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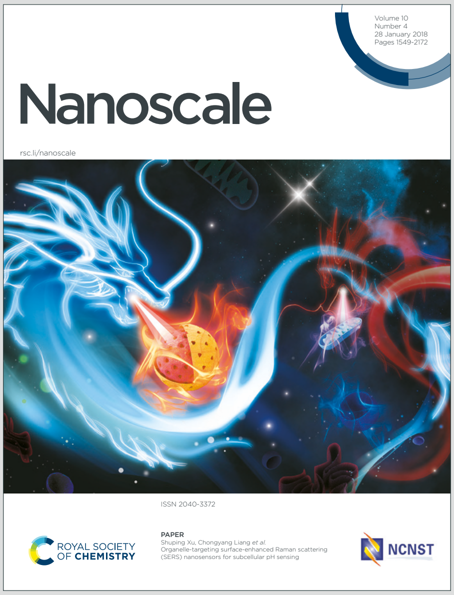

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ARTICLE

Dual-Function Electrodes for Photo-Rechargeable Batteries: Mechanisms, Designs, and Applications

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Photo-rechargeable batteries emerge as an integrated solution for simultaneous solar energy harvesting and storage. Central to these systems are dual-function electrode materials that intrinsically combine photoactivity and ion storage capabilities. Through synergistic interactions with electrolytes, these materials enable efficient energy conversion and storage, demonstrating significant potential for next-generation energy technologies. This review begins by exploring the synergistic operating mechanisms of dual-function electrode materials in photo-rechargeable batteries. It then delves into design strategies for both inorganic and organic electrodes, emphasizing hierarchical structures and atomic-scale interface engineering to optimize light absorption and ion transport. Subsequently, we examine their implementation in photovoltaic devices, focusing specifically on dye-sensitized and perovskite solar cells, and evaluate their primary applications in photo-rechargeable batteries. The findings presented in this work offer valuable insights into the future potential of next-generation photo-rechargeable batteries.

1. Introduction

The urgent need for sustainable energy solutions has driven the convergence of photovoltaics and energy storage technologies, aiming to overcome the inefficiencies of decoupled solar harvesting and rechargeable battery systems.[1-3] Conventional decoupled architectures, which isolate photovoltaic (PV) modules from electrochemical storage units, face critical limitations: (a) 10-15% energy losses at PV-battery-electrolyte interfaces, (b) spatial mismatches hindering system integration, and (c) safety hazards from flammable liquid electrolytes, including leakage and thermal runaway.[4, 5] Photo-rechargeable batteries represent a transformative paradigm in energy technology, unifying light absorption, charge generation, and energy storage within a single compact architecture. Central to this innovation are dual-function electrode materials and electrolytes, which synergistically enable several key advantages: (i) Enhanced electrochemical performance: the dual-function nature of the materials enables them to perform multiple roles, such as ion conduction and energy storage or conversion. (ii) High operational efficiency: by combining these advanced materials, the system offers enhanced operational efficiency, including faster charge/discharge cycles and better energy density. (iii) Interfacial stability: synergistic effect of electrodes and electrolytes enhance interface stability, reducing degradation over time. (iv) Mechanical flexibility: these materials enable flexibility, making them ideal for wearable and bendable devices.[6, 7]

The design of photo-rechargeable batteries demands a delicate balance between photonic and electrochemical functionalities. Efficient solar energy conversion requires materials with broad-spectrum light absorption (300-1500 nm), high carrier mobility (>10 cm^2 V^{-1} s^{-1}), and rapid charge separation, while robust energy storage relies on stable frameworks with high ionic conductivity (>1 mS cm^{-1}) and reversible ion intercalation.[8-10] Furthermore, electrolytes, including sulfide-based, oxide-based, and polymer-ceramic hybrids, play a pivotal role in addressing these challenges. For instance, sulfide electrolytes eliminate solvent decomposition risks under illumination while providing ion transport pathways via "hopping" mechanisms. Atomic-layer-deposited buffer layers further stabilize electrode-electrolyte interfaces, mitigating delamination and lattice mismatch.[11-14] Therefore, the synergistic interaction between dual-function electrode materials and electrolytes plays a vital role in enhancing the performance of photo-rechargeable batteries, making it a current research hotspot in this field.

Recent breakthroughs underscore the synergy between dual-function electrodes and solid-state architectures.[15-17] Chandra *et al.* studied the interface between perovskite and thin film LiCoO$_2$ cathode layer. They found that the structural order of LiCoO$_2$ is increased at a moderate temperature when the elements are mixed, especially the diffusion of cobalt to perovskite.[18] Cheng *et al.* discussed a novel type of perovskite, specifically a reduced-dimensional perovskite. They conducted a detailed analysis of the effects of multiple quantum wells on the structural characteristics,

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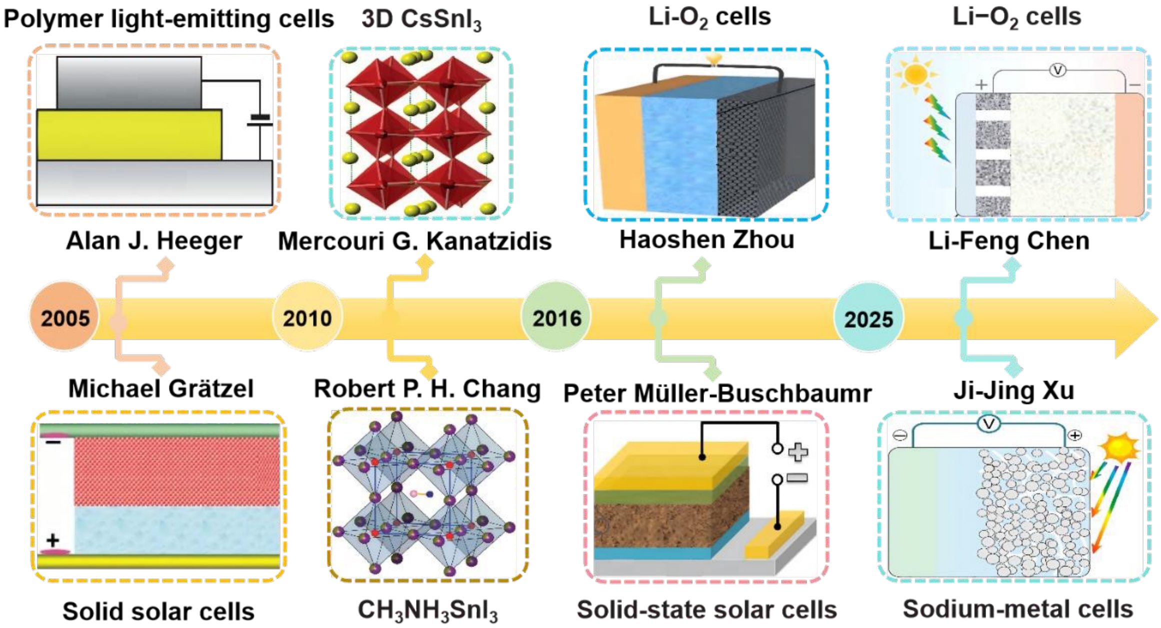

Fig. 1. Historical development of photo-rechargeable batteries over the past two decades. Polymer light-emitting cells. Copyright 2007,[19] Wiley-VCH. Solid solar cells. Copyright 2008,[20] Wiley-VCH. 3D CsSnI3. Copyright 2012,[21] Nature. CH3NH3SnI3. Copyright 2014,[22] Nature. Solid-state Li-O2 cells. Copyright 2018,[23] Elsevier. Solid-state solar cells. Copyright 2017,[24] Elsevier. Solid-state Li-O2 cells. Copyright 2025,[25] Wiley-VCH. Solid-state sodium-metal cells. (SMBs) Copyright 2023,[26] American Chemical Society.

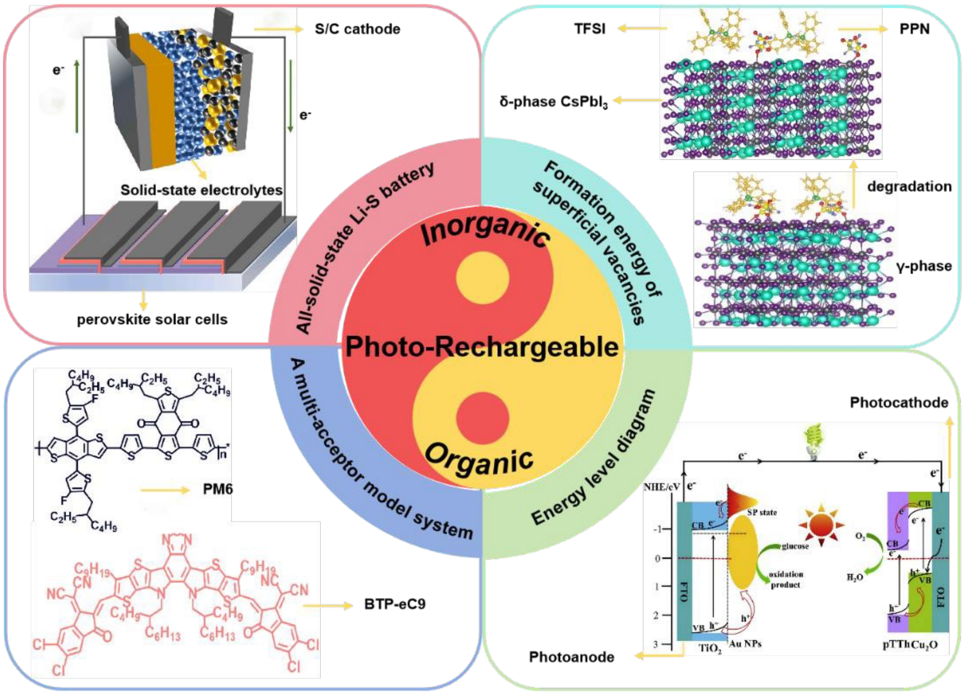

Fig. 2. Organic and inorganic photovoltaic energy storage electrode materials in photo-rechargeable batteries. All-solid-state Li-S battery. Copyright 2023,[27] Elsevier. Formation energy of superficial vacancies. Copyright 2023,[28] American Association for the Advancement of Science. A multi-acceptor model system. Copyright 2024,[29] The Royal Society of Chemistry. Energy level diagram. Copyright 2019,[30] Elsevier.

