, Q., Li, X., Shuai, J., 2022. A review on plasmonic nanostructures for efficiency enhancement of organic solar cells. Materials Today Physics. 24, 100680 https://doi.org/10.1016/j.mtphys.2022.100680.
[80] Xie, F., Zhang, D., Su, H., Ren, X., Wong, K., Gratzel, M., Choy, W., 2015. Vacuumassisted thermal annealing of CH3NH3PbI3 for highly stable and efficient perovskite solar cells. ACS Nano 9, 639–646. https://doi.org/10.1021/nn505978r.
[81] Liao, W., Zhao, D., Yu, Y., Grice, C., Wang, C., Cimaroli, A., Schulz, P., Meng, W., Zhu, K., Xiong, R., 2016. Lead-free inverted planar formamidinium tin triiodide perovskite solar cells achieving power conversion efficiencies up to 6.22%. Adv. Mater. 28, 9333–9340. https://doi.org/10.1002/adma.201602992.
[82] Volonakis, G., Filip, M., Haghighirad, A., Sakai, N., Wenger, B., Snaith, H., Giustino, F., 2016. Lead-free halide double perovskites via heterovalent substitution of noble metals. J. Phys. Chem. Lett. 7, 1254–1259.
[83] You, J., Meng, L., Song, T., Guo, T., Yang, Y., Chang, W., Hong, Z., Chen, H., Zhou, H., Chen, Q., 2016. Improved air stability of perovskite solar cells via solutionprocessed metal oxide transport layers. Nat. Nanotechnol. 11, 75–81. https://doi.org/10.1038/nnano.2015.230.
[84] Zhang, T., Wang, M., Yang, H., 2018. A Review of the Energy Performance and Life-Cycle Assessment of Building-Integrated Photovoltaic (BIPV) Systems. Energies 11, 3157. https://doi.org/10.3390/en11113157.
[85] Almansouri, I., Ho-Baillie, A., Green, M., 2015. Ultimate Efficiency Limit of Single-Junction Perovskite and Dual-Junction Perovskite/Silicon Two-Terminal Devices. Jpn. J. Appl. Phys. 54, 08KD4. https://doi.org/10.7567/JJAP.54.08KD04.
[86] Marti, A., Araujo, G., 1996. Limiting Efficiencies for Photovoltaic Energy Conversion in Multigap Systems. Sol. Energy Mater. Sol. Cells. 43, 203–222. https://doi.org/10.1088/0022-3727/12/3/014.
[87] Futscher, M., Ehrler, B., 2016. Efficiency Limit of Perovskite/Si Tandem Solar Cells. ACS Energy Lett. 1, 863–868. https://doi.org/10.1021/acsenergylett.6b00405.
[88] Papež, N., 2021. 2021.. Degradation of GaAs Solar Cells. Brno University of Technology, Brno, Czech Republic. Ph.D. Thesis,.
[89] Jain, N ,Hudait, M. III–V multijunction solar cell integration with silicon: present status, challenges and future Outlook. Energy Harvesting and Systems. 2014; 1(3-4).
[90] Iles, P., 2001. Evolution of space solar cells. Sol. Energy Mater. Sol. Cells. 68, 1–13. https://doi.org/10.1016/S0927-0248(00)00341-X.
[91] Yamaguchi, M, Takamoto, T, Araki, K. Present and future of super high efficiency multi-junction solar cells, in: M. Osinski, F. Henneberger, K. Edamatsu (Eds.), Proc. SPIE, 2008: p. 688906. . 2008. 10.1117/12.784117.
[92] King, R.R., Law, D.C., Edmondson, K.M., Fetzer, C.M., Kinsey, G.S., Yoon, H., Sherif, R.A., Karam, N.H., 2007. 40% efficient metamorphic GaInP/GaInAs/Ge multijunction solar cells. Appl. Phys. Lett. 90, 183516 https://doi.org/10.1063/1.2734507.
[93] Han, S., Dhungel, S.K., Park, S., de Assis Rabelo, M., Pham, D.P., Kim, Y., Yi, J., 2023. Integration of Subcells in III-V//Si Tandem Solar Cells. Trans. Electr. Electron. Mater. https://doi.org/10.1007/s42341-023-00430-2.
