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Transparent Floating Solar Cells: Advancing Renewable Energy with Dual-Use Technology

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Abstract: The emergence of transparent solar cells in floating stations is an original concept. It can produce energy without requiring significant, substantial land, and it helps prevent evaporation, which results in the loss of between 50% and 70% of water. Their continuous cooling benefits, weight, and high absorption range favor their use. Transparent floating solar panels are also favored for their lowest cost. Many studies are focused on their potential dual-use applications, cost-effective manufacturing methods, and promising raw materials for this technology. This paper surveys suitable transparent solar cells that can be used in floating stations instead of silicon-based solar cells according to their features, adaptability, and efficiency, which can sometimes surpass conventional solar cells.

Keywords :Transparent solar cells, Floating solar stations, Perovskite solar cells, DSSCs, OVP, Agrivoltaic. Aquaculture, hydroponics.

1. Introduction

Transparent floating solar cells represent a cutting-edge innovation in renewable energy; the emergence of transparent solar cells in floating stations could provide a significant. A special feature of these cells is their extended absorption of ultraviolet (UV) and infrared (IR) light, as well as visible light. This results in improved energy conversion efficiency [1]. This increased spectral range enhances their energy harvesting capacities and makes them a viable technology for future solar power applications.

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Fig1. Transparent solar cell.

According to recent studies, floating solar station technology produces 0.6% to 4.4% more electricity than ground-based solar power stations [2]. Integrating these specialized cells allows simultaneous solar energy production and other activities such as aquaculture [3] and hydroponics [4], reducing water evaporation and promoting ecosystem development.

Transparent panels can be used for solar energy production and environmental monitoring. By allowing sunlight to shine downstream, we can promote biodiversity and increase the valuable use of water bodies, compared with traditional opaque panels that block the sunlight and prevent dual utilization. They are more attractive than conventional opaque panels and can be used as transparent or colorful construction [5] . In tourism, they help to develop the aesthetic value of water bodies. They allow for control of the marine landmarks below while promoting the sun's sustainable energy.

Historically, the origin of photovoltaic cell technologies dates back two centuries. The first land-based solar cell was made from selenium chips in 1883 [6]. It was later improved with silicon to reach a conversion efficiency of 6% [7]. Significant progress has been made to improve cost and accessibility [8]. Driven by economic necessity and the desire for broader adoption, solar cell prices have fallen from $350 per watt in 1956 to 50 cents per watt [9]. However, to minimize land use, several states prioritize floating solar cell technology over traditional terrestrial solar power stations, allocating substantial funds for development and installation [10].

2. Floating solar cells

A floating solar energy system was raised for the first time in the reservoir of a hydroelectric dam in Aichi, Japan, in 2007, with a production capacity of 20 kW, as mentioned by Ueda et al [11], Japan's National Institute of Advanced Industrial Science and Technology has created a system to inspect the performance of exclusively water and air-cooled PVs [12]. Floating PV solar power plants were 10% more efficient than terrestrial ones, as fixed by Choi & al [13]. Both technologies have improved efficiency, but floating solar panels remain the most efficient right now, According to the latest research articles and industry reports [2, 14, 15].

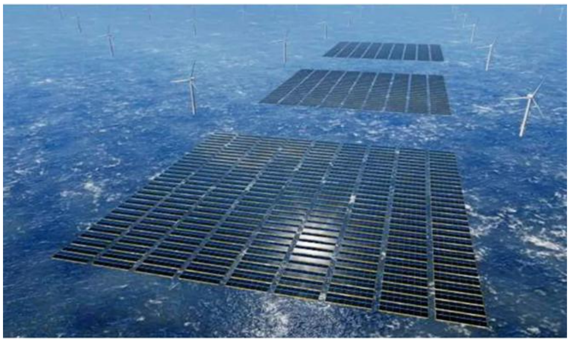


Fig.2. Floating solar blocks within offshore wind farms [16].

3. Floating photovoltaic structure

System's floating photovoltaic structures are classified in two ways: some are based on tracking the PV modules, and others are based on the type of floating system used. In the first case, the photovoltaic module is fixed at a determined angle to track the azimuth and altitude of the sun. Choi et al. proposed a tracking system for a 100 kW floating photovoltaic station [17]. The two main reasons for increasing efficiency are the reduction of reflectivity and the lack of thermal drift, which are done in submergible floating PV modules [18].

Thermal drift in photovoltaic systems refers to variations in power output or performance caused by changes in temperature. It is a common problem that can affect the efficiency and reliability of photovoltaic systems [19].