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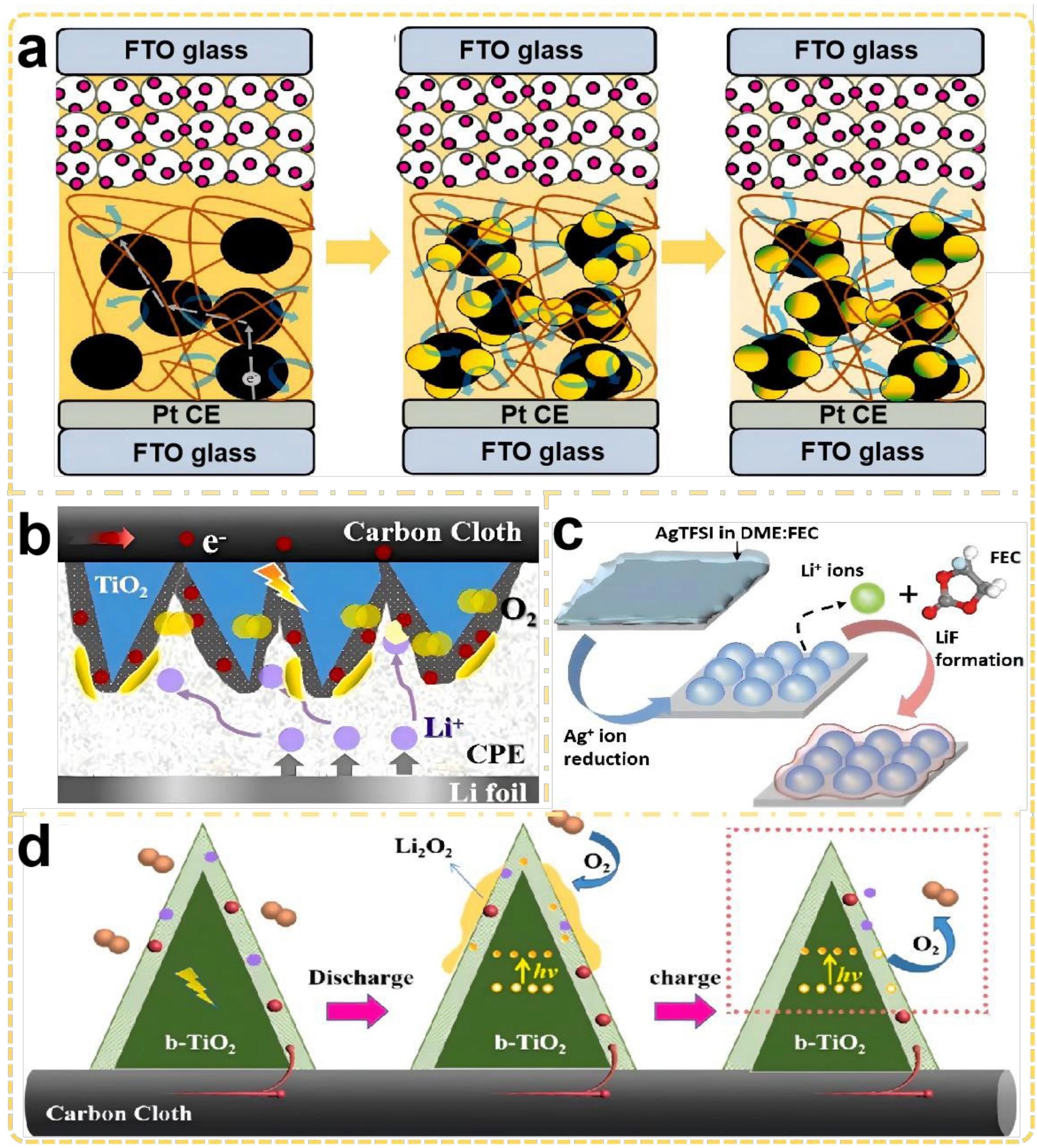

Fig. 3. (a) Schematic diagrams of solid-state dye-sensitized solar cells using CB, Pt/CB, and Pt-Ni alloy/CB as nanofillers in composite polymer electrolytes. Copyright 2025,[31] Elsevier. (b) The transformation mechanism schematic of Li$^+$, e$^-$, and O$_2$ inside the battery. Copyright 2019, Wiley-VCH. (c) Schematic representation of the formation of a Li-Ag-LiF surface. Copyright 2019,[32] Wiley-VCH. (d) The schematic of the proposed mechanism of photo-electric-thermal synergy for solid-state Li-O$_2$ battery. Copyright 2022,[33] Elsevier.

carrier recombination dynamics, and optoelectronic properties of these materials. Their work aims to provide a deeper understanding of reduced-dimensional perovskites to facilitate their further development and application in the field of optoelectronics.[34] The Noel team employed a mixed-cation surface-doped perovskite to effectively enhance the hole extraction efficiency in perovskite solar cells. They demonstrated that molecular doping is a viable method for adjusting and controlling the surface properties of metal halide perovskites.[35] The field remains in its nascent phase, necessitating sustained investigation (**Fig. 1**). Over the past two decades, advancements in photo-rechargeable battery research have catalyzed remarkable strides in integrated photovoltaic energy storage systems. These developments underscore the intrinsic capacity of solid-state systems to integrate light absorption, carrier dynamics, and ion transport. However, critical challenges persist.[36] The kinetic competition between photogenerated carrier separation and ion transport limits energy density, and scalable fabrication of nanostructured electrodes remains hindered by cost and yield constraints.[37, 38]

Overall, an ideal photo-rechargeable battery should embody three defining attributes: (a) High solar-to-electricity efficiency: broad-spectrum light absorption coupled with rapid charge separation and minimized interfacial energy losses, enabling high photon-to-ion conversion efficiency. (b) Extended cycle life: stable dual-function materials with >1,000 cycles at 90% capacity retention and ionic conductivities exceeding 1 mS cm^{-1}, where photogenerated carriers (electrons/holes) synergistically drive or replace conventional ion storage processes. (c) Adaptive functionality: mechanical flexibility, temperature resilience, and scalable manufacturing protocols for grid-level deployment. This review systematically explores solid-state electrolyte innovations and dual-function electrode design strategies to overcome these barriers. We systematically analyze design strategies for inorganic and organic electrodes (**Fig. 2**), emphasizing hierarchical architectures and atomic-scale interface engineering to simultaneously optimize light absorption and ion transport dynamics. We elucidate mechanisms governing light-electricity-ion coupling, analyze hierarchical architectures for balancing optoelectronic and ionic properties, and summarize applications in photo-rechargeable batteries. By bridging photo-electrochemistry and solid-state battery science, this work offers valuable insights into the future potential of next-generation photo-rechargeable batteries.

2. Synergistic Operating Mechanisms of Photo-Rechargeable Batteries

The core innovation of photo-rechargeable batteries lies in the synergistic design of dual-function electrodes and electrolytes. Through integrated photo-electro-chemical mechanisms, this synergy enables efficient harvesting, conversion, and storage of solar energy. [39, 40] Solid-state electrolytes are pivotal enablers of high-performance photo-rechargeable batteries, offering unparalleled advantages over liquid counterparts, including intrinsic safety, wide electrochemical stability, and compatibility with dual-function electrodes.[41-43] This section explores recent breakthroughs in solid-state electrolytes materials and their synergistic interplay with photoelectrochemical processes.

2.1 Synergistic Light-Electricity-Ion Coupling

Photo-rechargeable batteries typically operate through a synergistic mechanism that combines the photoelectric conversion of solar energy with the electrochemical storage of charge. To gain a deeper understanding of the working principles of these photo-rechargeable batteries, it is essential to investigate the interactions between photoactive materials, electrolytes, and bifunctional electrodes. Together, these components enable efficient energy conversion and storage.[44-46] The photoelectric conversion process is the core mechanism of the photo-rechargeable batteries. When exposed to light, the photoactive material in the battery absorbs photons, generating electron-hole pairs. These excited charge carriers (electrons and holes) are separated and transported through the system.

In solid-state systems, this charge separation and transport typically rely on the interface between the photoactive electrode and the solid electrolyte, where a suitable energy alignment and efficient carrier mobility are crucial. The ion conduction in solid electrolytes plays a complementary role, transporting ions between the electrodes to maintain charge neutrality and support continuous cycling.[47, 48] For high-efficiency photo-rechargeable batteries, the photoactive material must possess several key properties: high light absorption, effective charge carrier separation, and minimal recombination.[49, 50] The transport of these carriers from the photoactive material to the electrode is enhanced by optimizing the morphology and structure of the electrode, ensuring that charge carriers can be efficiently extracted. Ren *et al.* proposed a multifunctional composite cathode with synergistic photoelectric-thermal-electrochemical effects, paired with a polymer solid-state electrolyte, to create a Li-O_2 battery with superior flexibility and mechanical stability.[33] As shown in **Fig. 3b**, they suggested a potential transport mechanism for the three-phase reaction interface. At the electrolyte-electrode interface, the disordered layer on the b-TiO_2 surface enhances both the ion conductivity and electron conductivity. Additionally, the presence of numerous pores ensures the diffusion of oxygen molecules and maintains continuous transport paths for lithium ions, electrons, and oxygen molecules. In terms of the photoelectric-thermal synergistic effect mechanism, photo-generated holes are transported to the disordered layer as a result of the combined photoelectric-thermal effect in the reversible charging process. Driven by the reduction of charge voltage, they decompose into O_2 and Li^+, which then immediately combine to form LiO_2. Due to the instability of LiO_2, it experiences a second electron reduction, resulting in the formation of Li_2O_2. The charging process follows the identical reaction mechanism as general systems, where O_2 and Li^+ are directly released without intermediate products (**Fig. 3d**). This is similar to introducing a redox mediator into the Li-O_2 battery system, significantly improving the battery's performance.

