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A Review of Emerging Photovoltaic Construction Technologies to Increase Efficiencies in Solar as a Renewable Energy Source

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Abstract

The need to reduce photovoltaic cell manufacturing and project development costs while focusing on providing cheap and highly efficient photovoltaic cells has led to the emergence of innovative technological advances in the photovoltaic cell materials and fabrication. This study carries out a systematic overview of the latest design technologies in the solar cell materials, shape and layout that have emerged and recorded high efficiencies. For each emerging solar cell technology, the most recent advances are outlined with their respective achieved theoretical efficiencies. Besides the silicon-based solar cells that have been highly commercialized with less than 20% theoretical power conversion efficiency (PCE) and currently having the largest market share, it has been found that the emerging technologies in solar cell materials and fabrication have recorded significantly improved efficiencies of up to 47%. Based on the ongoing research and developments in the engineering of photovoltaic cell materials, renewable solar energy promises a huge potential and growth towards global energy sustainability and this paper provides a guide in the policy making, commercialization and future investments in solar energy.

Keywords: renewable energy; photovoltaic cells; semiconductor material; crystalline silicon; solar radiation; power conversion efficiency.

1. Introduction

Solar energy is one of the environmental-friendly, economical and renewable energy sources that has minimum operation and maintenance costs with relatively high efficiencies [1]. Currently, its use is increasingly being integrated in both small-scale applications like domestic homes and large-scale applications in smart cities and various industries around the world.

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The top five leading installations of solar power globally are China (45%), India (11%), United States (11%), Japan (7%) and Australia (3%). These five countries account to 77% of the total installed global capacity [2, 3]. In the past decade, several countries have recorded an exponential growth in their solar power generation with a mean compound rate of more than 36% every year [2, 4] and as of 2019, approximately 590 GW [3, 5] of solar energy that was newly installed.

The increasing trend in PV panels installations has triggered novel improvements in design technology, increased efficiencies as well as reduced fabrication costs. This growing trend of global solar energy installations is shown in figure 1:

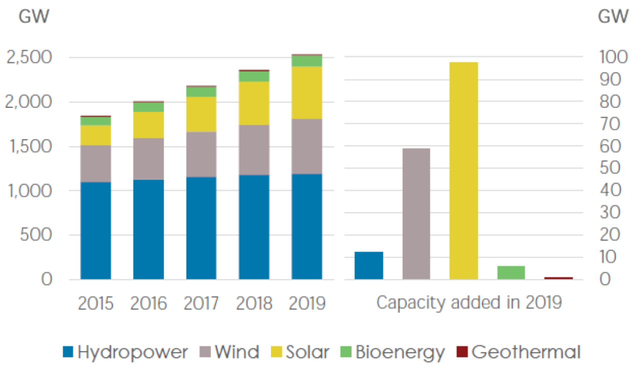

Figure 1: renewable energy power capacity growth [3].

Table 1: African countries with highest solar radiation [8].

Country	Solar Irradiance (annual kWh/m^2)	Country	Solar Irradiance (annual kWh/m^2)
Kenya	2837	Botswana	3000
Egypt	2036	Sudan	1888
South Africa	2156	Morocco	1789
Niger	1540	Chad	1651
Senegal	1518	Madagascar	1962
Zambia	2004	Sudan	1888

In 2019, 591GW cumulative installed solar power globally was added to the grid of which the European Union dominated with over 133 GW [6] whereas Africa constituted the least proportion of about 9% of the total capacity that is 556 MW [7]. Among the African counties, the highest solar energy utilization is in South Africa and Morocco, which is still low when compared to countries with highest solar production and utilization countries like China, Spain, Germany, Denmark and even the USA. Notably, most African countries have high solar radiations that makes them have high potential in solar energy installations in the future and some of the countries with the highest solar radiations are shown in table 1.

There are two technically established configurations of the solar power system that are integrated with energy storage systems in order to provide sustainable electrical energy. These are the Photovoltaic (PV) system and the Concentrating Solar-thermal Power (CSP) system [9]. The PV system relies on the photovoltaic effect of the solar cell materials with a simple energy generation and hence it is the preferred configuration whereas the CSP system relies on parabolic concentrators with complex energy conversion process which has limited its widespread adoption.

A typical solar power PV system primarily consists of a PV panel which generates electrical power based on the mechanism of photovoltaic effect, and a battery which stores the electric energy generated from the PV panel as shown in in figure 2. Photovoltaic process is the conversion of light energy into electric energy in the solar cells and its efficiency is influenced by factors which include the nature of the solar cell material, the solar cell shape,

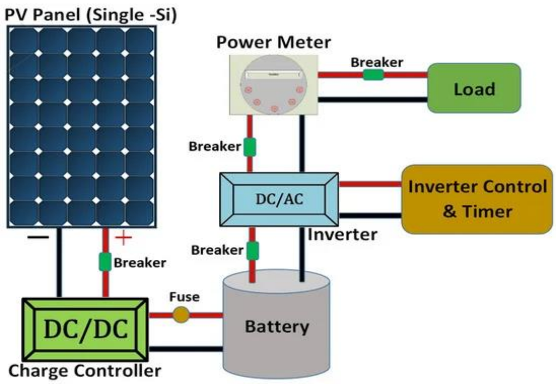

Figure 2: schematic of a typical solar PV system [6].

size and layout as well as the intensity of incident solar radiation from the sun [4]. The intermediary between the PV panel and the battery is served by a charge controller which is a DC/DC converter responsible for regulating the energy that is stored in the battery. When a load (a power consuming device) is connected to the battery, a DC/AC inverter is applied as an intermediary that converts the power from a direct current (dc) power that is stored in the battery to an alternating current (ac) power required by the utility device.