[94] Geisz, J., France, R., KL, S, Steiner, M, Norman, A, Guthrey, H, Young, M, Song, T, Moriarty, T., 2020. Six-junction III–V solar cells with 47.1% conversion efficiency under 143 suns concentration. Nature. Energy 5, 326. https://doi.org/10.1038/s41560-020-0598-5.
[95] Geisz, J., Kurtz, S., Wanlass, M., Ward, J., Duda, A., Friedman, D., Olson, J., McMahon, W., Moriarty, T., Kiehl, J., 2007. High-efficiency GaInP/GaAs/InGaAs triple-junction solar cells grown inverted with a metamorphic bottom junction. Appl Phys Lett 91, 023502. https://doi.org/10.1063/1.2753729.
[96] Kao, Y., Chou, H., Hsu, S., Lin, A., Lin, C., Shih, Z., Chang, C., Hong, H., Horng, R., 2019. Performancec omparison of III–V//Si and III–V//InGaAs multi-junction solar cells fabricated by the combination of mechanical stacking and wire bonding. Sci Rep 9, 4308. https://doi.org/10.1038/s41598-019-40727-y.
[97] Geisz, J., Friedman, D., Ward, J., Duda, A., Olavarria, W., Moriarty, T., Kiehl, J., Romero, M., Norman, A., Jones, K., 2008. 40.8% efficient inverted triple-junction solar cell with two independently metamorphic junctions. Appl Phys Lett 93, 123505. https://doi.org/10.1063/1.2988497.
[98] Dimroth, F., Grave, M., Beutel, P., Fiedeler, U., Karcher, C., Tibbits, T., Oliva, E., Siefer, G., Schachtner, M., Wekkeli, A., Bett, A., Krause, R., Piccin, M., Blanc, N., Drazek, C., Guiot, E., Ghyselen, B., Salvetat, T., Tauzin, A., Signamarcheix, T., Dobrich, A., Hannappel, T., Schwarzburg, K., 2014. Wafer bonded four-junction GaInP/GaAs//GaInAsP/GaInAs concentrator solar cells with 44.7% efficiency. Prog Photovoltaics Res Appl 22, 277–282.
[99] Abdi-Jalebi, M., Andaji-Garmaroudi, Z., Cacovich, S., Stavrakas, C., Philippe, B., Richter, J.M., Alsari, M., Booker, E.P., Hutter, E.M., Pearson, A.J., Lilliu, S., Savenije, T.J., Rensmo, H., Divitini, G., Ducati, C., Friend, R.H., Stranks, S.D., 2018. Maximizing and stabilizing luminescence from halide perovskites with potassium passivation. Nature 555 (7697), 497–501. https://doi.org/10.1038/nature25989.
[100] Jäger, K., Sutter, J., Hammerschmidt, M., Schneider, P.-I., Becker, C., 2020. Prospects of light management in perovskite/silicon tandem solar cells. Nanophotonics. 10, 1991–2000.
[101] Liu, J., Aydin, E., Yin, J., Bastiani, M., Isikgor, F., Rehman, A., Yengel, E., Ugur, E., Harrison, G., Wang, M., Gao, Y., Khan, J., Babics, M., Allen, T., Subbiah, A., Zhu, K., Zheng, X., Yan, W., Xu, F., Salvador, M., Bakr, O., Anthopoulos, T., Lanza, M., Mohammed, O., Laquai, F., Wolf, S., 2021. 28.2%-efficient, outdoor-stable perovskite/silicon tandem solar cell, Joule. 5, 3169–3186. https://doi.org/10.1016/j.joule.2021.11.003.
[102] Yan, L, Qiu, S, Yu, B, Huang, J, Qiu, J, Zhang, C, Guo, F, Yang, Y, Mai, Y. Synergistic Passivation of Perovskite Absorber Films for Efficient Four-Terminal Perovskite/Silicon Tandem Solar Cells. Advanced Energy and Sustainability Research. n/a(n/a): 2100199. 10.1002/aesr.202100199.
