

The Recent Advancements Pushing the Narratives of Solar Photovoltaic Electricity Generation

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ABSTRACT

As the energy needs to power nations' economies continue to follow an upward trend, concerns about climate change continue to pose a constant consideration for its source of generation. Solar energy is a renewable form of energy with global reach and offers the potential to meet the global energy needs if properly harnessed. The major challenge to the technology of this energy source, however, has been low capacity factor and susceptibility to local weather conditions. The narratives are, however, changing due to ongoing studies that are leading to advancements in its technology. Although, there are several literatures on technological advances on solar photovoltaics, most of them have always concentrated only along a single front. The studies are along new forms and applications, the development of new materials and cell structures, and the deployment of Smart technology and artificial intelligence, and provides a handy platform for quick reference and guide to interested scholars on solar photovoltaic technology. The challenges of these new technologies and mitigation strategies were stated, and comparative performance indicators were provided. Despite a few challenges, these recent technological advances have led to improvements in performance and a better way to predict and manage power generation in relation to the local prevailing weather conditions.

Keywords: Energy; Floatovoltaics; Panels; Perovskites; Renewables; Technology

History

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1. Introduction

A relationship exists between energy consumption, economic activities, and environmental impacts. The industrialisation and development of any nation are strongly tied to the availability of adequate energy for powering the wheels of its economy. While many means are available for energy generation, there has been a huge dependency on fossil fuels. Fossil fuels are combusted in engines to generate energy, and are currently the most common means of energy generation [1] due to the mature technology. However, its non-renewable nature, coupled with its dwindling amount and environmental pollution effects, is a major concern [2-4]. Global average temperatures have increased by over 1.5 °C above the pre-industrial era in 2024 [5-6] and in some regions pre-2024 [7], causing the melting of the polar caps, greenhouse warming, and frequent wildfires. This situation, more than ever before, requires drastic action to remedy it. The popularly touted

solution has always been to stop fossil fuel usage and shift to renewable energy. However, among other things, low energy returns due to low capacity factor have always been a challenge to the use of some renewables for energy generation [8-10]. Energy generation from some renewable sources is also influenced by prevailing local weather conditions and, by extension, the impacts of climate change [11]. While the issue of local weather conditions is beyond human control, it is, however, possible to predict them. The constraint of low energy returns due to low capacity factor is, however, in the purview of humans to address, and this, as expected, is receiving adequate research attention.

Energy generation from the sun (solar) using photovoltaics or concentrators is one of the most attractive renewable energy sources for reducing greenhouse gas emissions. Solar energy is abundantly available across the universe and is harnessed from the sun. This energy can be harnessed through two means: solar

thermal systems and solar photovoltaics. Energy is harnessed through solar thermal systems in the form of heat, which can then be utilised to power heat engines for electricity generation. In the case of solar photovoltaics, solar energy is directly converted to electricity by the panels, and this is then converted from direct current to alternating current in an inverter. The reduction in the cost of solar photovoltaic-generated energy, coupled with advanced technology, versatility, scalability, and sustainability, is making it popular. Solar energy now holds the title for the highest growth in the energy generation sector; a growth rate of about fifty-eight per cent was recorded from 2017 through 2021, and the technology for its deployment can now be said to have attained maturity [12-13].

The most popular renewable energy source with mature technology is hydropower. Hydropower is a major player among global energy generators, contributing about 17% of global electricity generation, and by far the highest renewable energy source [14]. Wind-generated energy using turbines, especially the offshore types, is also receiving immense attention, especially from developed countries that boast of developed favourable policies and frameworks to ensure its continued growth [13] above its 7% contributing quota to global energy generation in 2021 [15]. It recorded a growth rate of approximately 17% in the year 2023.

While its contribution to global energy generation stood at about 3.6% in the year 2020 [13] and below hydropower and wind, the fraction has, however, increased to about 5.5% in the year 2023 [16] due to the ease of scalability and simplicity, which separates solar photovoltaic from the others, making it of immense interest recently. Aside from its integration into satellites designed for space operations, it is helping to advance research.

Solar photovoltaics are expected to be a huge contributor to future clean energy generation due to some of their advantageous peculiarities. The plummeting price to approximately 82% between the years 2010 and 2019, and its offer of cheaper pricing in about 60% of the world in comparison to fossils [17], is a testament that its share of the global energy generation is expected to grow faster than any other technology [18]. Energy generation from photovoltaics, just like other renewables, is faced with challenges: environmental and technical. Bamisile *et al.* [16] discussed some of these environmental challenges in detail, stating their implications, and the discussed factors are depicted in Figure 1.