This study is based on the latest research and technological developments in renewable solar power and will show the recent advancements with promising high solar cell efficiencies with focus on PV material fabrication, outline the novel technologies of the PV panels based on their layout and configuration, and lastly provide an assessment of the social, economic and environmental impact of the emerging PV technologies. The study can be used as a guide in the future investments in the solar PV technology.

2. Current Technology in PV Cell Materials

Research is ongoing for various materials to be used in the design of the solar panels with an interest in minimizing the cost and improving the efficiency of the PV cells. Silicon, sometimes referred to the first-generation solar cells, was the first viable solar cell material to be used and even currently it still dominates the commercially available solar cells in the market, however it has relatively low solar efficiencies ranging from 12 to 16% as well as high manufacturing costs [10]. The silicon-based solar cells can be classified into two broad categories [4] that is (1) Crystalline Silicon (c-SI) solar cells – this is the most popular class of solar cells that were designed using the water-based technology which can be divided further into monocrystalline or polycrystalline and (2) Amorphous Silicon (a-SI) solar cells – the a-SI solar cells were designed using the thin film technology and their development led to advanced solar-cells known as Hydrogenated Amorphous Silicon (a-Si:H). During the manufacturing of the silicon-based PV (Si-PV) cells, the fabrication is exclusively implemented based on the first-generation technology. Typically, the Si-PV cells has a silicon semi-conductor p-n junction as the basic unit in the solar cell structure as shown in figure 3:

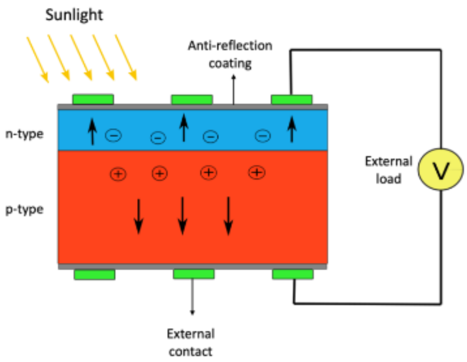

Figure 3: silicon semi-conductor p-n junction [10].

Further developments resulted into second-generation solar cells based on the integration of multiple semiconductor materials. As a result, two classes of solar cells that emerged [4] are (1) III-V Single-Junction solar cells – this solar-cells were essentially a combination of group III and group V elements of the periodic table using the wafer-based technology, examples include the GAInP (Gallium Indium Phosphorus) and GaAs (Gallium Arsenide); (2) Chalcogenides solar cells – this solar-cells were developed from combination of various chalcogen semiconductor elements that were fabricated using thin film technology. These solar cells include CdTe (Cadmium Telluride), CZTS (Copper Zinc Tin Sulphide) and CIGS (Copper Indium Gallium Diselenide).

Eventually, the third-generation technology is the latest emerging technology in the construction and materials used in solar cells. This novel technology relies entirely on the thin-film technology and it has made it possible to modify the traditional PV cell technology with the aim of increasing the power conversion efficiency (PCE) and minimizing the fabrication cost and hence reducing the overall cost of the solar panel. The following are the most intensely researched and promising technologies [4] for optimal semi-conductor PV cell material:

2.1 Passivated Emitter and Rear PV Technology

The Passivated Emitter and Rear Cell (PERCs) are a modification of a typical monocrystalline c-SI solar cell where photons are reflected back through the crystal lattice using a passivation layer integrated at the back-side of the solar panel. As a further modification of the aluminium back surface field (Al-BSF) technology, the PERC solar cells include a local rear contacts using the laser ablation process. Also, the integration of the passivation layer through the Plasma Enhanced Chemical Vapor Deposition (PECVD) technique improves the opto-electrical properties of the solar cell [5]. The general structure of the PERC is shown in the figure 4.

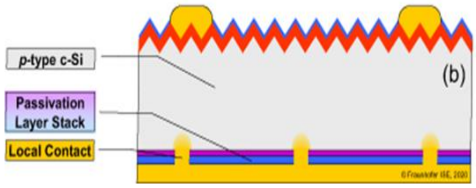

Figure 4: passivated emitter and rear cell (PERC) structure [5].

There are tremendous developments that have been made for the PERC design that include (1) large-scale and low-cost fabrication and commercialization of the PERCs due to the novel design with addition of aluminum oxide into the passivation layer, selective emitter process and hydrogenation step with reduced recombination limitations that have resulted to 22-23.4% efficiency in production [5], (2) quality enhancements in the bulk and surface passivation layers as well as optimization of the back-surface field that has contributed to minimal contact recombination. In addition to these advances, ongoing research for multi-busbar and fine-line printing has been implemented which has led to a higher efficiency of 24% [12] for the PERC cell structure and (3) research [11] that has shown that through integration of technology components, front-contact improvement and optimization of the passivation layer stack and the emitter achieves a further enhanced efficiency of 26%.