Besides, interface stability is another critical aspect of the operation of photo-rechargeable batteries.[51] To prevent degradation of the battery's performance, it is essential for the interface amid the photoactive electrode and the solid electrolyte to remain stable during repeated charge-discharge cycles. If the interface becomes unstable, issues such as ion migration, poor charge transfer, or material degradation can arise, which would compromise the efficiency and longevity of the device.[52, 53] Therefore, it is very important to select the appropriate solid electrolyte for different electrode materials. The solid electrolyte not only serves as an ion conductor but also provides mechanical support to the photoactive electrode. Electrochemical reactions that occur at the interface must be carefully controlled to prevent unwanted side reactions, such as the formation of insulating layers or the degradation of the electrode materials. Researchers have developed various strategies to improve interface stability, such as using protective interlayers or optimizing the solid electrolyte's composition to ensure better adhesion and stability during operation. Chen's research team introduced carbon-supported Pt-Ni nano-fillers into composite polymer electrolytes.[31] In the composite polymer electrolyte, they initially added carbon black (CB) nano-fillers to provide a continuous conductive pathway network in **Fig. 3a**. This reticular structure facilitates the transfer of electrons from the counter electrode to the I_3^- ions, which in turn lowers the charge transfer resistance. When Pt/CB nano-fillers were

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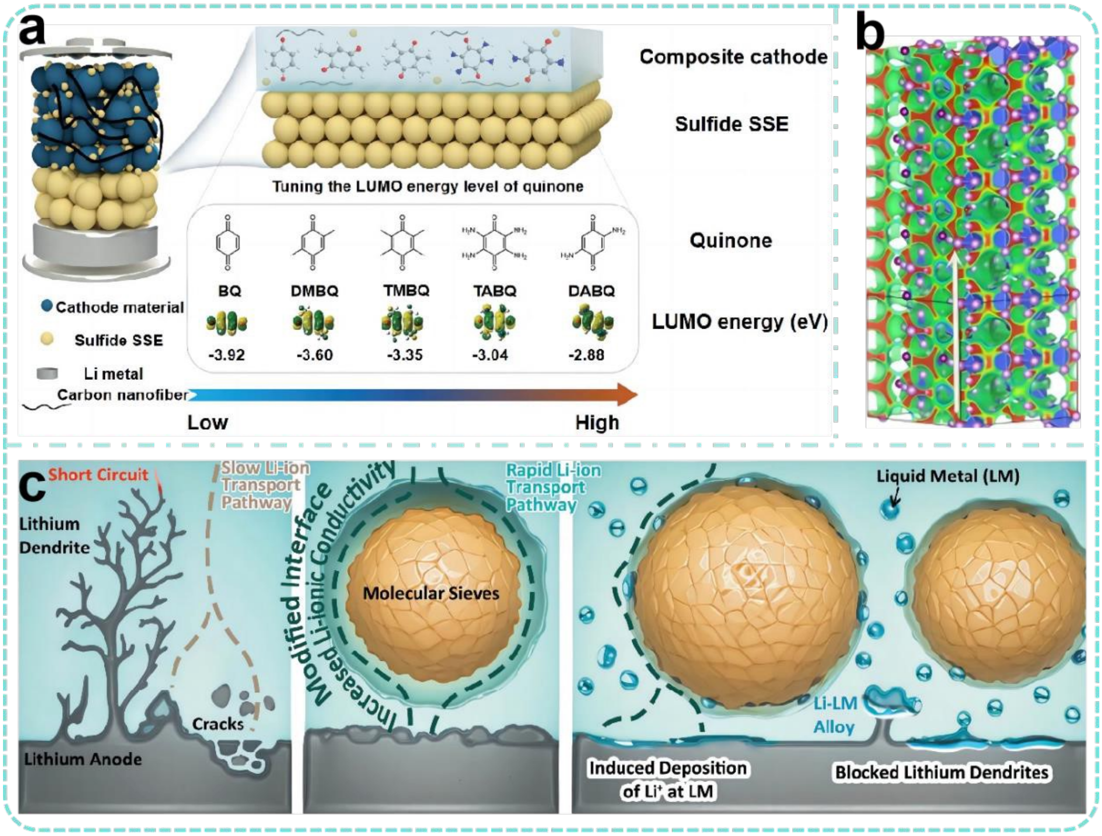

Fig. 4. Solid-state electrolytes: (a) Schematics of the solid-state organic battery. Copyright 2024,[54] Wiley-VCH. (b) Li+ probability density, represented by isosurfaces from ab initio molecular dynamics simulations in solid-state electrolytes lattice. Copyright 2024,[55] Wiley-VCH. (c) Schematic diagram of action mechanism of the pristine PEO, MS-PEO, and LM-MS-PEO solid-state electrolyte and protection layer. Copyright 2024,[56] Wiley-VCH.

incorporated into the composite polymer electrolyte, the Pt on the CB acted as an efficient catalyst, promoting the timely regeneration and transport of I_3^- ions, which aids in the rapid regeneration of the dye and consequently enhances the short-circuit current density. Therefore, platinum-modified CB nano-fillers can further reduce the charge transfer resistance while improving the ion conductivity of the composite polymer electrolyte. Additionally, by alloying Pt with Ni on the CB, the thermodynamically favorable reaction between Ni and I_3^- further enhances the open-circuit voltage. The formation of Ni-I compounds reduces the number of free I_3^- ions in the electrolyte, thus increasing the resistance between the dye-adsorbed TiO_2 photoanode and the electrolyte, minimizing the open-circuit voltage losses. This synergistic effect improves both the conversion efficiency and stability of solid-state dye-sensitized solar cells.

In addition to the photoelectric conversion process, the electrochemical charge storage and recharging mechanisms are vital to the performance of photo-rechargeable batteries. During the discharge process, ions from the solid electrolyte migrate to the anode, where they are stored as charge carriers. On charging, the reverse process occurs, and the ions are released back into the electrolyte from the anode to restore the battery's state of charge. This process is similar to that of traditional solid-state batteries, but it is coupled with the ability of the photoactive material to regenerate energy from light.[1, 57] Peng *et al.* reported a simple method to form a ternary surface that, in synergy with the solid-state electrolyte, effectively protects the lithium metal anode.[32] They treated the surface of the lithium metal with a silver ion precursor solution composed of 1,2-dimethoxyethane, fluoroethylene carbonate, and silver bis(trifluoromethanesulfonyl)imide. Due to the strong oxidative properties of silver ions, abundant silver nanoparticles can be formed on the lithium surface. These silver particles act as nucleation sites for lithium deposition and reduce the overpotential, leading to a high exchange current density and a very uniform lithium plating/stripping morphology. At the same time, the lithium ions released during the reduction of silver ion can effectively react with the fluoride ions derived from the decomposition of fluoroethylene carbonate, forming a LiF-rich cross-linked interface. This LiF-rich SEI layer formed during the initial cycles effectively

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protects the lithium metal anode, enabling long-term cycling stability (**Fig. 3c**).

One of the challenges in photo-rechargeable batteries is optimizing the balance between charge storage capacity and charge transport efficiency.[58] High-energy-density electrodes must be paired with electrolytes that allow for fast ion diffusion without compromising the stability of the interface. Additionally, during recharging, the light energy must be efficiently converted into electrical energy, which is then stored in the electrochemical system. The dual functionality of photoelectric conversion and electrochemical energy storage gives solid-state photo-rechargeable batteries a unique advantage over traditional batteries and solar cells. An effective solid-state photo-rechargeable battery not only requires efficient light harvesting and photoelectric conversion but also demands seamless coupling with ion transport mechanisms within the solid electrolyte. The integration of these two functions (photoelectric conversion and electrochemical ion storage) is what defines the synergistic operation of the battery. The efficiency of the battery depends on how well these two processes are coupled, where the photo-generated electrons and holes are efficiently managed in conjunction with ion flow through the solid electrolyte.

In order to achieve high efficiency and stability in solid-state photo-rechargeable batteries, several performance optimization strategies have been developed. These strategies target the optimization of both photoactive electrode materials and solid electrolytes, as well as improving the interfaces between them. Common approaches include the development of composite materials, surface modifications, and the use of interfacial layers to reduce recombination losses and enhance charge transfer.[59, 60] Further, the selection of solid-state electrolytes plays a critical role in improving the overall performance of solid-state photo-rechargeable batteries. The electrolyte must possess high ionic conductivity, stability under operating conditions, and the ability to form stable interfaces with both the photoactive electrode and the charge storage materials.

2.2 Advanced solid-state electrolytes

The ion transport mechanism and interface stability of solid-state electrolytes are crucial factors influencing the performance of solid-state photo-chargeable batteries. Common types of solid-state electrolytes include sulfide-based, oxide-based, and polymer-based electrolytes.[61-63] Sulfide solid-state electrolytes exhibit ultrahigh ionic conductivities (>5 mS cm^{-1} at room temperature) due to their soft lattice frameworks and "hopping" Li$^+$ migration mechanisms. Their low grain boundary resistance and deformability enable intimate electrode-electrolyte contact, minimizing interfacial impedance.[64] Lin *et al.* performed density functional theory calculations on the lowest unoccupied molecular orbital (LUMO) energy levels of p-benzoquinone (BQ), 2,5-dimethyl-1,4-benzoquinone (DMBQ), 2,3,5,6-tetramethyl-1,4-benzoquinone (TMBQ), 2,3,5,6-tetraamino-1,4-benzoquinone (TABQ), and 2,5-diamino-1,4-benzoquinone (DABQ), identifying the quinone derivatives that pair best with sulfur-based compounds (**Fig. 4a**).[54] Due to the stronger electron-donating effect of the amino group compared to the methyl group, the LUMO energy levels of DABQ and TABQ are significantly higher than those of DMBQ and TMBQ. In the case of DABQ, both amino groups can act as electron donors conjugated to the para-benzoquinone segment. In contrast, for TABQ, only two of the four amino groups conjugate with the para-benzoquinone segment, while the remaining two amino groups function as sigma electron acceptors, exhibiting an electron-withdrawing effect. As a result, the electron density on the para-benzoquinone segment of TABQ is lower than that in DABQ. This difference in electronic structure contributes to the superior performance of their assembled advanced sulfurized solid-state organic lithium metal batteries (**Fig. 4a**). Oxide solid-state electrolytes provide exceptional thermal stability (>300 °C) and wide electrochemical windows (>5 V), effectively suppressing parasitic reactions at high voltages.[65, 66] Ma *et al.* designed a low-cost, environmentally friendly, and sustainable halogenated oxynitride solid-state electrolyte.[55] Through ab initio molecular dynamics simulations, they elucidated the rapid diffusion of lithium ions within the lattice of this solid-state electrolyte and described the ability of lithium ions to move quickly along the three-dimensional channels (**Fig. 4b**). They demonstrated that this oxide-based solid-state electrolyte exhibits good chemical stability and high interfacial energy, effectively suppressing the growth of lithium dendrites and the self-degradation of the lithium metal interface. Hybrid systems combine the flexibility of polymers with the ionic conductivity of ceramics. The combination of different types of polymers, inorganic materials, and organic plasticizers can effectively enhance the room-temperature conductivity of polymer electrolytes, improve the electrode/electrolyte interface, and maintain a certain level of mechanical strength.[67-69] In this study, the Qian team integrated molecular sieves (MS) as inert fillers into polyethylene oxide (PEO) and used liquid metals (LM) as functional modules to form the "LM-MS-PEO" composite material. This composite serves as a solid-state electrolyte to enhance ion conductivity while also acting as a protective layer against lithium dendrites. Specifically, when lithium ions migrate and deposit in pure PEO, the process is unconstrained and uninfluenced. However, with the incorporation of MS, the lithium-ion conductivity of PEO is significantly improved due to the reduced crystallinity of PEO near the MS. Furthermore, the addition of the LM component leads to noticeable changes in the transport and deposition behavior of lithium ions. By reacting with lithium dendrites to form alloys or by extending the growth path of the dendrites, the LM effectively blocks their growth, reducing the possibility of short circuits and providing protection to the battery (**Fig. 4c**). These hybrids are particularly suited for flexible solid-state photo-rechargeable batteries in wearable electronics. This section aims to provide a comprehensive understanding of the working mechanisms that make photo-rechargeable batteries effective in both photoelectric conversion and electrochemical charge storage. By focusing on the synergy between the photoactive materials, solid-state electrolytes, and electrodes, this section outlines the critical factors and current challenges in enhancing the performance and efficiency of these photo-rechargeable batteries.