[103] Singh, A.K., Chauhan, M.S., Patel, S.P., Singh, R.S., Singh, V.K., 2023. MAPbI3-on-CuInSe2 two-terminal monolithically integrated and four-terminal mechanically stacked tandem solar cells: A Theoretical Investigation Using SCAPS-1D. Results in Optics. 10, 100358 https://doi.org/10.1016/j.rio.2023.100358.
[104] Okil, M., Shaker, A., Ahmed, I.S., Abdolkader, T.M., Salem, M.S., 2023. Design and analysis of Sb2S3/Si thin film tandem solar cell. Sol. Energy Mater. Sol. Cells 253, 112210. https://doi.org/10.1016/j.solmat.2023.112210.
[105] Babics, M., De Bastiani, M., Ugur, E., Xu, L., Bristow, H., Toniolo, F., Raja, W., Subbiah, A.S., Liu, J., Torres Merino, L.V., Aydin, E., Sarwade, S., Allen, T.G., Razzaq, A., Wehbe, N., Salvador, M.F., De Wolf, S., 2023. One-year outdoor operation of monolithic perovskite/silicon tandem solar cells. Cell Reports Physical Science. 4 (2), 101280 https://doi.org/10.1016/j.xcrp.2023.101280.
[106] Mailoa, J., Bailie, C., Johlin, E., Hoke, E., Akey, A., Nguyen, W., McGehee, M., Buonassisi, T., 2015. A 2-terminal perovskite/silicon multijunction solar cell enabled by a silicon tunnel junction. Appl Phys Lett. 106, 121105 https://doi.org/10.1063/1.4914179.
[107] Werner, J., Dubuis, G., Walter, A., Löper, P., Moon, S., Nicolay, S., Masis, M., Wolf, S., Niesen, B., Ballif, C., 2015. Sputtered rear electrode with broadband transparency for perovskite solar cells. Sol. Energy Mater. Sol. Cells 141, 407–413. https://doi.org/10.1016/j.solmat.2015.06.024.
[108] Werner, J., Barraud, L., Walter, A., Bräuninger, M., Sahli, F., Sacchetto, D., Tétreault, N., Paviet-Salomon, B., Moon, S.-J., Allebé, C., Despeisse, M., Nicolay, S., De Wolf, S., Niesen, B., Ballif, C., 2016. Efficient Near-Infrared-Transparent Perovskite Solar Cells Enabling Direct Comparison of 4-Terminal and Monolithic Perovskite/Silicon Tandem Cells. ACS Energy Lett. 1 (2), 474–480. https://doi.org/10.1021/acsenergylett.6b00254.

[109] Chen, B., Bai, Y., Yu, Z., Li, T., Zheng, X., Dong, O., Shen, L., Boccard, M., Gruverman, A., Holman, Z., Huang, J., 2016. Efficient semitransparent perovskite solar cells for 23.0%-Efficiency perovskite/silicon four-terminal tandem cells. Adv Energy Mater. 6, 1601128. https://doi.org/10.1002/aenm.201601128.
[110] Fan, R., Zhou, N., Zhang, L., Yang, R., Meng, Y., Guo, L., Chen, Y., Xu, Z., Zheng, G., Huang, Y., Li, L., Qin, L., Qiu, X., Chen, Q., Zhou, H., 2017. Toward full solution processed perovskite/Si monolithic tandem solar device with PCE exceeding 20%. Solar RRL. 1, 1700149. https://doi.org/10.1002/solr.201700149.
[111] Duong, T., Wu, Y., Shen, H., Peng, J., Fu, X., Jacobs, D., Wang, E.-C., Kho, T.C., Fong, K.C., Stocks, M., Franklin, E., Blakers, A., Zin, N., McIntosh, K., Li, W., Cheng, Y.-B., White, T.P., Weber, K., Catchpole, K., 2017. Rubidium Multication Perovskite with Optimized Bandgap for Perovskite-Silicon Tandem with over 26% Efficiency. Adv. Energy Mater. 7 (14), 1700228. https://doi.org/10.1002/aenm.201700228.