Therefore, this technology has a huge potential growth and commercialization due to its promising higher efficiency. Currently, the PERCs offers the lowest cost in terms of production, hence have dominated and taken a market in lead the global commercialization of solar cells [5, 11] with high efficiencies in production. The PERCs have become popular due to the enhanced screen-printing technologies of the solar cells that minimize both light energy and electrical energy losses, thus contributing to the high efficiencies [12]. The main challenge that has been experienced in the PERC construction is the surface and bulk carrier recombination losses though this has been minimized to a larger degree through enhanced effectiveness of the back-surface field, selective emitters and bulk lifetime as well as the implementation of advanced metallization process [5]. With their optimal performance and popularity in the solar industry, it is evident that the PERCs will continue to dominate the other solar cell technologies.

2.2 Organic PV Technology

The organic solar cells (OSCs) cells have been fabricated using molecular-based structures (polymers that are utilized to absorb light energy) characterized by electron donor and acceptor mechanism [1], [13]. The basic configuration and structure of the OSCs as shown in figure 5 comprises of the following materials [14]: polyethylene terephthalate (PET) substrate – this is a flexible polymer substrate and encapsulant for absorbing the radiant light; transparent conductive oxide (TCO) – this is a tin oxide layer that serves as the cell electrode; hole transport material (HTM) layer – this serves as the hole transporting matrix of the OSC; electron transport layer (ETL) – this is the surface where electrons are transported and therefore serves as an active layer of the OSC and aluminium back electrode – this layer is coated with a shallow lithium fluoride layer.

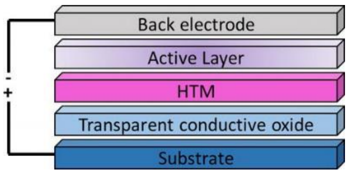

Figure 5: graphical representation of a general organic solar cell (OSC) structure [14].

The most appealing characteristic of the OSCs is their low fabrication costs due to low-cost active layer material and PET substrate [4]. These OSC cells are designed for low intensity light applications and consequently, these cells are usually preferred for indoor solar energy applications. The latest developments in the organic PV technology are (1) research that [15] has developed an optimal morphology network for the active layer of the OSCs where the top layer has a conjugated polymer while the subsequent layer has a non-fullerene acceptor (NFA) material with which a PCE of 16.5% has been achieved in this two-phased structure that is based on an active layer control method, (2) progress being made [16] in developing single-junction chlorinated OSC that has recorded a PCE of 17%, (3) a new strategy has developed an alloy-like state that has further optimized the ternary active layers and through this advancement a PCE of 17.22% has been achieved [17], (4) research [18] has developed a single-junction OSC that has a highly augmented molecular configuration and this has attained a maximum PCE of 17.8% and (5) an improved technology by [13] has recorded a higher efficiency of around 20%.

The fabrication of the OSCs result in a thin and flexible solar panel which can be attributed to its salient features which include coloration, flexibility and compactness in its structure as well as simple fabrication process. Further, the OSCs have higher performance and Life Cycle Assessment (LCA) than the silicon-based PV (Si-PV) panels due to their lower Energy Pay-Back Time (EPBT) and Carbon Pay-Back Time (CPBT). When compared with the conventional Si-PV solar panels, the major drawback of the OSCs is their lower power conversion efficiency (PCE) and shorter lifetime which pose a major hinderance in their commercialization. Another limitation that is associated with the OSCs is the non-biodegradable polyethylene terephthalate (PET) substrate material present in its construction. The PET substrate has raised ecotoxic concerns on the environment especially when it is disintegrated and hence, this limitation continues to generate more challenges in regard to the safe use and disposal of the OSCs. As a result, there is an ongoing research to address the need of a better eco-design substrate material that will be non-toxic, mechanically stable with little natural photo-disintegration and enhanced LCA. Finally, this assessment reveals numerous desirable construction functionalities of the OSCs. However, it will be remarkable to undertake research that will develop an eco-design with possible biodegradability, less toxicity and high efficiencies as way of providing a novel PV construction technology with a promising success in the future [13, 14].

2.3 Dye Sensitized PV Technology

The Dye Sensitized Solar Cells (DSSCs) are made by integrating photosensitized anode to an electrolyte and the structure, as shown in figure 6, comprises of the following cell layers [19] conductive transparent substrate – this is a polymer-based substrate on both sides of the solar cell and provides charge mobility for electrons around the cell; photosensitizer – this is the sensitive layer with dye having special material properties and serves as the source of excited electrons when hit by the radiant light; metal oxide mesoporous semiconductor – this is a mesoporous layer that traps the excited electrons from the die and directs them to the conductive substrate, therefore it acts at a photo-anode (PE) in the DSSC; electrolyte – this is a material medium (usually a liquid solvent) that serves to regenerate the die whose electrons have been excited and also transports the positive charge to the counter electrode and catalytic counter electrode (CE) – this is a kind of a conductive substrate layer that has a catalyst, usually platinum integrated in it and serves as the material medium for the occurrence of the reduction reaction:

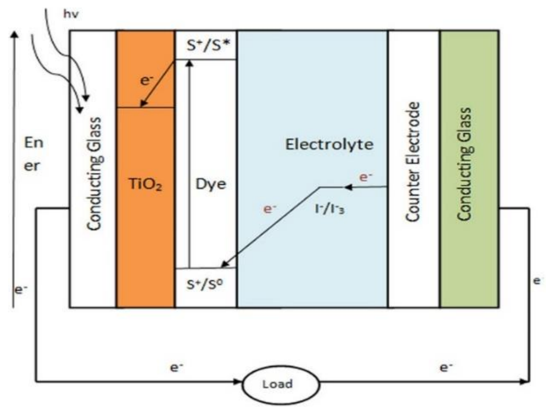

Figure 6: configuration of different material layers of a dye sensitized solar cells (DSSC) structure [19].