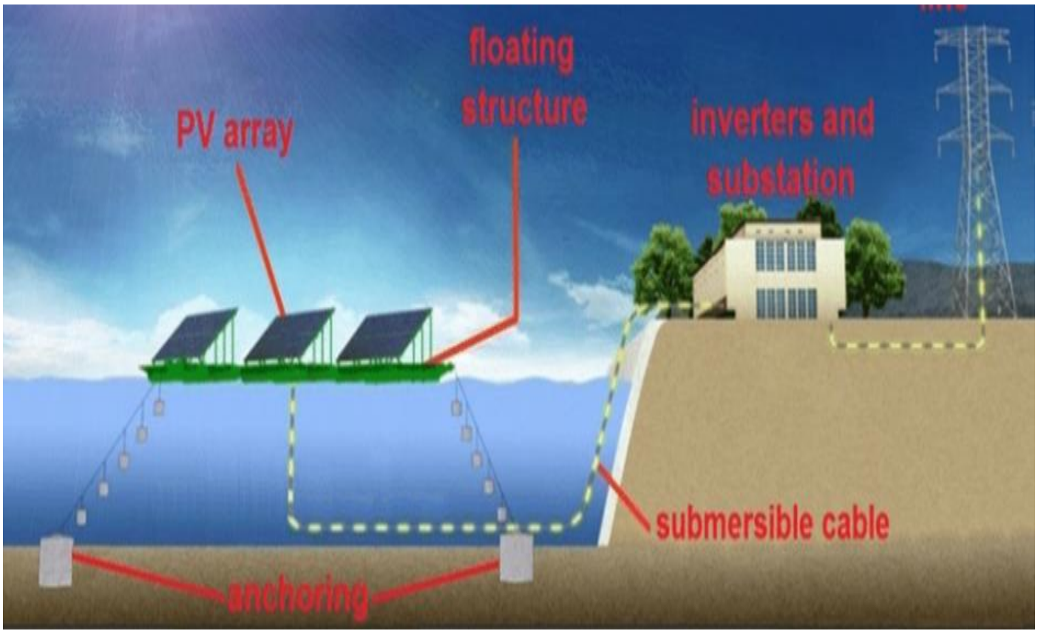


Fig. 3. Main components of floating photovoltaic system [20].

The output power of a solar cell module is directly influenced by its temperature; each 1°C increase in PV module surface temperature results in a 0.5% reduction of efficiency [21]. Additionally, temperature variations between modules can cause mismatch effects; some modules produce more power than others. Additional fees are necessary to mitigate these effects by incorporating photovoltaic inverters with temperature compensation algorithms [22], which leads to minimizing the profit.

Water can conserve continuous cooling for a floating photovoltaic system; efficiency can increase by about 35% [23], overcoming the thermal drift effect. The light reflection could also be circumvented by using transparent solar cells.

4. Transparent solar cells

Transparent solar cell technology holds great promise for the widespread and affordable use of solar power on previously inaccessible surfaces, such as skyscrapers, car windows, cell phones, and watches. About $6 \times 10^6 m^2$of glass surfaces in the US could only provide 40% of the country's energy, the same amount ground-based solar panels could provide. More than 2 billion people still don't have access to electricity. And another billion people use electricity less than 10 hours a day. In these cases, transparent solar cells are the cost-effective means for them to obtain energy [24]. The applications of transparent solar cell technology are practically limitless; this paper exposes their main kinds and the suitability and effectiveness of their use in floating stations.

5. Main generation of transparent solar cells

The challenges faced by all solar cells are cost, efficiency, and operating lifetime. The second generation of the photovoltaic system, after silicon-based solar cells, are the Heterojunction (HJT) solar cells, where Amorphous silicon (a-Si), Copper Indium Gallium Selenide (CIGS), Gallium Arsenide (GaAs), and Cadmium Telluride (CdTe) are the most commonly used materials.

HJT technology permits using less material, significantly reducing manufacturing costs. Still, they are not transparent, and as some of them are noxious substances, they are inappropriate for integration into floating solar stations. However, third-generation solar cells offer significant potential for the future of solar energy, especially for more efficient, affordable, and versatile solar power solutions.

The National Renewable Energy Laboratory (NREL) recently released a database of the highest-proven electrical energy conversion efficiencies for various solar technologies. The chart below shows how photovoltaic technology, as well as third-generation solar cells, has evolved.