Technical factors that influence solar photovoltaic performance include orientation, shading, durability, tracking systems, and cell efficiency [16]. Recent advances in solar photovoltaics seek to address these challenges while optimising design for improved output. This study is thus focused on the advances of solar photovoltaics that are making it more popular and efficient, and central to the global energy transition. Although there exists literature on advances in solar photovoltaic technology, this has always focused on either cell materials, new forms, or smart technology individually. This study, however, presents the advances along all these major fronts: new forms and applications, advanced material cells and structure, Smart technology and Artificial Intelligence (AI), and provide a handy literature for recent technology advances on solar photovoltaics.

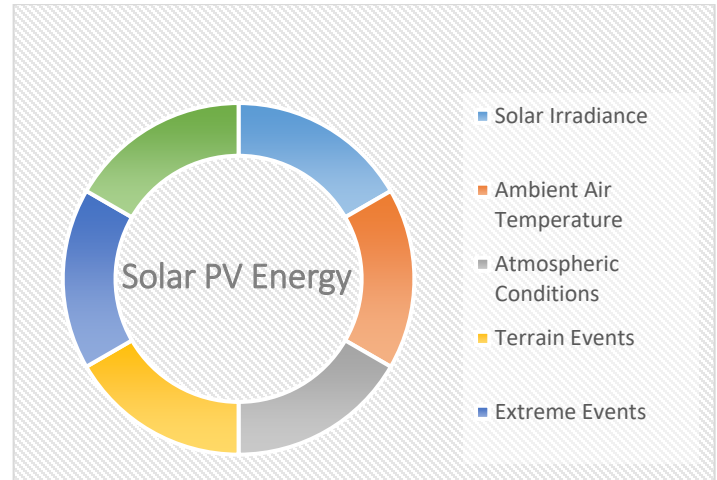


Figure 1. Environmental factors that influence the energy output of solar photovoltaics

2. Methodology

This article conducts a review of over 80 peer-reviewed publications, focusing on the recent advancements driving the adoption of solar photovoltaic generated electricity. This review comprises of scholarly materials, including research articles, critical reviews, and proceedings of conferences. The analyzed publications in this study were sourced from reputable databases, such as Scopus, ScienceDirect, IEEE, DOAJ, Copernicus, and Google Scholar, with the bulk indexed in the Scopus database which is reputed for its high h-index scores reinforcing their significance. A substantial part – more than 65 of the reviewed publications falls within the five-year recent gap an indication of the core reason of study (recent advancements), with the search tailored to renewables focused on solar photovoltaics and peer reviewed materials. Similar studies outputs were used to buttress the results. These reviews were utilized in this study with the aim of presenting the advancements which are pushing the fonts of the solar photovoltaics in the generation of electricity. The remaining part of this work focus on the major fronts of advancement.

3. New Forms and Applications

Solar photovoltaics are plagued by low efficiencies, which are influenced by several factors, the dominant of which is temperature [13]. The efficiency of the solar photovoltaics is an inverse function of its temperature [19]. A One-degree Celsius increment in temperature of the polycrystalline photovoltaic panel can result in about 0.12 V voltage drop [20] and is equivalent to about 0.4 – 0.5 % drop in efficiency [16]. High solar cell temperature is also a recipe for lower lifespan due to rapid degradation; the degradation rate approximately doubles for every 10 K increment of operating temperature [21]. The development of floating photovoltaics (floatovoltaics) was a strategy developed to overcome this and involves installing photovoltaics on the body of water, thereby benefiting from natural cooling. This technology is now approaching its second decade [22], and aside from the natural cooling which it offers, it also reduces land usage and water vapour loss from the body of water it is installed on [13]. The adoption of floatovoltaics requires a lifecycle analysis pertaining to the additional complexities involved in its

installation and the resultant gains from its installation. Typical structural types for floatovoltaics installations are; rafts built with parallel HDPE cylinders as floats with supporting structures, individual panels fixed in individual floats accompanied by built-in rails without a supporting structure, widespread floating platform like an island, to hold the PV modules along with a space to walk in between them, PV modules in the floating structure over a water body that is partially submersible and can float back to the surface, and flexible structure developed for thin-film modules made of neoprene sheets, enclosed by floats [13]. While the environmental impact assessment results of installing floatovoltaics have remained sparse, and available literature suggest no aquatic environmental disruption [23], a win-win scenario will be to install such on existing dams as against current untapped water bodies, as studies have suggested that instalment on about 10% body of existing hydropower dams will produced an equivalent amount of electricity being generated from fossil fuels [24]. The utilisation of less than a third of the over 111,000 globally available reservoirs could potentially translate to about 9434 TWh/year of Electricity [25].