[112] Qiu, Z., Xu, Z., Li, N., Zhou, N., Chen, Y., Wan, X., Liu, J., Li, N., Hao, X., Bi, P., Chen, Q., Cao, B., Zhou, H., 2018. Monolithic perovskite/Si tandem solar cells exceeding 22% efficiency via optimizing top cell absorber. Nano Energy 53, 798–807. https://doi.org/10.1016/j.nanoen.2018.09.052.
[113] He, Y., Tang, Z., Mao, L., Yang, S., Yang, T., Xie, M., Chang, Q., Ding, L., He, B., Peng, C., Yu, C., Hao, X., Zhang, J., Zheng, K., Han, C., Zhang, Y., Yan, H., Xu, X. M., 2021. Minimizing Open-Circuit Voltage Loss in Perovskite/Si Tandem Solar Cells via Exploring the Synergic Effect of Cations and Anions. physica status solidi (RRL) – Rapid Research Letters 15, 2100119.
[114] Mazzarella, L., Lin, Y., Kirner, S., Vilches, A., Korte, L., Albrecht, S., Crossland, E., Stannowski, B., Case, C., Snaith, H., Schlatmann, R., 2019. Infrared light management using a nanocrystalline silicon oxide interlayer in monolithic perovskite/silicon heterojunction tandem solar cells with efficiency above 25%. Adv Energy Mater. 9, 1803241. https://doi.org/10.1002/aenm.201803241.
[115] Chen, B., Bai, Y., Yu, Z., Li, T., Zheng, X., Dong, Q., Shen, L., Boccard, M., Gruverman, A., Holman, Z., Huang, J., 2016. Efficient Semitransparent Perovskite Solar Cells for 23.0%-Efficiency Perovskite/Silicon Four-Terminal Tandem Cells. Adv. Energy Mater. 6 (19), 1601128. https://doi.org/10.1002/aenm.201601128.
[116] Hou, Y., Aydin, E., De Bastiani, M., Xiao, C., Isikgor, F.H., Xue, D.J., Chen, B., Chen, H., Bahrami, B., Chowdhury, A.H., Johnston, A.K., Baek, S.-W., Huang, Z., Wei, M., Dong, Y., Troughton, J., Jalmood, R., Mirabelli, A.J., Allen, T.G., van Kerschaver, E., Saidaminov, M.I., Baran, D., Qiao, Q., Zhu, K., De Wolf, S., Sargent, E.H., 2020. Efficient tandem solar cells with solution-processed perovskite on textured crystalline silicon. Science 367, 1135–1140.
[117] Gharibzadeh, S., Hossain, I.M., Fassl, P., Nejand, B.A., Abzieher, T., Schultes, M., Ahlswede, E., Jackson, P., Powalla, M., Schäfer, S., Rienäcker, M., Wietler, T., Peibst, R., Lemmer, U., Richards, B.S., Paetzold, U.W., 2020. 2D/3D Heterostructure for Semitransparent Perovskite Solar Cells with Engineered Bandgap Enables Efficiencies Exceeding 25% in Four-Terminal Tandems with Silicon and CIGS. Adv. Funct. Mater. 30 (19), 1909919. https://doi.org/10.1002/adfm.201909919.
[118] Yang, D., Zhang, X., Hou, Y., Wang, K., Ye, T., Yoon, J., Wu, C., Sanghadasa, M., Liu, S., Priya, S., 2021. 28.3%-efficiency perovskite/silicon tandem solar cell by optimal transparent electrode for high efficient semitransparent top cell. Nano Energy 84, 105934. https://doi.org/10.1016/j.nanoen.2021.105934.
[119] Wang, L., Song, Q., Pei, F., Chen, Y., Dou, J., Wang, H., Shi, C., Zhang, X., Fan, R., Zhou, W., Qiu, Z., Kang, J., Wang, X., Lambertz, A., Sun, M., Niu, X., Ma, Y., Zhu, C., Zhou, H., Hong, J., Bai, Y., Duan, W., Ding, K., Chen, Q., 2022. Strain Modulation for Light-Stable n-i-p Perovskite/Silicon Tandem Solar Cells. Adv Mater. e2201315.