3. Photo-Rechargeable Dual-Function Electrode Materials

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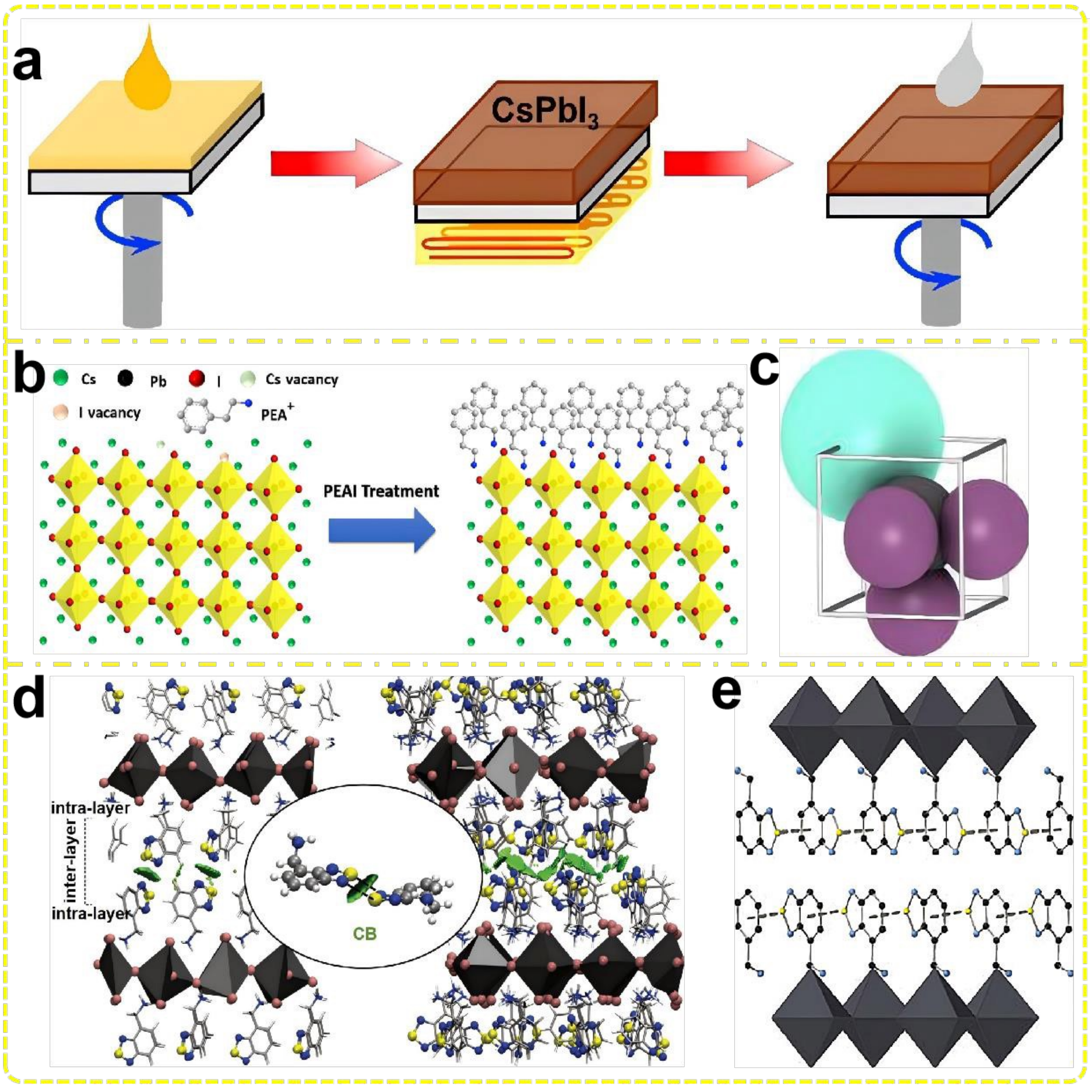

Fig. 5. (a) Schematic procedures for the deposition and post-synthesis treatment of CsPbI3 perovskite with organic cation iodide solution. Copyright 2018, Elsevier. (b) Schematic illustration of organic cation surface termination using phenylethylammonium iodide (PEAI). Copyright 2018,[70] Elsevier. (c) Perovskite structures. Copyright 2013,[71] The Royal Society of Chemistry. (d) Theoretical analysis of the formation of chalcogen bonding in model system of low-dimensional perovskites. Copyright 2024, Wiley-VCH. (e) two-dimensional (2D) perovskite (corner-sharing octahedra; stabilized via S–π interactions indicated by dashed lines. Copyright 2024,[72] Wiley-VCH.

Photo-rechargeable batteries rely on advanced electrode materials that integrate light absorption and ion storage functionalities. A key component of these systems is the electrode materials, which play a critical role in determining the overall efficiency, stability, and performance of photo-rechargeable batteries.[73-75] The materials used for electrodes must be capable of facilitating effective charge transport, interacting efficiently with the electrolyte, and exhibiting good photoactivity. This section categorizes the electrode materials into two primary types: inorganic and organic materials. It provides an in-depth review of the latest advancements in these materials, their advantages and challenges, and the ongoing trends in research aimed at enhancing photo-rechargeable batteries performance.[76]

3.1 Inorganic Electrode Materials in Photo-Rechargeable Batteries

Inorganic electrode materials are among the most widely researched materials for photo-rechargeable batteries due to their high stability, good conductivity, and well-established performance in traditional battery applications.[77, 78] Common inorganic electrode materials include metal oxides, sulfides, and phosphates. Metal oxides: materials such as titanium dioxide, zinc oxide, and tungsten oxide have shown great promise in photo-rechargeable batteries, particularly in terms of their stability and charge storage capabilities.

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Sulfides and phosphates: another promising class of inorganic materials includes metal sulfides and phosphates, such as copper sulfide and lithium iron phosphate. These materials are valued for their ability to deliver high capacity and fast ion diffusion, which are essential for high-performance photo-rechargeable batteries. Research in this area has largely focused on optimizing the interfaces between the electrodes and electrolytes, ensuring high ionic conductivity and long-term stability.[79, 80] Recent research has focused on improving their electronic conductivity and enhancing their photo-charge conversion efficiency. Wang *et al.* found neither solid-state nor sequential cation exchange processes allow $CsPbI_3$ to form a two-dimensional perovskite capping layer. [70] Instead, they improved the material's phase stability and moisture resistance by effectively exchanging cations between the organic components, thereby creating a defect-passivating organic cation-terminated surface on top of a-$CsPbI_3$. The researchers employed a typical cation exchange reaction using phenylethylammonium iodide (PEAI) solution, which was spin-coated onto the $CsPbI_3$ perovskite thin film (**Fig. 5a**). The surface termination mechanism involves the passivation of Cs^+ and I^+ vacancies or defects on the $CsPbI_3$ surface by the PEA^+ and I^+ ions. Additionally, some Cs^+ ions on the surface may be replaced by the PEA^+ cations, thereby terminating the surface with PEA^+ organic ions (**Fig. 5b**). This simple yet innovative strategy for organic cation surface termination offers a promising approach for developing highly reproducible, high-performance perovskite solar cells with enhanced device stability. While metal halide perovskites are outstanding solid-state semiconductors, they are also ionic compounds, and ion migration is essential to their formation, photovoltaic performance, and long-term stability. The Salvador team, utilizing molecular dynamics simulations with classical force fields, density functional theory calculations, and genetic algorithms, developed a fully transferable classical force field.[71] This force field is specifically designed for the benchmark inorganic perovskite composition, $CsPb(Br_xI_{1-x})_3$ (**Fig. 5c**), and is applied to study the properties of metal halide perovskites, including lattice dynamics and ion migration. Luo *et al.* conducted research aiming to enhance the stability of organic-inorganic halide perovskite hybrid semiconductors through supramolecular engineering, focusing on non-covalent interactions between organic and inorganic components, such as hydrogen bonding and traditional van der Waals interactions.[72] They explored the ability to form unique low-dimensional perovskite structures by combining benzothiazole-based groups, investigating non-typical sulfur-mediated interactions. Using density functional theory and ab initio molecular dynamics simulations, they evaluated the preferred structural arrangements of layered hybrid perovskite materials, considering both initial molecular configurations with and without carbon bonds, without assuming a preferential orientation of the organic components within the layers (**Fig. 5d**). The simulations revealed the formation of sulfur-mediated low-dimensional structures, such as one-dimensional and layered two-dimensional perovskite phases, which were assembled through sulfur bonds and S-π interactions (**Fig. 5e**). The materials developed by the team were used in both n-i-p and p-i-n perovskite solar cells, showing improved performance and operational stability, thus demonstrating a universal supramolecular strategy for photovoltaic devices.

Integrating inorganic materials into photo-rechargeable batteries presents several challenges, including the need for precise control over material composition and structure to enhance light absorption properties and improve charge transport.[81, 82] Additionally, while the de-fatting process of certain inorganic cathode/anode materials can be facilitated by photogenerated holes, the high oxidative power of these high-energy holes may cause reactions with the electrolyte or harm the materials, leading to undesirable outcomes. As a result, this decreases the efficiency of solar energy storage and causes stability problems.[83, 84] Furthermore, the inherently short carrier lifetimes and diffusion times in inorganic materials often result in significant recombination or trapping losses, compromising solar energy storage efficiency in associated devices. Continuous advances in nanostructures and hybrid material design, however, are anticipated to overcome these limitations through precise control of charge carrier dynamics, ultimately enhancing overall device performance.