Studies by different scholars have proven that floatovoltaics perform better than land-based photovoltaics in terms of generated electrical energy, with reported percentages in the range of 0.6 – 35.9 [13]. With the conduct of experiment as the mode of study, an increased electrical energy generation range of (8 – 35.9) % was reported by Nisar *et al.*, [26], an increase of 2.33 % was reported Hammoumi *et al.*, [27] respectively, and a percentage increase in electrical energy generation of 20.27 was reported by Junianto *et al.*, [28]. This led to a corresponding increment in efficiency of floatovoltaics over land-based photovoltaics by (1 – 4), (1.87 – 2.57), and 1.20, respectively [26-29].

Floatovoltaics is witnessing increased deployment in several countries, with China leading, while Japan, Korea, Singapore, the Philippines, India, and European countries also follow [29-31].

Advances in the technology of solar photovoltaics along the front of new forms and applications are also seeing the deployment of transparent photovoltaic glass due to the superior property of glass in preventing the sticking of dust compared to other common materials [32], the turning of any sheet of glass into an energy generation device [33]. The power output of solar photovoltaics is affected by dust layer thickness, and in desert regions, this power reduction can be up to 60% [16]. Hence, using materials with a lower affinity for dust in their construction is welcomed. Transparent photovoltaic glass is attracting attention not only because of energy generation capabilities, but also due to its potential for dual usage: energy generation and structural applications as curtain walls in buildings [34]. These systems offer a return on investment by reducing electricity costs. The deployment of transparent photovoltaic glass as a building structure is classed as Building Integrated Photovoltaics (BIPV), and finds use as facades, translucent/semi-transparent solar windows, skylines, etc., where it can offer the functions of electricity generation, shading and glare control, structural strength, aesthetics, sound protection, and thermal control [33-35].

Solar photovoltaics have also seen advancement based on the available surfaces for energy generation. Traditional

photovoltaics have only one active surface. Bifacial solar modules, however, are so designed to capture energy on both surfaces, front and rear, and effectively utilise reflected and diffused sunlight, thereby increasing energy generation [35-36]. The dual active surfaces increase overall energy output and benefit more in environments with high reflectivity; literature states efficiency gains of up to 30% are possible with the use of bifacial modules [37].

An advancement in the form of photovoltaics with huge potential of revolutionising light absorption and ultimately efficiency values lies in the full development of textured solar cells. These cells are designed to capture more daylight than conventional cells [38-39], as they feature small bumps that allow for light absorption from a wider range of directions.

4. Advances In Solar Panel Design with Focus on Materials and Cell Structure

The efficiency values of photovoltaics have seen a huge jump from the previous values of approximately 10% to more than 25% [40] due to the innovation and development of new materials. A passivation layer created through chemical-vapour deposition and high-temperature annealing is added to standard monocrystalline solar cells, referred to as Monocrystalline Passivated Emitter and Rear Cell (Mono PERC), to improve light absorption, reflect unused photons to the cell, and limit electron recombination. The literature shows that Mono PERC offers improved efficiency of around 23%, increased power output, better performance in low-light conditions, improved lifetime cost [41], and better temperature coefficients. Another evolving passivated technology is the Tunnel Oxide Passivated Contact (TOPCon) photovoltaics. It builds on the Mono PERC, adding a super-thin oxide layer to reduce energy losses and improve performance. It can also find application in the bifacial photovoltaic application mode, where it offers increased efficiency, lower temperature coefficient and hence, is suited for high-temperature environments, reliable durability, and low-light improved performance [36].