[120] Raza, E., Ahmad, Z., Aziz, F., Asif, M., Mehmood, M.Q., Bhadra, J., Al-Thani, N.J., 2023. Design and optimization of four-terminal mechanically stacked and optically coupled silicon/perovskite tandem solar cells with over 28% efficiency. Heliyon. 9 (2), e13477.
[121] Roser, M, Why did renewables become so cheap so fast? August 21, 2021. 2021.
[122] Kristiawan, R., Widiastuti, I., Suharno, S., 2018. Technical and economical feasibility analysis of photovoltaic power installation on a university campus in indonesia. MATEC Web of Conferences. 197, 08012. https://doi.org/10.1051/matecconf/201819708012.
[123] Kamal, M.M., Ashraf, I., 2021:. Modeling and assessment of economic viability of grid-connected photovoltaic system for rural electrification. Energy Sources Part A 1–18. https://doi.org/10.1080/15567036.2021.1905108.
[124] Virtuani, A, Pavanello, D, Friesen, G. Overview of temperature coefficients of different thin film photovoltaic technologies, 25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain. 2010. doi:DOI: 10.4229%2F25thEUPVSEC2010-4AV.3.83.
[126] Rubaiee, S., Fazal, M.A., 2022. The Influence of Various Solar Radiations on the Efficiency of a Photovoltaic Solar Module Integrated with a Passive Cooling System. Energies 15. https://doi.org/10.3390/en15249584.
[127] Kang, M., Rohatgi, A., Ristow, A., 2014. Development of a simple analytical model to quantify the PV module cost premium associated with module efficiency and cell technology. Renew. Sustain. Energy Rev. 37, 380–385. https://doi.org/10.1016/j.rser.2014.05.027.
[128] Chandra, S ,Yadav, A. An analysis of material technology dependent choice for customers to install PV projects. Materials Today: Proceedings. 2021; (in press). 10.1016/j.matpr.2021.11.079.
[129] Sharma, V., Sastry, O., Kumar, A., Bora, B., Chandel, S., 2014. Degradation analysis of a-Si, (HIT) hetro-junction intrinsic thin layer silicon and m-C-Si solar photovoltaic technologies under outdoor. Energy 72, 536–546. https://doi.org/10.1016/j.energy.2014.05.078.
[130] Wu, M, Ladi, N, Yi, Z, Li, H, Shen, Y, Wang, M. Stability Issue of Perovskite Solar Cells under Real-World Operating Conditions. Energy Technology 2019; 8. doi: https://doi-org.sdl.idm.oclc.org/10.1002/ente.201900744.
[131] Christensen, E., 1985. Flat-plate Solar Array Project 10 years of Progress. DOE, JPL, NASA. Appl. Energy 299, 117302. https://doi.org/10.1016/j.rser.2020.110589.
[132] Wiser, R., BM, Seel J., 2020. Benchmarking Utility-Scale PV Operational Expenses and Project Lifetimes: Results from a Survey of U.S. Solar Industry Professionals. https://doi.org/10.2172/1631678.
[133] Santhakumari, M., Sagar, N. A review of the environmental factors degrading the performance of silicon wafer-based photovoltaic modules: Failure detection methods and essential mitigation techniques. Renewable and Sustainable Energy Reviews. 2019; 110: 83–100. . 10.1016/j.rser.2019.04.024.
[134] Rajput, P., Tiwari, G., Sastry, O., Bora, B., Sharma, V., 2016. Degradation of mono-crystalline photovoltaic modules after 22 years of outdoor exposure in the composite climate of India. Sol. Energy 135, 786–795. https://doi.org/10.1016/j.solener.2016.06. 047.
[135] Ndiaye, A., Charki, A., Kobi, A., Kébé, C., Ndiaye, P., Sambou, V., 2013. Degradations of silicon photovoltaic modules: A literature review. Sol Energy 96, 140–151. https://doi.org/10.1016/j.solener.2013.07.005.