3.2 Organic Electrode Materials in Photo-Rechargeable Batteries

Organic electrode materials have garnered increasing attention in the development of photo-rechargeable batteries due to their unique advantages, including flexibility, tunability, and the potential for high energy densities.[85-87] Organic materials, such as conjugated polymers and small organic molecules, offer the possibility of tailoring the material properties for specific applications, making them ideal candidates for next-generation photo-rechargeable batteries. Conjugated polymers: conjugated polymers like poly(3-hexylthiophene) and poly(phenylene vinylene) are widely studied due to their excellent electronic properties, which allow for efficient charge transport. These materials are particularly attractive because of their ease of fabrication, low cost, and high versatility in device design. Conjugated polymers also have the ability to absorb light over a broad range of wavelengths, making them suitable for use in photoactive electrodes in photo-rechargeable batteries. However, challenges remain in improving their long-term stability and charge retention, as organic materials can be susceptible to environmental degradation and loss of functionality over time. Small organic molecules: small organic molecules, such as fullerene derivatives and organic dyes, are also being explored as electrode materials for photo-rechargeable batteries. These materials can be precisely engineered to enhance their optical absorption properties, as well as their electronic and ionic conductivity. They also offer the advantage of being lightweight and flexible, which is particularly important for applications in flexible or portable energy storage devices.[88-91] One of the major challenges with small organic molecules is their tendency to undergo irreversible degradation over repeated charge-discharge cycles, which limits their long-term performance in photo-rechargeable batteries. Guo *et al.* employed a "polycrystal-induced aggregation" strategy to enhance the structural order of polymer donor (PM6) and non-fullerene acceptor (L8-BO) molecules in the active layer, thereby improving the efficiency of solid-state solar cells.[92] The core of this strategy is the preparation of PM6 polycrystals. In this process, PM6 is first dissolved in an o-dichlorobenzene (DCB) solution, which is then placed into a sealed bottle containing methanol vapor as an anti-solvent. The slow diffusion of methanol into the DCB solution causes the PM6 molecules at the interface between the DCB solution and methanol

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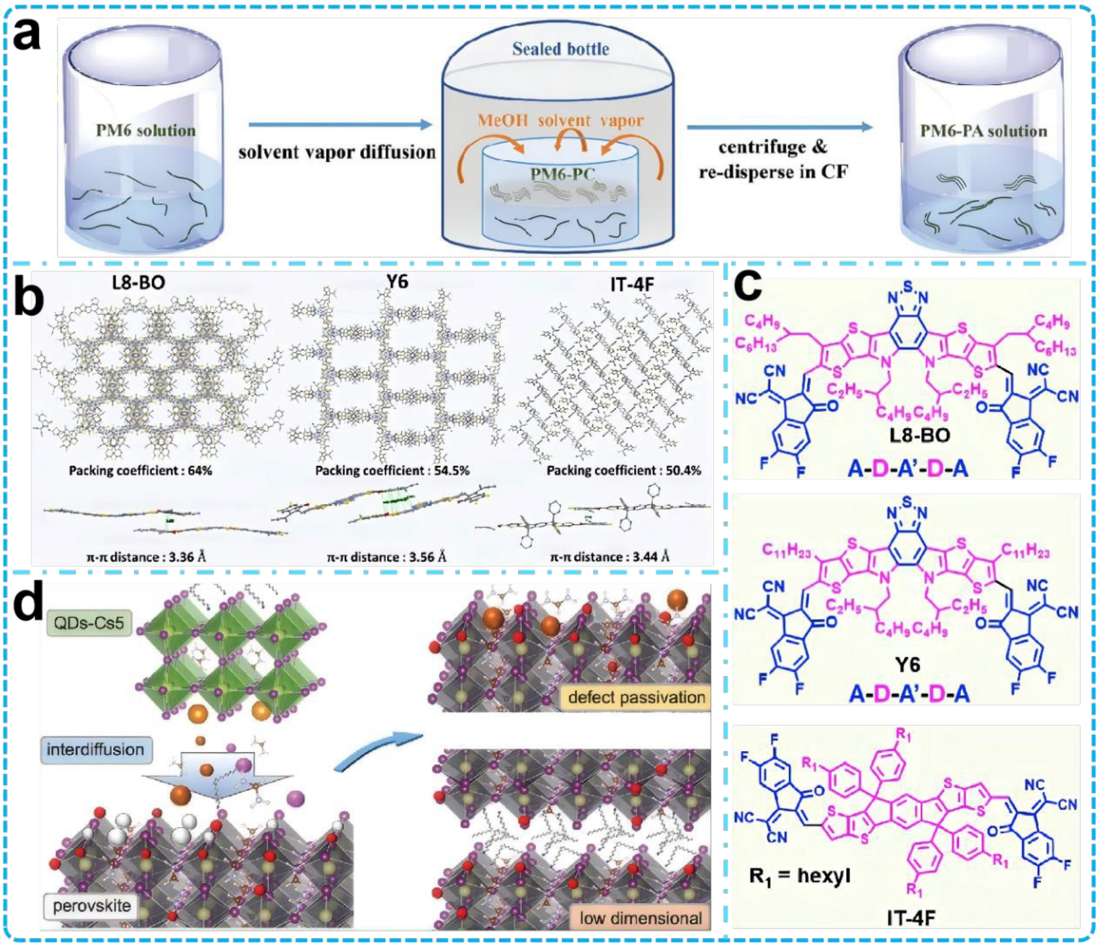

Fig. 6. (a) Schematic illustration of the preparation of PM6-PC and PM6-PA solution. Copyright 2023,[92] Wiley-VCH. (b) Illustrated molecular packing properties of L8-BO, Y6, and IT-4F in solid states based on the main view of molecular conformation and packing sketch maps according to single-crystal data. (c) Chemical structure of L8-BO, Y6, and IT-4F. Copyright 2022,[93] Elsevier. (d) Schematic of proposed ionic defect passivation mechanism achieved through QDs-Cs5 modification. Copyright 2020,[94] Wiley-VCH**.**

vapor to precipitate. The resulting PM6 precipitate is then centrifuged in a vacuum environment, and the residual solvent is removed (**Fig. 6a**). This research provides a novel strategy for optimizing molecular aggregation in solid-state photovoltaic cells using polycrystalline seeds to enhance power conversion efficiency. In organic solar cells, the fill factor is a crucial photovoltaic parameter, often below 0.8, indicating that it still requires optimization. To address this, Zhang *et al.* proposed a study that revealed the impact of dielectric properties on achieving high fill factor and photovoltaic efficiency in organic solar cells.[93] They increased the molecular packing density (MPD) of the non-fullerene acceptors (NFAs) in the solid state, which in turn enhanced the dielectric constant (ε) of the NFAs and the bulk heterojunction films. To explain the modulation of fill factor, they selected three representative NFAs (L8-BO, Y6, and IT-4F) (**Fig. 6c**). Considering that the differences in effective conjugation length among these NFAs are not correlated with their relative dielectric constants (ε_r), they rationalized the differences in ε_r based on the MPD obtained from a single-crystal dataset. The MPD of single-crystal L8-BO, Y6, and IT-4F was estimated using the molecular volume per unit cell, and the MPD values were found to be 64.1%, 54.5%, and 50.4%, respectively (**Fig. 6b**). The researchers suggest that the increase in MPD in L8-BO leads to a higher molecular polarization, which results in a higher ε_r. This study sheds light on the important role of dielectric properties in optimizing the fill factor and efficiency of organic solar cells, offering a pathway to improve their performance. The research team led by Xie *et al.* developed a solid-state interdiffusion process using multi-cation hybrid halide perovskite quantum dots (QDs) to repair ion defects at the surface and grain boundaries (GBs) of organic-inorganic hybrid perovskites (OIHPs).[94] In this strategy, the cations and anions of $Cs_{0.05}(MA_{0.17}FA_{0.83})_{0.95}PbBr_3$ (QDs-Cs5) occupy ion vacancies at the OIHPs surface and GBs through solid-state interdiffusion, reducing

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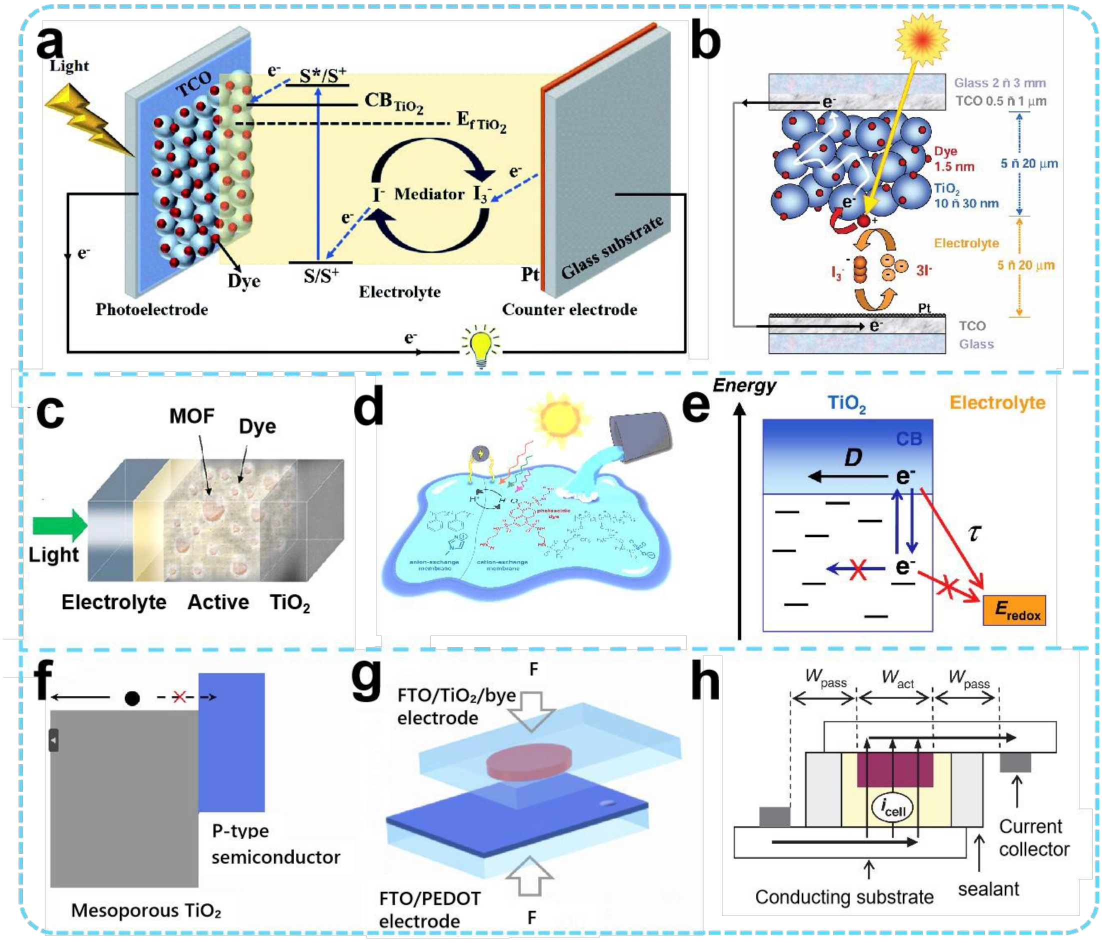