A promising material advancement for solar photovoltaics is the use of perovskites [41]. Perovskites are materials that absorb a broader range of sunlight: visible and near-infrared light, as opposed to traditional photovoltaics. They are created using techniques like spin-coating and vapour deposition, and are lighter in comparison to silicon photovoltaics. The crystalline structure of a typical perovskite is depicted in Figure 2 [45]. The potential for improved efficiency over traditional photovoltaics is a huge driver for its development, coupled with its reduced manufacturing cost due to simpler and low-temperature manufacturing requirements [41-42]. In the pipeline is the commercial development of perovskite-silicon tandem cells, built of perovskite layers over silicon. These innovation captures more sunlight and have improved efficiencies over traditional silicon photovoltaics. Efficiencies are said to be around 27% [43]. The lifespan of perovskites, however, remains shorter in comparison to silicon photovoltaics, due to their susceptibility to moisture and heat [41], but this can be mitigated with the evolving technology of protective layer encapsulation [44]. The lightweight and flexibility which perovskite offers make it a good candidate for

integration into portable devices and hence, for revolutionising the solar technology utilisation.

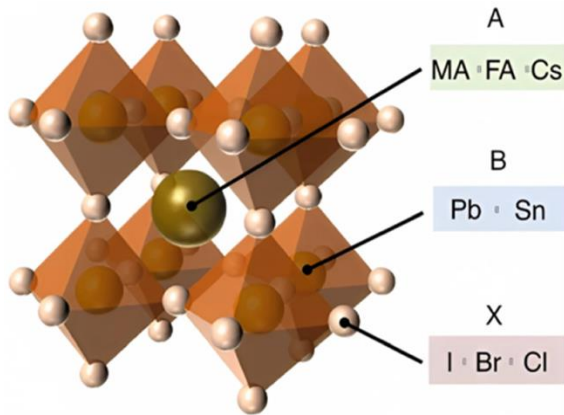


Figure 2. Typical structure of a perovskite crystal material

The strength of having stacked multiple layers of semiconductor, with each designed to capture a different part of the solar spectrum, is put to advantage in the concept of heterojunction/multi-junction solar cells. The solar spectrum is maximised with the use of multi-junction solar photovoltaics. This results in increased panel efficiency, as a broader spectrum of light is absorbed and converted into electricity with the minimisation of electron recombination [36,43,46]. The advanced solar photovoltaics have a favourable temperature coefficient, making them ideal for hot temperature climates and specialised applications [36,43]. Past study carried out by scholars have shown that photo-conversion efficiencies of such panels using semi-conductors can exceed efficiency values of 47% [46], as was the case for a 6-junction.

The concept of multi-junction solar cells is employed in Tandem solar panels. Here, two or more layers of different photovoltaic materials are stacked together to capture a broader range of the solar spectrum, resulting in increased efficiency [47-48]. Studies have shown that tandem cells of perovskite stacked on silicon help to overcome the efficiency limits of single-material panels [42,46], and the same is applicable with the use of different Gallium compounds [46]. The perovskite-silicon tandems are increasingly pushing the advancement of solar photovoltaics forward, primarily due to high absorption capabilities and cost effectiveness [46], and studies have proved a boost in efficiencies to values surpassing 30% [44].

Another area of advancement on materials used for solar photovoltaics lies in semiconducting organic materials or polymers, which are termed organic photovoltaics. They come with the twin advantage of light weight and lower production cost [42-43]. Organic photovoltaics are generally categorised as single-layer, bilayer, and bulk heterojunction cells [43], with the bulk heterojunction organic cells having the best power conversion rate of the three. Interfacial area and exciton diffusion are maximised in bulk heterojunction organic cells through the blending of donor and acceptor materials into a thin film with a dispersed interface, leading to superior power conversion [43]. The efficiency of organic photovoltaics still falls below that of conventional silicon-based solar panels. However, studies are showing promising results in the efficiency of organic

photovoltaics; an efficiency value of 16.5% was recorded for a single-junction organic solar cell in 2018 [49], while by the year 2023, an efficiency value of 19.2% was reported [50]. Organic photovoltaics also offer the ability to be integrated into various surfaces, thereby increasing the scope of their application and making them a candidate for deployment in the new technology of solar fabric.