The recent technological developments in the design of the DSSCs include (1) an improvement in the DSSC material based on novel development of a new HxTI-based organic die compound [20] that has recorded a maximum efficiency of 14.2% and (2) an exceptional development in the DSSCs which has given the highest DSSC efficiency of 34% under normal light radiation through the use of copper (II/I) electrolyte in a method known as co-sensitization technology [21].

The DSSCs are cheaper to manufacture while providing integrated aesthetics and can respond in low radiation intensity. Their efficiencies are considerably lower in comparison with other conventional Si-PV panels in production. However, the main limitation of the DSSCs is the durability that is, minimized lifetime due to the corrosion, leakage and evaporation of the highly volatile liquid electrolyte. For this reason, numerous efforts have been made to develop a multi-phase optimal electrolyte, and even application of quasi-solid electrolyte that have shown an optimal balance between lifetime and efficiency and solid-state electrolyte that have revealed optimal mechanical stability, high safety, easy fabrication and reduced efficiency. Also, LCA has established that the synthesis and production of the coated conducting glass has a high energy demand which impact environment. A highly optimal fabrication process is required in order to achieve better LCA results. In conclusion, it would be interesting when more research will provide optimal synthesis, dye renewal and address the liquid solvent limitation as a strategy for developing highly sustainable DSSCs for commercialization [1, 14].

2.4 Colloidal Quantum-dot PV Technology

The Colloidal Quantum-dot Solar Cells (CQSCs) rely on colloidal metal chalcogenide quantum dots (CQDs) which are basically nano-crystal particles in the p-type hole-transport layer (HTL) of a semiconductor material [22]. These nanocrystals have a high quantum light efficiency [23] and they are used in the CQSCs as the medium for absorption of light radiation. Since they are based on nanostructures whose size and properties can be varied easily, the CQSCs offers a wider flexibility and control in their applications and for this reason they can be configured to absorb different spectrums of light [4]. The basic structure of the CQSCs consists of the Hole Transport Layer (HTL), chalcogenide quantum dot (CQD) layer, active layer, electron transport layer (ETL) and indium tin oxide (ITO) back-surface. The schematic diagram of the CQSC is shown in figure 7.

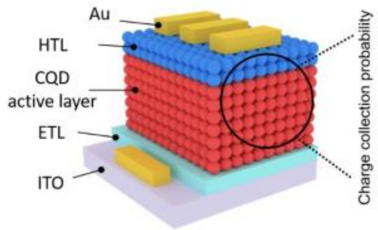

Figure 7: Colloidal quantum-dot solar cells (CQSCs) structure [22].

The recent advancements that have been realized in the CQSCs design include (1) progress being made in the development of cross-linked colloidal quantum dots in the active layer resulting to an orthogonal hole-transport layer with recorded efficiency of 13.0% [22], (2) a 13.25% efficiency that has been recorded as a result of the development of a new hole-transport layer structure that utilizes green-solvents like 2-methylanisole [24] and (3) research [23] that has advanced a multi-photon absorption (MPA) technology for the optimization of the excitation potential in the CQDs and through this development, a maximum efficiency of 19.5% and 11.6% have been realized under normal light conditions and indoor light conditions respectively [23].

The CQSCs have recently drawn much attention and research interest due to their capacity to absorb visible and near infra-red (IR) radiant light spectrums [24], cheap fabrication at low temperatures [25] and also flexibility that allows bandgap tuning of the stacked material layers in their structure [22]. For this reason, adoption of a solution-processed CQSCs has become a fabrication standard in order to use multiple exciton generation (MEG) in eliminating the Shockley-Queisser limit [25]. However, the tuning process is complex and is associated with declining charge extraction, which in turn hinders the optimal efficiencies that can be achieved. Therefore, future research that will develop highly stable, optimal bandgap control and tuning will greatly enhance the performance and efficiencies of the CQSC and influence their large-scale commercialization.

2.5 Perovskite PV Technology

The Perovskite Solar Cells (PSCs) are based on the hybrid metal halide perovskite (MHPs) which is the mineral $CaTiO_3$ and characterized by cheap cost and minimal recombination losses among other benefits [4, 5]. The PSC fabrication follows either a mesoscopic architecture or a planar architecture, as shown in figure 8, in order to achieve the following layers in their structure [4, 14]: transparent substrate – this forms a layer that coats the TCO and allows light to pass to the TCO layer; transparent conductive oxide (TCO) layer – this is a thin layer of TiO_2 that serves as hole blocking; electron transport layer (ETL) – this is an interface between the mesoporous layer and the TCO layer which permits the light photons transportation; perovskite layer – this is an infiltration layer with perovskite solution material; hole transport material (HTM) layer – serves as the hole transporting matrix of the OSC.

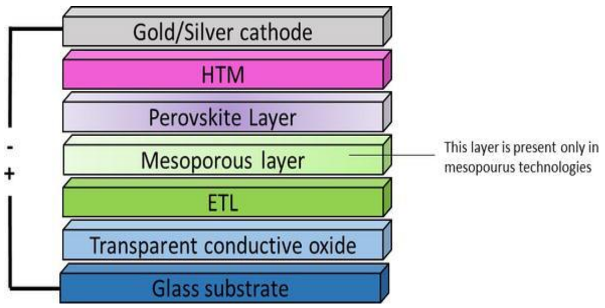

Figure 8: perovskite solar cells (PSCs) structure [14].