[136] Köntges, M., Kajari-Schröder, S., Kunze, I., 2012:. Cells Cracks Measured by UV Fluorescence in the Field, 27th. European Photovoltaic Solar Energy Conference and Exhibition. 3033–3040. https://doi.org/10.4229/27thEUPVSEC2012-4CO.11.4.
[137] Sánchez, L., López-Lara, G., Vera-Medina, J., Pérez-Aparicio, E., Lillo-Bravo, I., 2021. Degradation analysis of photovoltaic modules after operating for 22 years. A case study with comparisons. Sol. Energy 222, 84–94. https://doi.org/10.1016/j.solener.2021.04.026.
[138] Berardone, I., Lopez, G., Paggi, M., 2018. Analysis of electroluminescence and infrared thermal images of monocrystalline silicon photovoltaic modules after 20 years of outdoor use in a solar vehicle. Sol. Energy 173, 478–486. https://doi.org/10.1016/j.solener.2018.07.055.
[139] Islam, M., Hasanuzzaman, M., Rahim, N., 2018. Investigation of the potential induced degradation of on-site aged polycrystalline PV modules operating in Malaysia. Meas J Int Meas Confed 119, 283–294. https://doi.org/10.1016/j.measurement. 2018.01.061.
[140] Kahoul, N., Chenni, R., Cheghib, H., Mekhilef, S., 2017. Evaluating the reliability of crystalline silicon photovoltaic modules in harsh environment. Renew Energy. 109, 66–72. https://doi.org/10.1016/j.renene.2017.02.078.
[141] Pozza, A., Sample, T., 2016. Crystalline silicon PV module degradation after 20 years of field exposure studied by electrical tests, electroluminescence, and LBIC. Prog Photovoltaics Res Appl. 24, 368–378. https://doi.org/10.1002/pip.
[142] Bouraiou, A., Hamouda, M., Chaker, A., Lachtar, S., Neçaibia, A., Boutasseta, N., Mostefaoui, M., 2017. Experimental evaluation of the performance and degradation of single crystalline silicon photovoltaic modules in the Saharan environment. Energy 132, 22–30. https://doi.org/10.1016/j.energy.2017.05.056.
[143] Chandel, S., Nagaraju, N., Sharma, V., Chandel, R., 2015. Degradation analysis of 28 year field exposed mono-c-Si photovoltaic modules of a direct coupled solar water pumping system in western Himalayan region of India. Renew Energy. 78, 193–202. https://doi.org/10.1016/j.renene.2015.01.015.
[144] Bouraiou, A., Hamouda, M., Chaker, A., Neçaibia, A., Mostefaoui, M., Boutasseta, N., Zianea, A., Daboua, R., Sahouanea, N., Lachtar, S., 2018. Experimental investigation of observed defects in crystalline silicon PV modules under outdoor hot dry climatic conditions in Algeria. Sol. Energy 159, 475–487. https://doi.org/10.1016/j.solener.2017.11.018.
[145] Sharma, V., Chandel, S., 2016. A novel study for determining early life degradation of multi-crystalline-silicon photovoltaic modules observed in western Himalayan Indian climatic conditions. Sol Energy. 134, 32–44. https://doi.org/10.1016/j. solener.2016.04.023.
[146] Dolara, A., Lazaroiu, G., Leva, S., Manzolini, G., Votta, L., 2016. Snail trails and cell microcrack impact on PV module maximum power and energy production IEEE. J. Photovolt. 6, 1269–1277. https://doi.org/10.1109/JPHOTOV.2016.2576682.
[147] Sinha, A., Sastry, O., Gupta, R., 2016. Nondestructive characterization of encapsulant discoloration effects in crystalline-silicon PV modules. Sol. Energy Mater. Sol. Cells 155, 234–242. https://doi.org/10.1016/j.solmat.2016.06.019.
[148] Rubaiee, S., Fazal, M.A., 2023. Efficiency enhancement of photovoltaic solar system by integrating multi-pipe copper frame filled with ZnO-doped phase change material. MRS Energy & Sustainability. https://doi.org/10.1557/s43581-023-00063-1.