Nanomaterials such as graphene can be used to produce solar photovoltaics. Graphene is believed to hold the greatest scientific and technological potential for use in solar photovoltaics among nanomaterials [43]. It possesses properties that are crucial for the effective functioning of solar photovoltaics, such as excellent optical and electrical conductivity, which are a recipe for high mobility, optical transparency, stability, and flexibility [43,51-52]. The high optical transparency of graphene enhances sunlight absorption, and the high electron mobility and charge transport capabilities are necessary for increased collection of photo-generated electrons [51]. Literature has it reported that an efficiency rate of 29.1% was achieved in 2020 with the incorporation of nanomaterials in solar photovoltaic. Quantum Dot Solar Cells (QDSCs) are also an area of advancement in photovoltaics employing materials on a nanoscale. The nanomaterials in QDSCs are engineered to absorb different light wavelengths, making them potential candidates for better absorption compared to traditional silicon cells [40,53]. While studies are still at the early stage for the deployment of this technology, the future, however, looks promising to have efficiency value that will compete with that of traditional solar technologies, as data shows an achieved efficiency value of 19.1% in a laboratory environment [54].

Advancements in the technology of solar panels with efficiency improvements for high-temperature applications are possible with the use of Dye-sensitised solar cells (DSSCs), which come at a lower cost and offer flexibility in their design [55]. It can generate electricity in low light conditions. Dye-sensitised solar cells are typically manufactured from four components: photoactive layer, electrolyte, anode, and cathode [43,52]. The semiconductors primarily serve as charge transporters while the photosensitive dyes produce photoelectrons from the absorbed sunlight. This is in contrast to typical semiconductors, which perform the dual functions of light absorption and charge carrier [43,56]. A progression in the efficiency attained with DSSCs over the years was reported in the literature with advancements in studies; efficiency values have increased from figures of about 9.6% reported in 1993 to a value of 15.2% as reported in 2022 [43].

The reliance on rare earth materials for the production of solar photovoltaics can be over in no distant time if Kesterite solar cells materialise in terms of performance. Kesterite solar cells utilise earth-abundant materials, offering a greener alternative to traditional solar cells and come as the next big thing in the thin film solar panel world. Available data has shown an attained efficiency value of 14.2% in a study conducted in 2024 [57].

Another promising area of advancement in solar photovoltaics lies with artificially engineered materials having unique properties referred to as metamaterials. Electromagnetic waves can be manipulated using these materials, and their integration into solar photovoltaics offers light absorption enhancement [43]. Although

the technology is in its early stages, the potential of developing a perfect metamaterial absorber holds the key to solar photovoltaic efficiency improvement.

5. Smart Technology and Artificial Intelligence (AI)

Smart technology uses sensors to collect real-time data and advanced analytics to optimise processes, thus enhancing performance. Smart grids were introduced to the electricity grid to accommodate the variable nature of electricity generation from solar photovoltaics, thereby improving the resilience and reliability of the system.

The energy absorption rate from sunlight by solar photovoltaics is dependent on its angle of incidence. This angle of incidence is dependent on the time of day as the Earth continuously rotates about the Sun. For better performance of solar photovoltaics at all available sunshine hours of the day, it is necessary to ensure that the appropriate angle of incidence is maintained. This can be ensured with the use of smart technology and solar tracking systems.

The solar tracking system is an area of advancement in solar photovoltaics. It helps to optimise the orientation of the solar panel, such as to maximise the sunlight capture and power output. The tracking systems can either be active or passive [52]. The active tracking system is the common of the two, and makes use of actuators and gear trains to track the direction of sunlight. The passive tracking system's functionality is based on the action of solar heat on a low-boiling-point compressed gas [58]. The solar tracker can be either a single-axis or double-axis tracking system, with each more suited to different regions depending on the sun's relative position [58]. The focus of scholars on solar trackers is to optimise their performance. The electrical energy efficiency of a solar photovoltaic fitted with a dual-axis tracker was reported to increase by 44.89% on average by Jamroen et al [59]. Likewise, energy output increase in the range of (30 – 45) % was observed in studies conducted in Jordan, and an increase range of (29.3 – 34.6) % for a separate study in Turkey over a fixed axis, both using dual-axis trackers [58].

The internet of things (IoT) is also one of the advancements pushing the narratives of solar photovoltaics. The integration of IoT technology to photovoltaic systems is revolutionising predictive maintenance, data-driven optimisation, remote monitoring and control, and management [59-60] of the system. Performance parameters measured with appropriate sensors can be processed and transferred in real-time for the receiver to make an informed decision as appropriate. IoT-enabled systems are finding wide applications in fault detection and system optimisation across energy grids to prevent grid collapse; an embedded IoT architecture was utilised in studies by Dupont, et al to identify suboptimal operating conditions and real time monitoring in grid connected solar panels [61], an IoT-based data acquisition system for real time characterisation of a solar photovoltaic under varying climatic conditions was developed by Naudiyal et al, to assist in grid management [62]. The performance of solar panels has also improved with the technology of IoT and Smart technology. A coupled camera is used in detecting dust accumulation and triggers a microcontroller to initiate mechanical cleaning based on real-time monitoring [63].