Fig. 7. (a) Schematic illustration representing device structure and working principle of a dye-sensitized solar cell. (b) The structure and operation of the dye solar cell. (c) The Rayleigh scattering images of dye-sensitized solar cells are simulated by Mont Carlo ray tracing simulation. Copyright 2022,[95] Elsevier. (d) Bipolar ion exchange process. Copyright 2021,[96] Elsevier. (e) Electron trapping, transport and recombination processes in dye-sensitized solar cell. (f) Type II junction alignment of the band edges for the mesoporous TiO_2 film and a p-type semiconductor layer. (g) The sensitized TiO_2 electrode and the PEDOT semiconductor-based counter electrode are combined to form a new dye-sensitized solar cell structure. Copyright 2021,[97] The Royal Society of Chemistry. (h) Schematic cross-section geometry of a symmetric small dye-sensitized solar cell. Copyright 2010,[98] Wiley-VCH**.**

ion defects and suppressing non-radiative recombination at the interfaces (**Fig. 6d**). Additionally, the hydrophobic long-chain ligands from QDs-Cs5 form a low-dimensional perovskite phase at the surface, which improves the moisture resistance and environmental stability of the OIHP films. After treatment of the solar cell electrode materials, their photovoltaic performance was significantly enhanced. The power conversion efficiency of the cell exceeded 21%, and after more than 550 hours of continuous illumination, over 90% of the initial power conversion efficiency was retained. This work provides important insights into ion defect engineering for solid-state photovoltaic cells, contributing to high efficiency and long-term stability.

Although many organic materials based on photo-rechargeable batteries (Single-Component Semiconducting Polymer) show potential for direct solar energy conversion and storage, they still present several limitations. Unlike inorganic semiconductors, where photon absorption leads to the generation of free charges, organic semiconductors typically form tightly bound electron-hole pairs (excitons) upon light excitation. This occurs due to their low dielectric constant and weak intermolecular electronic coupling.[99, 100] Consequently, it is necessary to design donor-acceptor or related molecular structures that can effectively dissociate excitons and promote efficient charge separation. To address this, optimizing the molecular structures of organic materials is crucial. Materials with the ability to separate photoexcited electrons and holes can reduce

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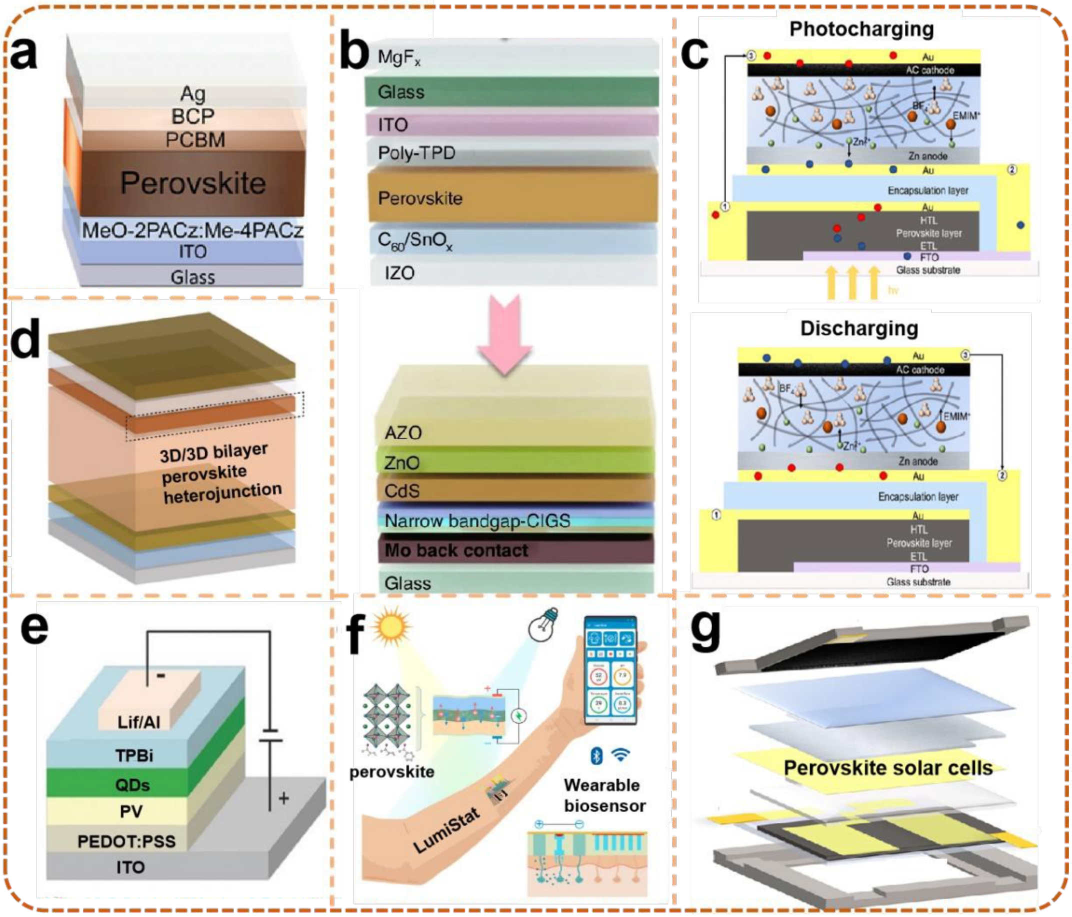

Fig. 8. (a) Solar cell device architecture. Copyright 2024,[101] Wiley-VCH. (b) Structure and performance of the semitransparent PSC solar cells. Copyright 2023,[102] The Royal Society of Chemistry. (c) Working principles of the Integrated photo-rechargeable systems. (d) The schematic structure of Pb-Sn perovskite solar cells with a 3D/3D bilayer perovskite heterojunction. Copyright 2023,[103] Nature. (e) Schematic illustration of the device structure. Copyright 2022,[104] Wiley-VCH. (f) Illustration of the energy-autonomous wearable device that is powered under both outdoor and indoor illumination. Copyright 2024,[105] Nature. (g) Schematic of the Integrated photo-rechargeable systems. Copyright 2024,[106] Wiley-VCH.

electron-hole recombination, thereby accelerating energy storage processes. Inorganic and organic electrode materials each offer distinct advantages, and much of the current research aims to combine the strengths of both material classes to overcome the limitations of individual materials. For instance, hybrid electrode systems, which combine inorganic nanoparticles with organic matrices, are being explored to enhance the overall performance, stability, and efficiency of photo-rechargeable batteries. The development of electrode materials for photo-rechargeable batteries represents a rapidly evolving field, with substantial advances occurring in both inorganic and organic systems. Inorganic materials typically offer superior stability and conductivity, whereas organic counterparts provide enhanced tunability and flexibility; both classes are thus essential for future progress. Consequently, continued investigation into hybrid materials and novel design strategies-aimed at improving stability, charge transport, and photoactivity-will prove critical for enhancing performance and facilitating the commercialization of high-efficiency photo-rechargeable batteries.

4. Applications of Novel Electrode Materials in Photo-Rechargeable Batteries

The integration of novel electrode materials into photo-rechargeable batteries is pivotal for enhancing both energy conversion and storage efficiencies. This section delves into key advancements in two prominent electrode materials: dye-sensitized solar batteries and perovskite solar batteries. Both material systems exhibit significant potential in optimizing photo-rechargeable systems, each offering distinct advantages in terms of material properties, efficiency, and scalability.[107-110]

Table 1 Typical dual-function electrode materials in photo-rechargeable devices and their performances.

Battery type	SPRBs materials	SSE	Capacity under dark/light	Cycle number	Ref.
$Li–O_2$	$p-MoS_2$	CPEs	a low voltage gap (0.27 V)	170	[111]
$Li–O_2$	$Ti_8O_8(OH)_4(BDC-NH_2)_6$	$Ti_8O_8(OH)_4(BDC-NH_2)_6$	a high energy efficiency (94.2%)	320	[26]
LMB	Li/LFP	PEO	140 mA g^{-1} at 1.0 C	150	[112]
LMB	$LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$	$Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$	166.7 mAh g^{-1} at 0.5C	200	[113]
LMB	Li/LFP	PEO	167.6 mAh g^{-1} at 0.1 C	200	[114]
LMB	BF@LPSC	Li_6PS_5Cl	capacity retention of 90.01%	1000 h	[115]
RZMB	i-Zn-MnO	PHPZ-30	214.14 Wh kg^{-1}	1000	[116]
PSSMB	ITO/TO_2	PEO/NaTFSI	117 mAh g^{-1}	300	[25]
SC	$ZnFe_2O_4$	$(CsFA)Pb(IBr)_3$	solar-to-hydrogen efficiency of 1.85%	30 h	[117]
DSSCs	TO_2	Dye WS-72	PCE > 11.5%	V_{OC} = 1.1 V	[118]
PSCs	MeO-2PACz:Me-4PACz	$FAPbI_3$	maximum PCE > 24%	400 h	[101]

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4.1 Dye-Sensitized Solar Batteries

Photo-rechargeable batteries represent a transformative integration of solar energy conversion and storage, leveraging dye-sensitized solar cell architectures to achieve efficient charge generation and retention. Dye-sensitized solar cells have emerged as a promising candidate for high-efficiency photo-rechargeable batteries due to their relatively simple fabrication process, low cost, and tunable efficiency. Dye-sensitized solar cells consist of a photoactive dye, a semiconductor layer (typically titanium dioxide), and a solid electrolyte. The unique advantage of dye-sensitized solar cells lies in their ability to convert light into electrical energy through the use of organic dyes that absorb visible light efficiently.[119, 120]