The recent technological developments in the PV construction utilizing the Perovskite technique are (1) research [5] that has developed an 802-cm^2 PSC with a lab efficiency of 16.1% using diverse techniques with an indication of great potential in upscaling for commercial production, (2) development of PSCs based on organometal halide perovskites with progressive enhancement of power conversion efficiencies from the initial 3.8% to almost 20% due to simple fabrication resulting from typical bulk chemical materials. Higher efficiencies which are above 20% are being reported as a result of photo-voltages that are provided by the mesoscopic oxide thin-film coating of the PSCs [4]. This is a promising technology towards cheap commercial fabrication of the PSCs. Also, (3) further improvements have been made and more advanced PSCs fabricated with an aim of achieving a higher efficiency and they have reported a PCE of up to 22.1% [1]. Finally, (4) a single-junction PSC has been demonstrated [5] through the use of specialized metal halide perovskite (MHP) known as formamidinium lead iodide ($FAPbI_3$) which has recorded an efficiency of 25.2%.

The PSCs have shown a promising trend of achieving almost equivalent results of power conversion efficiency when compared with the Si-PV panels already in production. In their cell structure, the main challenge that is brought about by almost all PSCs is the intrinsic toxicity due to the presence of the highly toxic lead metal and its derivatives in its cell structure as well as the lead emissions that occur during their production. The presence of the dangerous lead makes it difficult to safely dispose the PSCs, posing a threat to both human life through lead poisoning as well as the environmental ecosystem. Alongside the toxicity, the other drawbacks of the PSCs include reduced life-time and instability concerns. In order to accelerate their commercialization, more research could be done regarding the minimization of lead implementation and encapsulation methods in the PSC structure so as to reduce the human and environmental impact [14].

2.6 Multijunction PV Technology

The multijunction solar cell (MJSC) are based on multiple semiconductor material layers that are stacked together and the arrangement comprises of a window layer that allows the entry of the incident radiant light, a multilayer material stack separated by tunnel junctions and a buck surface layer that offers surface passivation. Through the material piling of the layers, there is a reduction in the thermal heat transfer losses and enhanced transmission efficiency of the excited electrons. The net effect of the multi-layer stacking is the improvement of the efficiency of the solar cell. Figure 9 shows a typical three-junction (InGaP//InGaAs/Ge) MJSC cell:

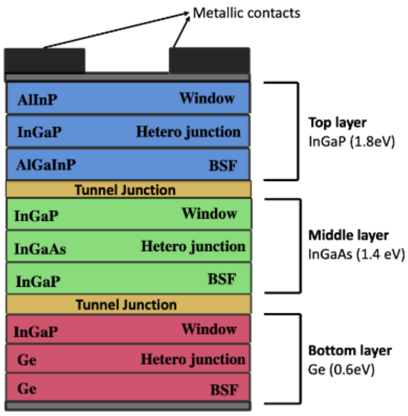

Figure 9: multi-junction solar cell (MJSC) structure [10].

The multi-junction (MJ) technology has currently shown that there is a high possibility of realizing solar panels with higher efficiency than the conventional efficiency of single-junction (SJ) solar panels which has a theoretical PCE limit of less than 30% [26]. The key milestone of the MJ based solar cells [26, 27, 28] are the development of (1) III-V//Si multi-junction solar cells based on two junctions that have realized an efficiency of 25.1%, (2) perovskite/Si tandem solar cells have demonstrated that the low-cost perovskite can achieve a higher performance of 29.5% efficiency [5] when integrated with the conventional Si-PV cells, (3) InGaP/AlGaAs//Si multi-junction solar cells which have three junctions with an improved efficiency of 30.8%, (4) hybrid tandem III-V/Si solar cells based on integration of dissimilar semiconductor materials with a recorded efficiency of 35.9%, (5) AlGaInP/AlGaAs/GaAs/GaInAs four-junction solar cells that have recorded a 47.1% solar cell efficiency [10] and (6) six-junction III-V solar cells [26] with six junctions which are metamorphically inverted and recorded a maximum efficiency of 47.1% under concentrated light intensity. Generally, when comparing the emerging technologies, the MJSCs have recorded the highest solar efficiencies which can be a great boost to solar energy production and energy sustainability when they will be commercialized and ultimately enter the market. However, the MJSCs are highly expensive to manufacture due to the high material costs and complicated fabrication process [4]. Consequently, they have not been largely commercialized even with their high potential efficiencies. If there will be future research and breakthrough on optimal alternative junction materials, then the MJSCs will offer an excellent solar cell technology in the solar industry that will offer a lower levelized-cost-of-electricity (LCOE) and a great potential towards their large-scale commercialization.

3. PV Designs with Special Technologies

There has been a growing trend in the introduction of innovative design technologies for the layout, shapes and configuration that have been utilized in the advancement and integration of highly efficient solar panels. Some of the most recent innovative technologies in the solar panels include:

3.1 Laser-Shaped PV Technology

Laser-Shaped PV (LPV) cells have been developed [29] by using laser-beam cutting technology where each photovoltaic cell is subjected to a direct abrasive process based on a special fiber optic laser-cutting arrangement. The result of this fiber cutting operation produces an edge isolation having a series-parallel arrangement of the photovoltaic cells and the entire combination is then coated with a reflective glass. Numerous unconventional solar cells shaped can be produced based on different cutting contours during the laser-cutting process. An illustration of the edge isolation during the laser-cutting process for the conventional Si-PV cell is shown in figure 11:

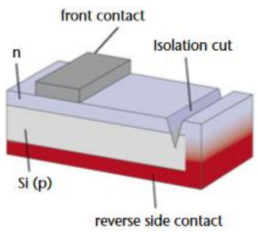

Figure 10: laser-shaped PV (LPV) cell processing [30].