Real-time data obtained through IoT technology is now being used in Artificial Intelligence (AI) to train the system. Artificial intelligence is changing the narratives of solar photovoltaics through the optimisation of efficiency and lifespan by enabling proactive data-driven adjustments and optimisation. The trained system provides maintenance needs forecast, smoother grid integration, and effective supply/demand balancing. This, in a broad sense, implies an increased overall system efficiency and reliability. The use of AI in solar photovoltaics is an evolving technology; it, however, possesses prospective capabilities especially in areas of design and development, operations and maintenance, and energy forecasting and management. It is optimising the maximum power point tracking for peak power delivery from solar photovoltaics [64].

The combination of batteries with smart systems helped in the revolutionising of solar photovoltaics. Without mincing words, the reduction in the cost of solar photovoltaics alone is not what changes the level of its adoption, but also due to battery technology advances for power storage. Battery energy storage systems smooth out the energy fluctuations, provide backup power, and increase the utilisation of solar photovoltaics [16,41]. The improved reliability and grid stability of solar photovoltaics are partly due to battery technology and are key to achieving sustainable and resilient systems [65].

6. Challenges to Recent Advances in Solar Photovoltaics and Performance Evaluation

While studies have led to improved performance of solar photovoltaics in electricity generation, some bottlenecks still exist that serve as limitations. Some of the common challenges to new technology in solar photovoltaics appear in Table 1.

As enumerated earlier, solar photovoltaics technological advancement led to the class of third-generation technology, also referred to as emerging technology. These include technologies for materials such as perovskites, organic, dye-sensitised, nanomaterials, and multi-junction. A comparison with traditional silicon photovoltaics in terms of some performance indicators is provided in Table 2, providing a glance at the impact.

7. Discussion and Outlook

Solar photovoltaics stands a great chance to benefit from the integration of the three areas of advancement.

The advancement in the form of use of photovoltaics is pushing the performance higher. Floatovoltaics have higher efficiency values than land-based photovoltaics benefiting from natural cooling to keep the panels temperature close to the optimum working temperature, while bi-facial PVs pose increased power generation due to active dual surfaces, and low temperature coefficient. The incorporation of better performing materials made available through material research in floatovoltaics/bi-facials will definitely boost their performance and push it beyond the reach of traditional PVs.

Likewise, the adoption of smart technology and artificial intelligence to the system will bring-on its advantage of better performance achieved through increased sunlight capture with the use of trackers, optimized system performance through training with real-time data, system resilience and reliability through smart

grids, and prompt maintenance with the use of IoT.

It is however, to be noted that some gaps need to be filled in order to be able to use each different developed new material in the new forms of PVs. While there will be a gain in performance parameters when newer materials like Mono PERC and TOPCon are utilized in bifacial new technology form while also incorporating smart technology and artificial intelligence. The use of the dual in floatovoltaics will expose them to constant moisture causing accelerated power degradation and corrosion. The same fate is what awaits other newly developed solar cell materials like

Perovskites, dye-sensitized, and Nano-scale quantum dots due to the degrading impact of moisture on them and making them unsuitable for floatovoltaics. To benefit from the advantages of using these new materials for floatovoltaics, superior encapsulation like Polyolefin Elastomer (POE) as against the traditional Ethylene Vinyl Acetate (EVA) is required.

Graphene oxide however, fits in for floatovoltaics as moisture acts as an active, high efficiency energy source for it, and enables direct electricity generation [81].