Mikko *et al.* explored the potential of using emerging materials and advanced fabrication techniques to enhance the individual components of dye-sensitized solar batteries.[97] As depicted in **Fig. 7a**, the fundamental design involves a mesoporous TiO_2 photoanode sensitized with organic dyes, a solid-state electrolyte, and a counter electrode. Light absorption by the dye initiates electron injection into the TiO_2 conduction band, driving redox reactions in the electrolyte that are critical for energy storage. Interface engineering plays a crucial role in minimizing voltage losses. Rough dye/TiO_2 surfaces often lead to non-radiative recombination, but atomic layer deposition of ultrathin Al_2O_3 passivation layers (**Fig. 7f**) reduce interface trap densities by 50%, leading to improved open-circuit voltage (V_{on}). Hybrid solid electrolytes, such as polymer-inorganic composites, address conductivity mismatches between TiO_2 and the solid electrolyte, enabling high ion transport rates at room temperature (**Fig. 7g**). Halme *et al.* summarized both the theoretical and practical aspects of modeling and characterization for fuel-sensitized solar cells, integrating these insights into a comprehensive dye-sensitized solar cell device model. The optoelectronic advantages of dyes, such as broad visible-light absorption and tunable energy levels, enable high incident photon-to-electron conversion efficiency, as shown in recent developments (**Fig. 7b**).[98] As shown in **Fig. 7e**, the electron capture, transport and recombination process. Collectively, these innovations boost the fill factor by optimizing charge transfer kinetics across the electrode/electrolyte interface. However, stability against moisture and thermal degradation remains a significant challenge. Hydrophobic metal-organic frameworks (MOF) coatings or cross-linked polymer encapsulations (**Fig. 7h**) help preserve 90% of the initial efficiency after 500 hours of continuous illumination, demonstrating enhanced environmental resilience. The protective role of MOFs is dual: enhancing both charge extraction (via surface area enhancement) and structural durability (via encapsulation). Kim *et al.* improved the power conversion efficiency of solid-state fuel dye-sensitized solar cells by incorporating MOF-801 into the mesoporous titanium dioxide (mp-TiO_2) layer of the photoanode. A key challenge in photo-rechargeable batteries design is optimizing charge separation at the dye/TiO_2/electrolyte interface. They simulated the effect of MOF on the optical absorption spectrum by Monte Carlo ray tracing (**Fig. 7c**). [95] The high surface area of MOFs promotes uniform dye loading, as evidenced by electrochemical impedance spectroscopy, which shows reduced series resistance and increased shunt resistance (**Fig. 7d**).

Despite these advancements, challenges remain, particularly in terms of improving the long-term stability of dye-sensitized solar cells under real-world conditions. Developing more robust and efficient solid-state electrolytes is imperative for enhancing dye-sensitized solar cells performance and commercial viability within photo-rechargeable systems. As dye-sensitized solar cells efficiencies progressively increase, their integration into next-generation photo-rechargeable batteries presents compelling prospects.

4.2 Perovskite Solar Batteries

Photo-rechargeable batteries represent a transformative technology for integrating solar energy conversion and storage within a single device, leveraging perovskite materials for their exceptional light-harvesting and charge transport properties. Perovskite solar cells have emerged as one of the most promising materials for high-efficiency solar energy harvesting due to their remarkable power conversion efficiencies and ease of fabrication. Perovskites, particularly hybrid organic-inorganic materials, exhibit a broad absorption spectrum, high carrier mobility, and excellent photophysical properties.[121-123] These attributes make perovskite-based electrodes highly suitable for photo-rechargeable battery applications.

Ji *et al.* proposed a novel method for forming a one-dimensional/three-dimensional (1D/3D) perovskite heterojunction by introducing choline acetate along with perovskite precursors at the buried interface of the perovskite active layer.[101] As shown in **Fig. 8a**, the core architecture of solid-state photo-rechargeable batteries typically consists of a perovskite photoanode, a solid-state electrolyte, and a counter electrode, with the perovskite layer serving as both the light absorber and charge generator. The unique optoelectronic characteristics of perovskites, such as tunable bandgaps (1.2-2.3 eV) and high extinction coefficients, enable efficient photon-to-charge conversion, as demonstrated in recent advancements (**Fig. 8b**).[102] Bi *et al.* developed an integrated photo-charging system by combining perovskite solar cells with solid-state zinc-ion hybrid capacitors.[106] One significant challenge in solid-state photo-rechargeable batteries is optimizing electron-hole separation and transport at the perovskite/electrolyte interface. Studies have shown that incorporating MOFs into mesoporous TiO_2 photoanodes (**Fig. 8c**) significantly enhances charge extraction efficiency. **Fig. 8g** shows a schematic diagram of the device for highly integrated perovskite solar cells. Lin *et al.* developed all-perovskite tandem solar cells using a 3D/3D double-layer perovskite

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heterojunction structure. (**Fig. 8d**).[103] The structural modifications increase the short-circuit current density by 30% compared to conventional TiO_2-based devices, as demonstrated in performance comparisons (**Fig. 8e**). Interface engineering remains essential for mitigating voltage losses in photo-rechargeable batteries. Perovskite films often exhibit rough surfaces that promote non-radiative recombination. In the application of autonomous wearable biosensors, the power conversion efficiency of perovskite solar cells is more than 31% under indoor illumination (**Fig. 8f**). These advancements collectively enhance the fill factor by optimizing charge transfer kinetics. Stability remains a critical challenge for perovskite-based photo-rechargeable batteries. The integration of perovskites into flexible architectures, such as fiber-shaped photo-rechargeable batteries, is made possible by the porous structure of MOF-modified photoanodes, which supports conformal coating on carbon nanotube yarns. This results in a power conversion efficiency of 6.5%, surpassing traditional solid-state dye-sensitized solar cells (4.19%). The mechanical robustness of these devices, including bendability (radius < 5 mm), is verified by the structural integrity visualized and durability insights from impedance analysis. In summary, perovskite materials offer exceptional potential for high-efficiency, flexible photo-rechargeable batteries through strategic structural design and interface engineering. While challenges related to long-term stability and large-scale fabrication remain, the integration of innovative materials and device architecture highlights the pathway for practical energy storage solutions. Despite the impressive progress, challenges remain in ensuring the long-term stability and commercial viability of perovskite-based photo-rechargeable batteries. Further research is needed to enhance the durability of perovskite electrodes under real-world operating conditions and to mitigate the effects of degradation over extended use periods.[124] This section examines recent advancements in dye-sensitized solar cells and perovskite solar cells, focusing on material innovations, efficiency enhancements, and persistent challenges in their development as electrodes for photo-rechargeable batteries. Moreover, we evaluate the performance metrics of dual-function electrode materials across representative photovoltaic devices, highlighting their critical role in enabling next-generation photo-rechargeable systems. (**Table 1**)

5. Conclusions

In recent years, photo-rechargeable batteries have garnered significant attention due to their promising potential for renewable energy storage and efficient conversion. This review has provided an in-depth analysis of the current advanced electrolytes and dual-function electrode materials, emphasizing their roles in enhancing the efficiency and stability of these energy storage systems. The development of advanced solid-state electrolytes, coupled with synergistic light-electricity-ion coupling, has opened new avenues for improving the performance of photo-rechargeable batteries, pushing them closer to commercial viability. The review highlights several key advancements in the field of photo-rechargeable batteries:

(a) Dual-function electrodes: dual-function electrodes, which combine both photoelectric and electrochemical capabilities, have proven to be critical for improving energy conversion and storage efficiencies. These electrodes, particularly those based on novel inorganic and organic materials, enable more efficient charge separation and reduce energy losses during photo-charging cycles.

(b) Solid-state electrolytes: the optimization of solid-state electrolytes has been crucial for the improvement of battery safety, energy density, and long-term stability. Recent innovations in inorganic and organic electrolyte materials have demonstrated promising ion conductivity and better thermal stability compared to their liquid counterparts.

(c) Material advancements: significant progress has been made in both inorganic and organic electrode materials. Inorganic materials, such as perovskites and transition metal oxides, exhibit excellent light absorption and high electrochemical stability. On the other hand, organic electrode materials, known for their flexibility, cost-effectiveness, and tunable properties, have emerged as viable alternatives for large-scale applications.

(d) Applications: the potential applications of photo-rechargeable batteries, particularly in devices like dye-sensitized solar cells and perovskite solar cells, have been demonstrated through the integration of novel electrode materials. These technologies offer significant improvements in terms of efficiency, stability, and cost-effectiveness, contributing to the development of next-generation energy storage systems.

Despite the significant progress made in the field, several challenges remain that must be addressed to fully realize the potential of photo-rechargeable batteries. These challenges encompass both material-related issues and system-level concerns: electrolyte stability and ionic conductivity: while many electrolytes show promise, achieving high ionic conductivity at room temperature and long-term stability remains a critical hurdle. Future research should focus on the development of advanced electrolyte materials that can maintain performance over extended cycles while being stable in a range of operating conditions. Charge separation efficiency: although dual-function electrodes have shown significant progress, optimizing the efficiency of charge separation and minimizing recombination losses remain essential for enhancing the overall performance of photo-rechargeable batteries. The development of new electrode materials with better light absorption and charge carrier mobility, as well as improved interfaces between the electrolyte and electrode, will be pivotal. Scalability and cost reduction: for widespread adoption, the scalability and cost-effectiveness of photo-rechargeable batteries must be improved. This includes addressing the challenges associated with the synthesis of high-quality materials and the integration of these materials into large-scale battery systems. Research into more sustainable and cost-effective fabrication techniques will be key in this regard. Long-term durability: the long-term performance and cycling stability of photo-rechargeable batteries must be enhanced to ensure their practical viability. This requires a better understanding of degradation mechanisms at the material interfaces, especially in complex systems involving light-absorption, charge transfer, and ion conduction.

Looking forward, the future of photo-rechargeable batteries appears promising, with several exciting directions for further research and development: smart materials and design: the use of smart materials, including stimuli-responsive polymers and hybrid materials, could lead to breakthroughs in the design of highly efficient photo-rechargeable batteries. These materials could offer enhanced light absorption properties, improved stability, and better charge carrier dynamics, pushing the boundaries of efficiency in energy storage devices. Next-generation electrodes: future research will likely focus on the development of next-generation electrode materials, including composite materials that combine organic and inorganic components to exploit the benefits of both. These materials could provide enhanced charge storage capacity, faster charge/discharge rates, and improved stability over time. Advanced photonic engineering: incorporating advanced photonic structures, such as plasmonic and nanostructured materials, into photo-rechargeable batteries could further enhance their light-harvesting capabilities, thus improving their overall energy conversion efficiency. These innovations could enable batteries that not only store energy more efficiently but also capture and utilize a wider range of the solar spectrum. Sustainability and Recycling: As environmental concerns grow, the sustainability of photo-rechargeable batteries will become a critical focus. Research into recyclable electrode and electrolyte materials, as well as environmentally friendly manufacturing processes, will play a crucial role in ensuring the long-term viability of these technologies.