With an optimal choice of the laser-beam properties, the resulting PV cell have an efficiency that is determined by the ratio of the surface area to that of the cutting contour. Besides the laser dependent efficiency, the LPV technology is promising a better performance during the fabrication of solar panels since the laser beam offers high quality, simple, consistent and reliable production. An example of the implementation of this technology in commercial production of the LPV is by the Rofin Company based in Germany [30]. Further, the implementation of the laser in the synthesis process is environmentally clean having no toxic emissions and has sustainable energy consumption. Therefore, the LPV cells present better LCA which is desirable for future commercialization of solar cell production.

3.2 Concentrated PV Technology

The Concentrated Photovoltaic (CPV) Cells have presented a shift in the conventional use of PV cell material to the use of optical reflective concentrators. The CPV cells, as shown in figure 12, utilizes the following components [10]: optical reflective concentrators – this are special-designed mirrors that focus the radiant solar energy to the thermal interface material for absorption; thermal interface material (TIM) – this is an intermediate material layer between optical-based solar cell and the heat-sink that enhances the thermal conductivity by increasing the heat-transfer of the solar-cell arrangement and heat-sink – this provides a thermal insulation for the solar cell.

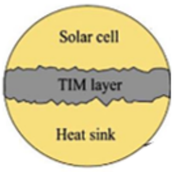

Figure 11: concentrated photovoltaic (CPV) cells configuration [10].

The recent research has come up with the following developments in the concentrated PV technology are (1) a Compound Parabolic CPV cell had been developed [31] by the integration of crystalline silicon solar cell sandwiched between dual symmetric parabolic mirrors has produced a compound parabolic concentrator photovoltaic cell with an enhanced PEC of 14.76%, (2) research that has developed [23] CPV with an efficiency of 21.29% [23] using polymer lens in the design of the Colloidal Quantum-dot Solar Cells (CQSCs) and (3) solar cells designed for space applications where an ultra-light concentrator has been designed [32] that achieve a 1-dimension concentration of the light radiation.

The CPV is a novel technology whose fabrication is relatively cheap since there rely more on optical mirrors and therefore, less PV material is required. The main challenge that greatly impacts the LCA of the CPV is the high temperatures generated by the optical reflective concentrators which hinder the efficiency and the lifetime of the solar cell. For this reason, thermoelectric generators (TEG) technology has been integrated into the CPV cells in order to optimize the efficiency at elevated temperatures as well as minimize these high operating temperatures [33]. This technology is growing and will be the heart of the future solar power industry based on the current optimized CPV innovations such as the CPV–thermal (CPV/T) and radiant light tracking together with the future advancements of the CPV cells.

3.3 Bifacial PV technology

The Bifacial PV (BPV) Cells utilize both the front and rear layer surfaces anti-reflection coatings to absorb radiant radiation with a configuration that consists of an emitter layer, depletion region and substrate layer that are sandwiched between anti-reflective coatings as shown in figure 13:

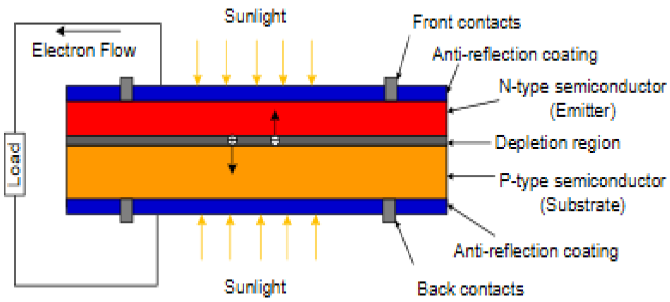

Figure 12: bifacial PV (BPV) cell [34].

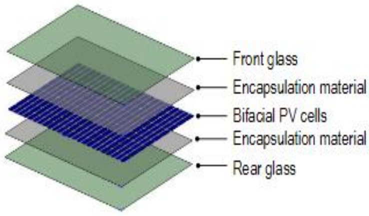

Figure 13: bifacial PV (BPV) cell layers configuration [34].

Recent development and research conducted by [34] has proposed a bi-facial photovoltaic (BPV) cell with dual light-absorption surfaces as shown in figure 14. With this design, the overall solar cell efficiency is improved since there is a combination of two surfaces for collecting the solar radiation energy and as a result offers the novel approach to achieve the minimum LCOE and have started to gain popularity in the commercialization of solar cells where they are currently regarded as a benchmark design for ground-mounted solar installations [5]. Further research that will model the optimal energy yield of the BPVs will make them an innovative solar design layout in the future.