Table 1. Challenges to new solar photovoltaic technology

New Technology	Challenges	Possible Mitigation
Perovskites	They are susceptible to moisture, heat, and light, leading to environmental instability and early degradation. Possibilities of lead leakage. Scalability and uniformity.	The technology of encapsulation and the additives, which are hydrophobic, offer a possible mitigation to the challenge of early degradation [41, 66-67]. Epoxy resin-based encapsulation can reduce lead leakage [68]; likewise, the use of lead-absorbing thin films, however, further research is required to allow for the use of lead-free materials to remove the challenge of lead leakage; materials like Copper Zinc Tin Sulfide and Copper Indium Gallium Selenide have been suggested [46]. Research into industrially viable deposition methods is needed to overcome the challenge of scalability and uniformity [67].
Bifacial	Performance monitoring is very complex due to albedo, making performance measurement difficult, while modelling and predicting become harder. Difficulty in modelling makes system integration difficult.	The redesigning of sensors to make them smarter, especially on the backside. This will make them more sensitive to sunlight reflection thereby improving modelling through better performance measurement.
Multi-junction	High production costs and complex manufacturing processes. Durability	The development of new materials, especially along the line of III-V semiconductors on silicon cells, promises to be an alternative and attractive pathway to reducing the high manufacturing costs [69]. Also, advancement in manufacturing technology is required to mitigate the complexity and cost of production. Transfer printing technology is an economically recommended manufacturing alternative, while studies are ongoing on electroplating fabrication methods [70].
Mono PERC	Light and heat-induced degradation, manufacturing cost and complexities.	The process of passivation and new material incorporation is being increasingly used to mitigate degradation. Research is ongoing on high-performing technologies to overcome manufacturing complexities. Emphasis is also to be made on material research to develop alternative materials to bring down costs.
Organic	Aside from the issue of lower efficiency, the organic photovoltaics are plagued by challenges of degradation, stability, and manufacturing difficulty due to morphology control.	The development of a robust encapsulation technique will help to mitigate the stability and degradation susceptibility, while advancements in printing technology and solvent engineering will help ease the manufacturing difficulty [71].
Floatovoltaics	Saltwater corrosion and the difficulty of installation	Scholars have suggested the use of high-density poly ethylene materials for the floating structures [13]. However, further studies are required in the development of new materials for the manufacture of photovoltaics with resistance to salty water (to prevent corrosion) and the development of better anchoring structures.
Nano-materials	Difficulty of manufacturing, high cost and stability issues. Environmental concerns	The technology of quantum dot solar cells was developed to ease the manufacturing process. Studies are ongoing to integrate nanomaterials into solar panels [44] to resolve manufacturing challenges and encapsulation to mitigate toxicity.
Dye-Sensitized	Dye-Sensitized Solar Cells (DSSCs) are faced with stability and durability issues.	Further studies are required, especially in material science, to overcome the challenges through the manipulation of their atomic structure, microstructure, and surfaces properties. This will help to resist mechanical stress and environmental degradation.

Table 2. Comparison between new solar photovoltaic technology and traditional silicon photovoltaics

Photo-voltaic	Efficiency (%)	Initial Cost and LCOE	Degradation (%/year)	Associated Risk
Perovskites	Studies have proven that the efficiency can reach 27% [43]. An efficiency value of 25.7% was reported by Khatoon et al [72]. This is higher than that of traditional silicon cells whose efficiency hovers between (15-23)%	It has low manufacturing cost making it cheaper than traditional silicon cells. However, because of its higher degradation rate, its LCOE is higher.	They degrade faster than traditional silicon cells. Presently it has system loss rate higher than the <1%/year required to retain 80% of its initial output [73].	Perovskite contain Lead a toxic metal in greater amount than silicon PVs that are more stable. This holds a risk of potential environmental contamination if damaged.
Organic	The efficiency is lower than that of traditional silicon cells. Efficiency value of 19.2% was reported for studies conducted in the year 2023 by Chao et al [50].	It has lower manufacturing cost in comparison with silicon PVs, however, the LCOE is higher due to lower efficiencies and shorter lifespan. Study by Mattiasson Bjuggren et al in the year 2025 reported LCOEs of \$0.19 and \$0.11 for efficiency/lifetime combinations of 3%/3 years and 5%/5 years respectively [74].	Organic Photo-voltaics degrade faster than traditional silicon PVs. Improvement in the rate of degradation is however close, as study put the value per year under 2% [75].	There is an environmental risk of the release of organic compound like conjugated polymers and nonfullerene and traces of Lead.
Dye-Sensitised	The efficiency is lower than that of the traditional silicon PVs, however, at high temperature (31 – 40) °C its efficiency is relatively stable as against that of traditional silicon PVs that drops with increment in temperature [76].	The capital cost of dye-sensitised PVs is relatively lower than that of traditional silicon PVs [55]. The LCOE of traditional silicon PVs is however, lesser when compared with that of dye-sensitised PVs. Study conducted by Syed and Wei on the LCOE of dye-sensitised PVs in Kansas reported a value of \$0.0438/kWh [77].	Although, dye-sensitised PVs degrade faster than traditional solar PVs, its rate of degradation has improved significantly over the years and are nearing the silicon PVs.	There is a risk of the leakage of toxic liquid electrolyte and synthetic dyes like ruthenium-based complex.
Multi-junction	They have higher efficiency values due to their ability to absorb broader light spectrum. High efficiency value of 47.1% has been reported by scholars [46,78].	The manufacturing cost is higher than that of silicon PVs, and also is the LCOE [79].	Multi-junction PVs have higher degradation rate than traditional silicon PVs. A system level degradation rate (median: 2.1%/year, mean: 2.47%/year) was reported by Chen et al as against (median: 1.00%/year, mean: 1.27%/year) for traditional PVs [80].	The overall life-cycle environmental impacts of multi-junction panels are similar or lesser in comparison with that of single silicon panels. However, multi-junctions pose additional risk of the release of hazardous metals on damage and end-of-life management.