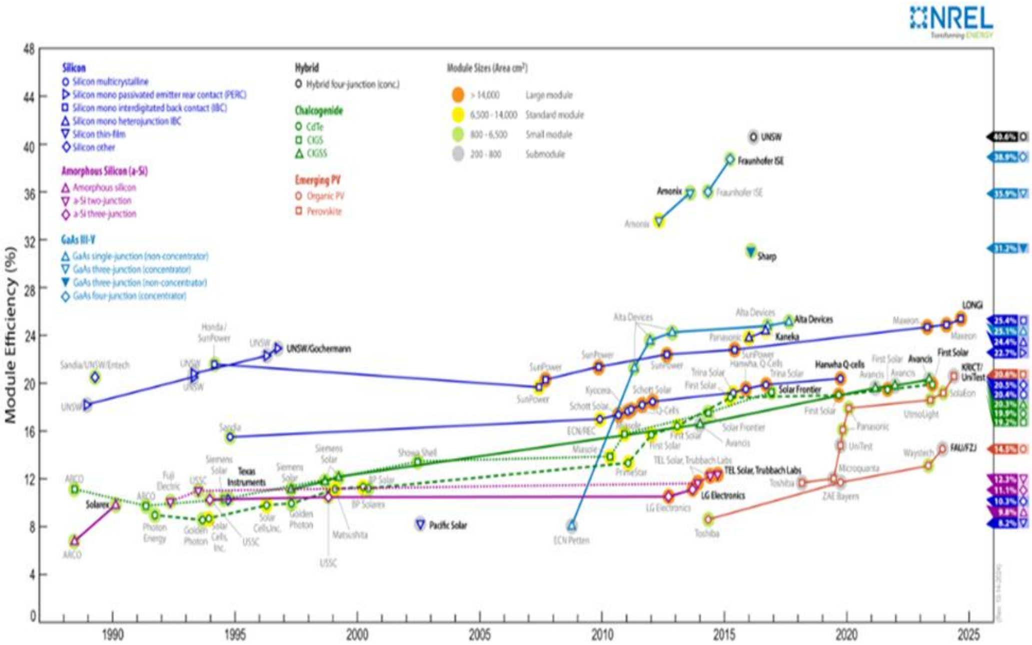


Fig.4. Database of efficiencies for various photovoltaic technologies from the National Renewable Energy Laboratory (NREL) [25].

It's important to note that the specific features of these technologies can vary depending on factors such as raw materials, industrial processes, and constant research advancements.

6. Breakdown of third-generation efficiency trends

Perovskite Solar Cells (PSCs) are the most prominent third-generation solar cells. Their efficiency has increased significantly in recent years. Figure 4 shows a focused upward trend for perovskite solar cells. In some cases, they have unprecedented efficiencies of more than 25%, surpassing conventional silicon-based solar cells.

Organic solar cells (OPVs) have also made significant progress, but their efficiency is still lower than perovskite and silicon cells. However, recent advances have pushed their efficiency beyond 19%. Dye-Sensitized Solar Cells (DSSCs) efficiency is relatively stable compared to other third-generation technologies. They offer advantages such as transparency and flexibility.

Efficiency is generally in the range of 10–14%. There are still challenges; these technologies hold immense potential to revolutionize the solar energy industry. Integrating these categories into floating solar stations requires a study of their designs, which are exposed in the following.

6. 1. Organic photovoltaic cells (OVP):

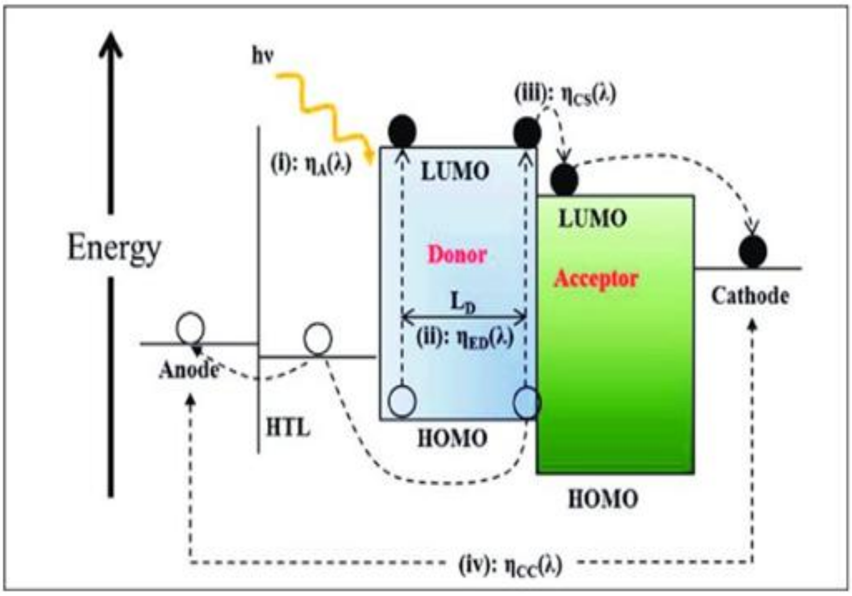


Fig.5. Working mechanism of organic solar cells [7].

The electric conversion process in OPVs, also known as plastic solar cells, is performed when solar light strikes the organic semiconductor layer. It excites electrons from the highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO). At the donor-acceptor interface, electrons and holes reach the electrodes, creating a potential difference that drives electric current through an external circuit, as mentioned in Figure 5.

OPV's performances are influenced by factors such as the absorption spectrum of the organic materials, the exciton diffusion length, charge separation efficiency, and charge transport properties of the materials.