3.4 Transparent PV technology

The Transparent PV (TPV) cells are a new emerging trend based on a transparent window glass and electrodes which makes them preferred technology for integration into smart buildings in homes, urban areas and cities [35]

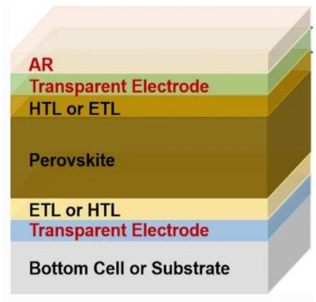

Figure 14: Transparent PV (TPV) cell structure [36].

and therefore, they combine improved power capacity as well as architectural aesthetics. The latest development on the TPV cells are based on the various solar cell material technologies already in development such as development of the (1) semi-transparent perovskite solar cell (ST-PSC) [36, 37] that has demonstrated capability of an almost-infrared transparency. This ST-PSC with a cerium-doped indium oxide transparent electrode has recorded an efficiency of 20.37% whose structure is shown in figure 15.

Another development is (2) a perovskite/silicon tandem solar cell [38] with 19.8% maximum efficiency based on a very optimal transparent electrode and semitransparent perovskite top cell as well as (3) semitransparent organic solar cells (ST-OSCs) [39] using indium tin oxide (ITO) electrodes with an improved efficiency than the conventional OSCs. Also, (4) a design proposed [40] that is based on CIGS chalcogenides solar cells integrating a semi-transparent ultra-thin glass (UTG) has realized a maximum efficiency of 13.23%.

When compared with the conventional Si-PV cells, the TPV cells have a relatively high record efficiencies as well as integrated aesthetics in energy generation [41]. The commercialization has already kicked-off with Heliatek GmbH Company that is based in German. The TPV have found a widespread implementation as Building Integrated PV (BIPV) as either partial-TPV or full-TPV and their commercialization will likely accelerate in the near future with the growing popularity.

3.5 Folding PV Technology

Folding PV (FPV) cells are designed for flexibility in providing convenient, portable and cheap energy alternative for outdoor applications. This flexible FPV cells are designed [42, 43] for various bending mechanisms (i.e. either bendable, stretchable or twistable) based on the organic solar cells with multiple optimized polymer layers having flexible substrate, ductile absorber as well as highly conductive and flexible PEDOT:PSS electrode. With current preference of portable solar power providers, the emerging developments in the FPV cells include (1) a folding organic solar cell has been developed [42] with 14.17% efficiency using acid-treated electrodes as shown in figure 16 (a) and (2) a foldable perovskite solar cells has been proposed with efficiencies of 17.03% [43] by using an ultra-thin PET substrate as shown in figure 16 (b) and 15.2% [44] by using carbon nanotubes-polyimide (PI) composite film as shown in figure 16 (c):

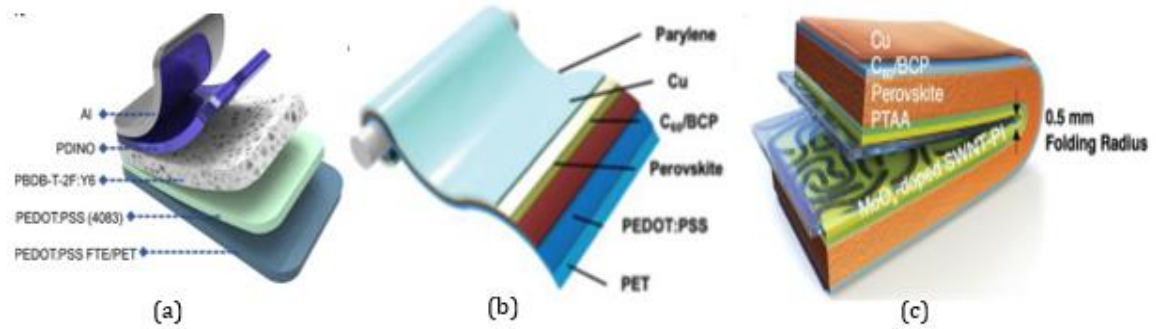

Figure 15: Folding PV (FPV) cell structures based on (a) PDINO [42], (b) Ultra-thin PET [43] and (c) PI [44].

The FPV cells are a breakthrough in PV panels and their development has unique features of semi or fully foldable, lightweight, mechanical stability, high conductivity, flexibility and resilience with relatively high efficiencies. Therefore, they can provide portable solar power for transit and outdoor applications like hiking and camping. The FPV will be amazing in the future and are going to revolutionize the next-generation solar-power integrated electronics.

4. Social, Economic and Environmental Impacts

The positive progress that is experienced towards the production of cost-saving and highly efficient solar panels has various social, economic and environmental impacts. Despite being an energy source that is characterized by viable, clean and renewable energy, its effects include following:

Hazardous materials

The emerging PV cells are mostly manufactured based on the thin-film technology which employs heavy Cadmium Telluride metal which is highly toxic and dangerous. Fortunately, research [6] has found that this hazard material can be controlled (but not fully eliminated) through regulation of temperature and concentration. In regard to global warming effects, the PV cells generate a clean energy without emitting harmful greenhouse gases like CO_2 that contribute to climate change [45].

Insolation

The incident solar radiation which varies with location and time has influenced the development of solar tracking control systems. These systems adjust the alignment of solar panels in relation to incident solar radiation in order to provide optimum orientation and inclination angle for maximum power outputs [46, 47].

Worker risks

The major challenge that is experienced in the production of the PV cells is the exposure of workers to the dangerous materials e.g. lead during fabrication and hazardous chemicals that are used in the PV production stages as well as after the lifespan of the PV cell owing to the fact that their disposal remains still to be a challenge [48]. Therefore, this is an occupational health risk.