The adoption of Smart technology and artificial intelligence to the other two fronts of advancement brings a win-win scenario. It seeks to optimize performance and reliability through the provision of tracking devices to ensure maximum energy generation from the system for a greater part of the day hence contributing to the reduction of LCOE, real-time data acquisition and system training for effective predictive maintenance, improved grid integration, and even self-maintenance.

Looking at the future, advanced material research will in no small way push the narratives of the solar photovoltaics. Perovskites materials are naturally abundant, while organic, dye-sensitized and graphene PVs materials are also widely available making the risk of scarcity minimal. However, these newer available materials still suffer from degradation and stability issues. Development of new materials with good performance at high temperature, low light intensity, and in moist air conditions through atoms restructuring/manipulation and advanced manufacturing processes promises to be a game changer. The

development of environmental friendly recycling processes to mitigate the risk of environmental contamination from toxic substances like Lead, Nonfullerene, and Ruthenium based-complex etc., which are active ingredients of new photovoltaic materials is crucial. Thus, as the better performing solar photovoltaics are continually being sought along the different fronts, the end-of-life processing technology must also continue to advance to guide against environmental contamination.

8. Conclusions

Solar photovoltaics have the potential to revolutionise the global electricity generation sector and make power available to remote areas. The non-dwindling and globally abundant energy available from sunlight makes it renewable and sustainable, which is a reason for the immense attention. This study considered recent advances made in the field of electricity generation using solar photovoltaics, and the following deductions are inferred;

1. Floatovoltaics not only offer efficiency improvements of solar photovoltaics, but they also prevent water loss from bodies of water, making it a sustainable technology. It helps in solving challenges to land use.
 2. Dual-use photovoltaics have been developed, referred to as transparent photovoltaic glass for use in buildings to generate energy and offer structural applications as windows and facades.
 3. Energy generation of solar photovoltaics is increased with the use of bifacial solar module technology.
 4. The technology of textured solar cells has the potential to capture more daylight than conventional cells, with an addition of up to two-thirds.
 5. Perovskite photovoltaics offer improved efficiency performance and ease of integration into portable devices, making them a candidate for revolutionising solar technology deployment and utilisation.
 6. Traditional efficiency limits have been breached with the deployment of tandem cells, which are anchored on the technology of multi-junction solar cells.
 7. The reliance on rare earth materials is starting to shift with the use of organic materials and ongoing studies on kesterite cells and metamaterials as photovoltaics.
 8. The technology of dye-sensitised solar cells offers high-temperature and low-light applications.
 9. The integration of nanomaterials offers improved efficiency over traditional cells.
- Smart technology and artificial intelligence have made solar photovoltaic-generated electricity more reliable, better integrated, and better managed.

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Nomenclature

<i>BIPV</i>	Building Integrated Photovoltaic
<i>DSSC</i>	Dye-Sensitized Solar Cell
<i>HPDE</i>	High-Density Polyethylene
<i>IoT</i>	Internet of Things
<i>LCOE</i>	Levelized Cost of Energy
<i>Mono PERC</i>	Monocrystalline Passivated Emitter and Rear Cell
<i>QDSC</i>	Quantum Dot Solar Cell
<i>PV</i>	Photovoltaic
<i>TOPCon</i>	Tunnel Oxide Passivated Contact

Conflict of Interest Statement

The author declares that there is no conflict of interest in the study.

CRediT Author Statement

Olumide A. Towoju: Conceptualization, Writing-original draft, Supervision, Formal analysis

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