They are lightweight, flexible, and can be made from low-cost materials. This makes them ultimate for various applications, including building-integrated photovoltaic (BIPV), wearable electronics, and remote sensing. OPVs can be produced using printing techniques, which makes them much cheaper than conventional silicon solar cells.

Their use in floating stations presents several advantages over traditional solar cells, mainly weight, flexibility, and efficiency under various environmental conditions. OPVs have a high specific power of 10-14 W/g, significantly higher than traditional silicon-based solar cells, around 0.38 W/g [26]. Their lightweight nature allows for easier installation and reduced structural requirements on floating platforms [26].

They can be fabricated on flexible surfaces, permitting them to conform to various shapes; this is useful for floating installations where movement and stress may occur [27] . This flexibility also allows for innovative designs that optimize light harvesting and energy generation in dynamic environments [27].

Organic photovoltaic cells prove vigorous performance at extreme temperatures. They maintain efficiency under conditions that naturally degrade conventional solar cells [26]. They are also less disposed to damage from UV rays and moisture. Therefore, they suit applications requiring constant water and sunlight exposure [28]. The PCE, power conversion efficiency of semi-transparent organic photovoltaic cells ST-OPV cells, has reached over 13%, and the AVT, the average visible transmittance, has exceeded 20% due to the unique absorption characteristics of semi-transparent organic materials of solar spectrum selectivity [29]. On the other hand, conventional solar panels provide higher efficiency and a longer lifespan than those on the ground; their inflexibility and weight can limit their use in floating environments. Constant progress in OPV technology may further improve their viability, potentially leading to a shift in preference towards floating stations.

6.2. Dye-sensitive solar cells, DSSCs

Fig . 6. Dye-sensitized solar cells DSSCs in agriculture [30].

Agrivoltaic combines agriculture and photovoltaic technologies. The main attempt of using dye-sensitive solar cells in greenhouses is to solve the energy cost problem, which reaches up to 28 percent. They can operate efficiently in low-light conditions; the photosensitive dye in DSSCs absorbs sunlight and generates electricity, performed by nanostructured coatings. They absorb UV light and retransmit it in the red and blue spectrum, which is helpful for plant photosynthesis without adversely affecting crop yield. It's a concrete application of dye-sensitive solar cells that has enhanced the yield.

DSSCs have been created around 1991 by O'Regan and Grätzell. Scientists were drawn by their low cost and the ease of manufacturing. The main components of an ideal DSSC are the dye-sensitized transparent conducting substrate and the semiconductor film such as Zinc Oxide (ZnO), Tin Dioxide (SnO_2), Niobium Pentoxide (Nb_2O_5), Titanium Dioxide (TiO_2)—the electrolyte and the counter [31].

Dye-sensitized solar cells use a variety of photosensitive dyes to absorb sunlight and initiate the process of converting light energy into electricity. The standard type is the Ruthenium due to its high efficiency and stability [32]. Ruthenium complexes, such as N719 and N3 [33], are preferred candidates due to their high light absorption and ability to inject electrons into semiconductors efficiently.

Organic dyes are also used; generally, they are obtained from organic molecules. They are characterized by their low cost, ease of synthesis

[34], and tunable optical properties. Porphyrins, phthalocyanines, and coumarins are some examples.

Natural dyes derived from plants, fruits, and other natural sources are also used in this category [35]. These colors are more sustainable and environmentally friendly alternatives to synthetic ones. Examples include anthocyanins, carotenoids, and chlorophyll.

Metal-free organic dyes [36] have the metal-free property, which makes them potentially less expensive and more environmentally friendly than metal-based ones, like Indoline and triphenylamine dyes.

Light absorption qualities, electron injection efficiency, stability, and cost are all important considerations when selecting a dye. Researchers are constantly looking for new and superior dyes to increase the performance and cost-effectiveness of DSSCs.

The descriptive scheme of a DSSC cell is illustrated in the following figure:

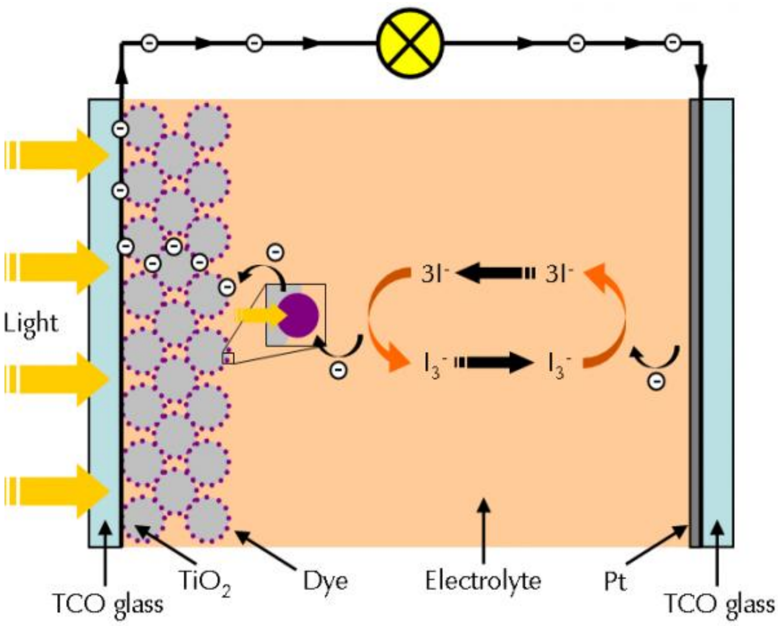


Fig. 7. Schematic overview of a dye-sensitized solar cell operational principle [37].

Photons of sunlight strike the dye molecules; the light energy absorbed excites electrons within the dye molecule, raising them to a higher energy level. Excited electrons are then injected into the conduction band of the titanium dioxide (TiO_2) semiconductor layer towards the transparent conducting oxide (TCO) layer, which acts as a current collector. At the counter electrode, a redox reaction occurs involving the electrolyte; the iodide ions (I^-) are oxidized to triiodide ions (I^{-3}) to complete the circuit. The flow of electrons from the TiO_2 layer to the counter electrode through the external circuit constitutes the electric current produced by the DSSC.

Broad-band metal semiconductors such as Titanium dioxide (TiO_2), Zinc oxide (ZnO), and Tin dioxide (SnO_2), which can generate currents of electron-hole pairs through photosynthesis and an organic dye, have made this generation a viable alternative to conventional solar cells [38], recent applications achieved an efficiency about 14.2% [39].

6. 2. 1. Dye-sensitive solar cell, DSSCS in floating stations

Dye-sensitized solar cells present a promising technology for floating solar stations due to their adaptability to aquatic environments and lightweight and flexible design.

Advances in polymer-based DSSCs have led to the development of flexible floating architectures that can endure severe environmental conditions, achieving conversion efficiencies above 5% [40]. Dye-sensitized solar cells can be deployed in floating stations to provide buoyancy; their ability to harvest sunlight from multiple angles and resist overheating makes them suitable for installation on water bodies.

Incorporating special hydrophobic surfaces avoids water accumulation, guaranteeing optimal performance and durability for floating applications [40].

DSSCs have demonstrated superior performance in underwater conditions, with only a 40.68% drop in power output at a depth of 20 cm, outpacing conventional silicon-based PVs [41]. Using broad-band ruthenium sensitizers increases the performance of DSSCs under diffused light conditions, making them suitable for underwater installations and for harvesting indirect diffused light [42].

Switching to water-based electrolytes in DSSCs reduces costs and improves environmental performance. Water availability significantly decreases expenses compared to traditional organic electrolytes [43]; water-based electrolytes are less harmful, more straightforward to dispose of, and safer for power generation in aquatic environments. This makes them ideal for large-scale deployment. Meanwhile, challenges remain in optimizing stability and efficiency to compete with their silicon-based counterparts.

Although ZnO-based DSSCs and TiO2-based DSSCs show promising efficiencies and stability. Due to its non-toxic nature, ease of fabrication, and low cost, it is the most compatible choice for floating stations. Meanwhile, the lower performance of SnO2-based DSSCs may limit their use in such environments.

Optimization of dye-sensitized solar cells (DSSCs) components is essential, like dyes, charge-selective contacts, anodes, and cathodes, but with complying criteria such as an excellent electron lifetime, high absorption spectrum, enhanced efficiency, and cost-effectiveness [31].

6. 3. Perovskite, PSCs

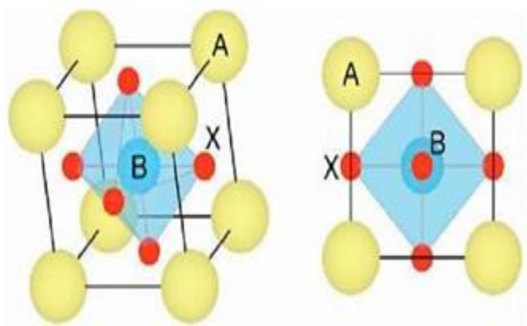


Fig. 9. Commonly perovskite crystal structure [44].

Perovskite (calcium titanium oxide) was discovered in 1839 by Russian mineralogist Alekseevich Perovski. He realized that all materials with the same CaTiO3 structure as ABX3 were perovskite.

For Perovskites solar cells (PSC), A is an organic cation, typically methylammonium (MA, CH_3NH^{+3}) or formamidinium (FA, $CH(NH_2)^{+2}$), B is a divalent metal cation, commonly lead (Pb^{+2}) or tin (Sn^{+2}), X is a halide anion, such as iodide (I^-), bromide (Br^-), chloride (Cl^-), or a combination of them. The halide composition determines the range of light that they can absorb. The methylammonium halides most common is the methylammonium lead triiodide ($CH_3NH_3PbI_3$), it has a high charge carrier mobility and lifetime [45].