Grid integration

The solar energy systems generate power with a higher short-circuit current than the nominal rating and hence easy integration into the power grid network without the need of power safety equipment which is a saving on the maintenance costs [45]. Further, when the solar power is integrated to the distribution network, there is an improved power sustainability [49].

Cost

The average cost of the PV panels in the market globally remains to be high due to the high manufacturing costs associated with the traditional PV construction technologies. However, these new emerging technologies are promising a future cost reduction in the PV fabrication and hence more affordable and increased installations in homesteads to supply cheap electricity.

Job opportunities

Development of mega-solar power projects for commercial power distribution will require more workers who will be responsible for the design, analysis and installation of the PV panels as well as its management and maintenance and in turn will create employment especially for the people living locally where the solar power stations are being setup [45].

Land

PV applications have greatly impacted the land-use. Consequently, the following new trends in the PV installations have emerged that focus on minimizing the land utilization:

(i) Floating PV Technology – this technology provides economic large-scale solar power production through PV architecture installations on water-bodies such as lakes as shown in figure 17 and hence, lower installation and maintenance costs as well as revealed an improved efficiency due to the cooling effect of water.

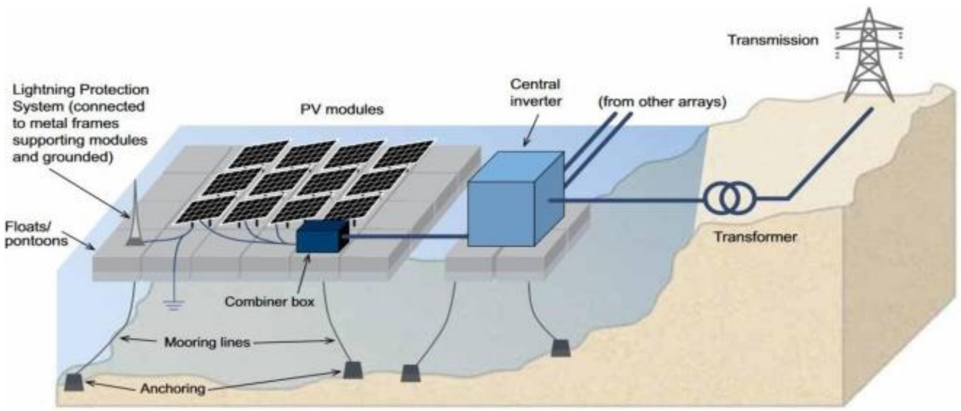

Figure 16: floating PV technology configuration [50].

(ii) Building-Integrated PV Technology (BIPV) – this is another impressive new technology that offers PV cell installations on windows (electrochromic, thermochromic and semitransparent), roofs and colorful wall facades of buildings [47] and hence, less land per MW power production with complements on the building aesthetics. These installations utilize building integrated semi-transparent photovoltaic (BISTPV) [51] that is based on either semitransparent organic solar cells (ST-OSC) or semitransparent perovskite solar cells (ST-PSC). Through the integration of a phase change material (PCM) that serves as the temperature regulator of the BIPV cells, an evolution referred to as BISTPV-PCM [52], several promising solar concentrating technological systems [53] have emerged which include (1) building integrated concentrated photovoltaic (BICPV), (2) building integrated concentrating solar thermal (BICST), (3) building integrated concentrating solar daylighting (BICSD), (4) building integrated concentrated photovoltaic/thermal (BICPV/T), (5) building integrated concentrated photovoltaic/daylighting (BICPV/D), (6) building integrated concentrated solar thermal/daylighting (BICST/D) and (7) building integrated concentrated photovoltaic/thermal/daylighting (BICPV/T/D).

5. Conclusion

Through the systematic review of emerging technologies and ongoing research of novel solar cell construction in this paper, there is a record of maximum power conversion efficiency (PCE) of 19.5%, 20%, 25.2%, 26%, 34% and 47.1% for the CQSCs, OSCs, PSCs, PERCs, DSSCs and MJSCs respectively. Further, it is demonstrated that these developments have improved cell PCE to a maximum of 47% in comparison to the conventional silicon-based PV (Si-PV) cells that has a theoretical maximum efficiency ranging from 20% to 22% in production. Also, these new solar material technologies have recorded reduced fabrication costs and levelized cost of energy (LCOE) as well as higher performance and LCA when compared with the Si-PV panels.

Despite these advances in in solar PV technologies, their shorter lifetime and cell stability issues are some of the major concerns that have been raised. Also, some of these emerging new technologies employ eco-toxic materials that are harmful to the environment. The toxic materials are the polyethylene terephthalate (PET) substrate in the OSCs as well as the highly toxic lead metal and its derivatives present in the PSC cell structure. As a result, these drawbacks of the new solar cell technologies have hindered their large-scale production and hence, the conventional Si-PV continue to lead in commercialization in the solar panels industry and account for about 90% market.

Future research and technological developments that will address and overcome the current limitations in terms of stability and life-time could yield a further enhanced efficiency and manufacturability. In addition to this, further research could be undertaken in order to create an eco-design with minimal human and environmental degradation impact and therefore, accelerate their production, lower Business Operation Strategy (BOS) costs, as well as lower module costs. In terms of policy uncertainties in several key countries (including Africa), the progress achieved in this study contributes to raising the awareness of PV’s potential. To that end, the solar energy, with the emerging PV technologies, will ultimately offer long-term solutions to the rising global demand and can now compete with other renewable energy sources.

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