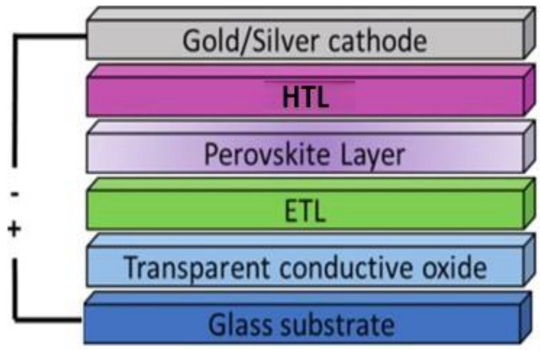


Fig. 10. General structure of a perovskite solar cell [46].

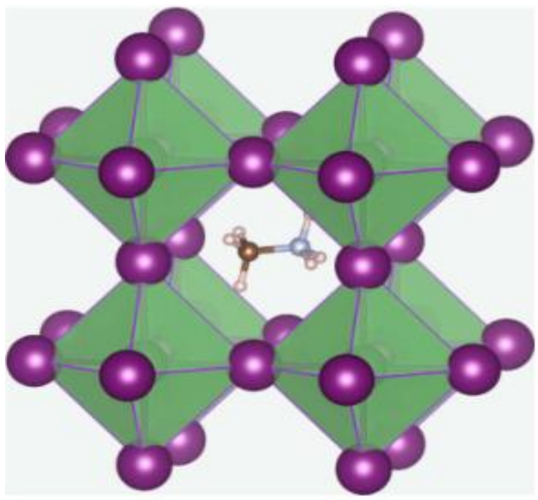


Fig. 11. Perovskite structure of $CH_3NH_3PbI_3$ [47].

The substrate is typically a transparent conductive oxide (TCO) or fluorine-doped tin oxide (FTO). The electron transport layer (ETL) is a semiconductor such as TiO_2 or SnO_2 [48]. The perovskite material, like $CH_3NH_3PbI_3$ [47], is the "light harvester" that converts sunlight into electrons. The hole transport layer (HTL), made of spiro-OMeTAD or PTAA [49], collects and transports holes. The back contact cathode is usually a metal electrode in a semi-transparent perovskite, such as gold, silver, or the TS-IZTO cathode [50]. PSCs can be made on flexible substrates, reducing overall weight, which is crucial for floating systems [51]. Recent advances have achieved power conversion efficiencies exceeding 31% [52], making them competitive with conventional solar technologies [53]. By combining additive halide ions, they can significantly improve their resistance to degradation. Introducing carbon nanotube electrodes leads to significant stability improvements, allowing devices to maintain efficiency for over 4000 hours [51].

6. 3. 1. The efficiency of transparent perovskite solar cells (TPSCs)

Recent studies indicate that TPSCs can achieve a balance between PCE, power conversion efficiency, and AVT, average visible transmittance, making them suitable for solar windows, aquaponics cultivation, BIPV, and floating stations. Transparent PSCs have reached PCEs exceeding 25% in optimal conditions depending on the materials and configurations used, with specific configurations yielding PCEs of 19.22% for $MAPbI_3$ at 250 nm thickness [54]. Semi-transparent perovskite solar cells have demonstrated PCEs around 22.85% with a thickness of 500 nm [55]. Other applications have achieved PCEs of 8.1% with AVT over 70% through effective passivation strategies [56, 57]. For applications requiring higher transparency, configurations like $SnO_2/MAPbBr_3$ have achieved an AVT of 29.2% while maintaining a PCE of 10.72% [54].

Although the advantages of PSCs for floating applications are compelling, challenges include long-term durability in harsh aquatic environments and deterioration that may occur due to moisture. This remains a concern that needs further exploration.

6. 3. 2. The integration of perovskite transparent solar cells (PTSCs) in aquatic environments:

Recent advancements have achieved semi-transparent perovskite solar cells with efficiencies of around 11.2% and average transparency of 24% [59]. This balance allows for dual functionality in floating stations, prioritizing aesthetics and energy generation.

Bifacial transparent perovskite solar cells can capture sunlight from both sides, providing an efficiency of 14.74% [60], showing up to 98% bifaciality factor [58]. This feature is particular, where reflections from water can enhance energy capture.

Integrating transparent perovskite solar cells with energy storage systems, such as supercapacitors, can provide a continuous power supply, addressing the intermittent nature of solar energy [61]. Their lightweight and flexible nature allows for easy installation on various floating structures, including solar farms and aquatic research stations [62].

6. 3. 3 The progress in the application of perovskite solar cells in aquatic environments

Recent studies highlight innovative designs and materials that facilitate the integration of perovskite technology into floating platforms, paving the way for sustainable energy solutions in aquatic environments. A highly integrated photo-rechargeable system combines perovskite solar cells with solid-state energy storage; it provides an overall efficiency of 10.01% while maintaining stability against moisture degradation [63]. This integration is crucial for floating systems, where energy storage is essential for continuous power supply. The development of lightweight perovskite-BiVO4 devices proves the potential for accessible solar fuel production with devices capable of floating and operating efficiently in water [51]. These devices utilize flexible substrates, permitting easier deployment and transport, which is vital for floating applications.

The growth of perovskite solar panels over large areas (up to 4.5 m2) in stand-alone solar farms indicates the technology's scalability and potential for outdoor applications, including in floating systems, by the near future [64]. These papers [65, 66] address the challenges of degradation when exposed to moisture and high temperatures by enhancing intrinsic stability, engineered device shape, and durable encapsulation materials [67]. Strategies such as composition manipulation and defect passivation can enhance the resilience of PSCs [68]. Also, developing streamlined manufacturing processes can help reduce costs and improve their scalability [63].

6. 3. 4. The suitable structure of transparent perovskite for a floating solar cell station

Under challenging conditions, the optimal perovskite solar cell structure design for floating solar cell stations emphasizes flexibility, durability, and environmental stability. The sandwich structure design, where the critical layer is placed at a neutral plane, minimizes bending stress, significantly enhancing mechanical stability and longevity [69]. Using transparent electrode-integrated flexible barriers, such as silicon nitride on polyethene terephthalate, provides adequate moisture protection while maintaining flexibility [70]. These structures improve power conversion efficiency by optimizing interface contacts, achieving efficiencies of up to 13.13% [71]. Sandwich-structured PSCs maintain over 85% efficiency after prolonged exposure to humidity, demonstrating their robustness in floating environments [72]. While these advancements present significant benefits, challenges remain in scaling production and ensuring long-term stability in diverse marine conditions.

6. 3. 5. Toxicity issues in perovskite solar cell:

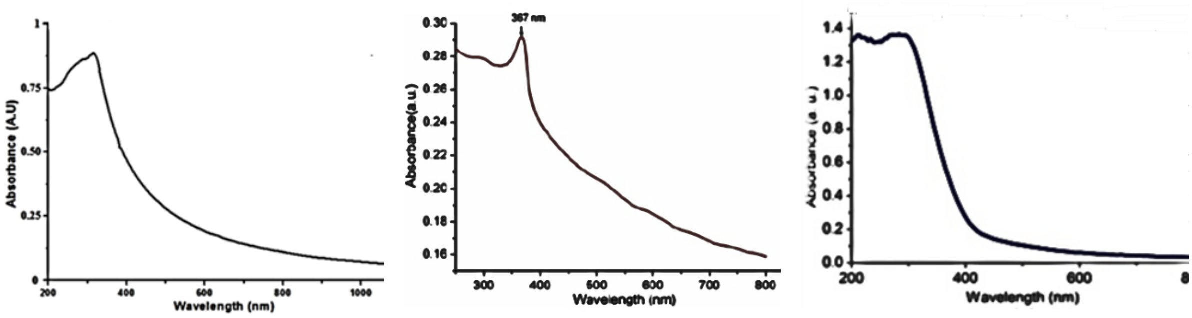
Several strategies have been proposed to prevent the toxicity of perovskite solar cells, particularly lead leakage. These approaches focus on encapsulation, lead absorption, and recycling methods to reduce the environmental and health risks associated with lead exposure. Some strategies propose using robust encapsulation techniques to shield PSCs from ecological factors and develop lead-free alternatives [73].

Incorporating mesoporous sulfonic acid-based resins within the perovskite structure can immobilize lead ions, effectively minimizing leakage to safe levels [74], and also employing lead-absorbing materials on both sides of perovskite solar cells, such as polymer resins and molecular films. These coatings effectively capture lead ions during device damage; they can retain up to 96% of lead sequestration from damaged devices, reducing environmental and public health risks without compromising device performance [75].

Another method is integrating Pb absorbents in various device layers, using a precise testing method, and developing low-cost recycling processes to enhance lead retention and reduce leaching. Methods such as polymer resin protective layers and self-healing encapsulation can achieve up to 95% lead capture under harsh conditions [76]. Challenges remain in scaling these solutions for extensive use.

7. The suitable semiconductor material for floating solar cells:

TiO2, ZnO, and SnO2 constitute fundamental semiconductor materials, especially for dye-sensitized solar cells (DSSCs), perovskite solar cells (PSCs), and organic photovoltaic cells (OPV). They frequently serve as electron transport layers (ETLs), effectively delivering electrons produced by the light-absorbing material to the anode. TiO_2 has a high electron mobility ranging from 0.1 to 10 cm²/Vs and excellent chemical stability; it is resistant to corrosion and degradation under various environmental conditions, and also easier to synthesize with a high surface area. TiO2 has a band gap of approximately of 3.2 eV for the anatase phase and 3.0 eV for the rutile phase, this wide bandgap allows TiO2 to absorb ultraviolet and visible light.



TiO_2 [1] ZnO [77] SnO_2 [78]

Fig. 8. Semiconductors spectrum curves of absorbance.

Referring to Figure 8, its high absorbance is in the ultraviolet range, it can achieve above 0.8 AU. ZnO has a high electron mobility of 200 to 1000 cm^2/Vs, it is inexpensive, and has a good light absorption due to its larger bandgap compared to TiO_2, which is about 3.37 eV.

It marks a good absorption of Ultraviolet rays, it has a moderate ability to absorb visible light, ZnO's disadvantage lies in its lower chemical stability than TiO_2, particularly in acidic environments, and its tendency to form defects that can delay electron transport.

SnO_2 has an electron mobility of about 200 cm²/Vs and a wide bandgap of 3.6 eV, similar to TiO_2 and ZnO. It is generally considered chemically stable, especially in neutral and alkaline environments; its high absorbance is distinguished in the UV range; however, the acidic conditions reduce its performance. It can be easily doped to improve its conductivity, but its absorbance is low compared to TiO_2 and ZnO in the visible range. Achieving a high surface area in its synthesis processes can be challenging.

Materials used for floating stations must resist corrosion and degradation from exposure to water and other environmental factors; they must have high light absorption and efficient charge transport to maximize energy production; and they should be relatively cheap, easy to produce, and environmentally friendly. TiO2 is generally considered the most suitable due to extensive research support, with some studies reporting up to 3.28% of efficiency after doping with transition metals [79]. It is known for its chemical stability, essential for floating applications where exposure to water and humidity is common [80]. The synthesis of TiO2 requires careful control of particle size and morphology to optimize performance [81]. ZnO has a proven efficiency of around 2.4% [79] due to its broad-band gap and effective electron transport properties. It is non-toxic and environmentally friendly, suitable for floating installations where ecological considerations are supreme [79]. It can be easily synthesized and integrated into flexible devices; this is useful for various installation conditions [82]. SnO2 generally exhibits lower efficiencies than TiO2 and ZnO [79]. Its stability in aquatic environments is less documented, which may raise concerns for floating applications.

TiO2 and ZnO generally are considered safe. They are widely used in various products, including inks, cosmetics, and food additives. Still, when these materials are in nanoparticle form, their toxicity can increase because nanoparticles can penetrate deeper into tissues and cells, potentially causing harm, so their manufacturing must be highly controlled.

8. Conclusion

This paper has exposed effective, transparent solar cells for floating solar stations, which serve purposes beyond power generation while maintaining minimal costs and good efficiency. The materials employed for floating stations must withstand corrosion and degradation due to water and environmental exposure; they should also exhibit high light absorption and excellent efficiency. The main types of the third generation's transparent solar cells were explored in different aspects: dye-sensitive solar cells (DSSC), organic photovoltaic cells (OPV), and perovskite (PSC) which was a beneficial candidate to substitute the heavy and expensive conventional solar cells. Transparent PSCs have reached PCEs exceeding 25%. With specific configurations, the average transparency can be 70%. Their flexibility to specify configurations allows for the balance between PCE and AVT, exploring dual functionality in floating stations such as aesthetics, marine activity, and energy generation. The exceptional trick of bifacial transparent perovskite solar cells permits achieving up to 14.74% efficiencies. This feature is particularly beneficial in floating applications, where reflections from the water can enhance energy capture. The conversion of 14.2% given by polymer-based DSSCs is promising for use in floating stations. The lightweight and flexible nature of perovskite solar cells allows for easy installation on various floating structures, including solar farms and aquatic research stations, which can be made from low-cost materials. They are also less susceptible to UV radiation and moisture damage and can operate efficiently in low-light conditions. Due to the non-toxic nature of DSSCs and OPVs, ease of fabrication, and low cost, they are also compatible with floating stations. They have demonstrated superior performance in underwater conditions, with only a 40.68% drop in power output at depths of 20 cm, outpacing conventional silicon-based PVs.

Additionally, the TS PSC competes with them in terms of efficiency, but a high measure of robust encapsulation and other techniques are mandatory to eliminate toxicity. These kinds of cells can be fabricated on flexible surfaces, permitting them to conform to various shapes; their flexibility also allows for innovative designs that can optimize light harvesting and energy generation in dynamic and aquatic environments. While integrating transparent solar cells into floating stations offers numerous benefits, long-term stability and durability challenges remain in harsh marine environments. Continued research is essential to address these issues and optimize their performance in real-world applications.

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