In conclusion, while photo-rechargeable batteries represent an exciting frontier in energy storage technologies, further innovations in materials, systems design, and scalability are required to bring them to commercial maturity. By addressing these challenges and seizing the opportunities presented by novel materials and integrated systems, the future of photo-rechargeable batteries looks increasingly bright, offering a sustainable solution for clean energy storage and conversion.

Author contributions

W. Z. Bao, Y. Y. Zhang and M. Yang contributed equally to this work. W. Z. Bao, Y. Y. Zhang, M. Yang, H. Shen, Y. Y. Wang, and K. W. Sun conceived and designed the structure of the review. Y. Y. Zhang collected the papers related to the topic of the review. W. Z. Bao co-wrote the paper with input from Y. Y. Zhang, M. Yang, H. Shen, R. H. Wang, Z. C. Yang, K. H. Zhang, G. Z. Zeng, D. Y. Cui, J. J. Xia, J. Liu, J. L. Li, H. Liu, C. Guo, B. Quan, F. Yu, J. F. Li and K. W. Sun. The paper was revised by all authors.

Conflicts of interest

There are no conflicts to declare.

Notes and references

[1] J. Lv, J. Xie, A. G. A. Mohamed, X. Zhang, Y. Wang, Photoelectrochemical energy storage materials: design principles and functional devices towards direct solar to electrochemical energy storage, Chemical Society Reviews, 51 (2022) 1511-1528.

[2] G. G. Farivar, W. Manalastas, H. D. Tafti, S. Ceballos, A. Sanchez-Ruiz, E. C. Lovell, G. Konstantinou, C. D. Townsend, M. Srinivasan, J. Pou, Grid-Connected Energy Storage Systems: State-of-the-Art and Emerging Technologies, Proceedings of the IEEE, 111 (2023) 397-420.

[3] Y. Che, X. Hu, R. Teodorescu, Opportunities for battery aging mode diagnosis of renewable energy storage, Joule, 7 (2023) 1405-1407.

[4] E. O'Shaughnessy, K. Ardani, P. Denholm, T. Mai, T. Silverman, J. Zuboy, R. Margolis, Policy-driven solar innovation and deployment remains critical for US grid decarbonization, Joule, 6 (2022) 1965-1968.

[5] C.-P. Lee, C.-T. Li, K.-C. Ho, Use of organic materials in dye-sensitized solar cells, Materials Today, 20 (2017) 267-283.

[6] W. Yan, Z. Mu, Z. Wang, Y. Huang, D. Wu, P. Lu, J. Lu, J. Xu, Y. Wu, T. Ma, M. Yang, X. Zhu, Y. Xia, S. Shi, L. Chen, H. Li, F. Wu, Hard-carbon-stabilized Li–Si anodes for high-performance all-solid-state Li-ion batteries, Nature Energy, 8 (2023) 800-813.

[7] K. Ueno, T. Oshikiri, Q. Sun, X. Shi, H. Misawa, Solid-State Plasmonic Solar Cells, Chemical Reviews, 118 (2018) 2955-2993.

[8] J. Y. Kim, J.-W. Lee, H. S. Jung, H. Shin, N.-G. Park, High-Efficiency Perovskite Solar Cells, Chemical Reviews, 120 (2020) 7867-7918.

[9] I. Mora-Seró, Current Challenges in the Development of Quantum Dot Sensitized Solar Cells, Advanced Energy Materials, 10 (2020) 2001774.

[10] X. Wei, P. Zhang, T. Xu, H. Zhou, Y. Bai, Q. Chen, Chemical approaches for electronic doping in photovoltaic materials beyond crystalline silicon, Chemical Society Reviews, 51 (2022) 10016-10063.

[11] D. Li, D. Qin, M. Deng, Y. Luo, Q. Meng, Optimization the solid-state electrolytes for dye-sensitized solar cells, Energy & Environmental Science, 2 (2009) 283-291.

[12] C. Wang, K. Fu, S. P. Kammampata, D. W. McOwen, A. J. Samson, L. Zhang, G. T. Hitz, A. M. Nolan, E. D. Wachsman, Y. Mo, V. Thangadurai, L. Hu, Garnet-Type Solid-State Electrolytes: Materials, Interfaces, and Batteries, Chemical Reviews, 120 (2020) 4257-4300.

[13] J. Hwang, K. Matsumoto, C.-Y. Chen, R. Hagiwara, Pseudo-solid-state electrolytes utilizing the ionic liquid family for rechargeable batteries, Energy & Environmental Science, 14 (2021) 5834-5863.

[14] Y. Kim, C. Li, J. Huang, Y. Yuan, Y. Tian, W. Zhang, Ionic Covalent Organic Framework Solid-State Electrolytes, Advanced Materials, 36 (2024) 2407761.

[15] D. Li, C. Zhao, X. Zhang, X. Zhao, H. Huang, H. Li, F. Li, J. Yuan, Dual-Phase Ligand Engineering Enables 18.21% FAPbI3 Quantum Dot Solar Cells, Advanced Materials, 37 (2025) 2417346.

[16] E. Stathatos, P. Lianos, Increase of the Efficiency of Quasi-Solid State Dye-Sensitized Solar Cells by a Synergy between Titania Nanocrystallites of Two Distinct Nanoparticle Sizes, Advanced Materials, 19 (2007) 3338-3341.

[17] S. Xiong, X. Xu, X. Jiao, Y. Wang, O. O. Kapitanova, Z. Song, Y. Liu, Mechanical Failure of Solid-State Electrolyte Rooted in Synergy of Interfacial and Internal Defects, Advanced Energy Materials, 13 (2023) 2203614.

[18] S. Chandra, Y. Kim, D. Vivona, I. Waluyo, A. Hunt, C. Schlueter, J. B. Lee, Y. Shao-Horn, B. Yildiz, Thermally-driven reactivity of Li0.35La0.55TiO3 solid electrolyte with LiCoO2 cathode, Journal of Materials Chemistry A, 10 (2022) 3485-3494.

[19] Y. Shao, G. C. Bazan, A. J. Heeger, Long-Lifetime Polymer Light-Emitting Electrochemical Cells, Advanced Materials, 19 (2007) 365-370.

View Article Online
DOI: 10.1039/D5NR02473K

[20] M. Wang, M. Xu, D. Shi, R. Li, F. Gao, G. Zhang, Z. Yi, R. Humphry-Baker, P. Wang, S. M. Zakeeruddin, M. Grätzel, High-Performance Liquid and Solid Dye-Sensitized Solar Cells Based on a Novel Metal-Free Organic Sensitizer, Advanced Materials, 20 (2008) 4460-4463.

[21] I. Chung, B. Lee, J. He, R. P. H. Chang, M. G. Kanatzidis, All-solid-state dye-sensitized solar cells with high efficiency, Nature, 485 (2012) 486-489.

[22] F. Hao, C. C. Stoumpos, D. H. Cao, R. P. H. Chang, M. G. Kanatzidis, Lead-free solid-state organic–inorganic halide perovskite solar cells, Nature Photonics, 8 (2014) 489-494.

[23] Y. Liu, J. Yi, Y. Qiao, D. Wang, P. He, Q. Li, S. Wu, H. Zhou, Solar-driven efficient Li_2O_2 oxidation in solid-state Li-ion O_2 batteries, Energy Storage Materials, 11 (2018) 170-175.

[24] L. Song, W. Wang, V. Körstgens, D. Moseguí González, F. C. Löhrer, C. J. Schaffer, J. Schlipf, K. Peters, T. Bein, D. Fattakhova-Rohlfing, S. V. Roth, P. Müller-Buschbaum, In situ study of spray deposited titania photoanodes for scalable fabrication of solid-state dye-sensitized solar cells, Nano Energy, 40 (2017) 317-326.

[25] R.-H. Wang, Y.-Z. Zhang, W. Wang, J.-H. Ni, W. Hu, L. Yue, W.-Q. Zhang, G. Pei, S. Yang, L.-F. Chen, Toward High-Performance, Flexible, Photo-Assisted All-Solid-State Sodium-Metal Batteries: Screening of Solid-Polymer-Based Electrolytes Coupled with Photoelectrochemical Storage Cathodes, Advanced Materials, 37 (2025) 2500348.

[26] X.-X. Wang, D.-H. Guan, C.-L. Miao, D.-C. Kong, L.-J. Zheng, J.-J. Xu, Metal–Organic Framework-Based Mixed Conductors Achieve Highly Stable Photo-assisted Solid-State Lithium–Oxygen Batteries, Journal of the American Chemical Society, 145 (2023) 5718-5729.

[27] T.-T. Li, Y.-B. Yang, B.-S. Zhao, Y. Wu, X.-W. Wu, P. Chen, X.-P. Gao, Photo-rechargeable all-solid-state lithium－sulfur batteries based on perovskite indoor photovoltaic modules, Chemical Engineering Journal, 455 (2023) 140684.

[28] C. Liu, X. Sun, Y. Yang, O. A. Syzgantseva, M. A. Syzgantseva, B. Ding, N. Shibayama, H. Kanda, F. Fadaei Tirani, R. Scopelliti, S. Zhang, K. G. Brooks, S. Dai, G. Cui, M. D. Irwin, Z. Shao, Y. Ding, Z. Fei, P. J. Dyson, M. K. Nazeeruddin, Retarding solid-state reactions enable efficient and stable all-inorganic perovskite solar cells and modules, Science Advances, 9 eadg0087.

[29] W. Zhang, Y. Yue, R. Yang, Y. Zhang, W. Du, G. Lu, J. Zhang, H. Zhou, X. Zhang, Y. Zhang, A high-efficiency and stable organic solar cell with balanced crystallization kinetics, Energy & Environmental Science, 17 (2024) 2182-2192.

[30] Y. Wang, H. Shi, K. Cui, J. Yu, Engineering organic/inorganic hierarchical photocathode for efficient and stable quasi-solid-state photoelectrochemical fuel cells, Applied Catalysis B: Environmental, 250 (2019) 171-180.

[31] H.-H. Chen, J.-Y. Hung, C.-L. Wang, Synergistic effects of Pt-Ni alloy-decorated carbon black nanofillers on performance and stability of quasi-solid-state dye-sensitized solar cells, Chemical Engineering Journal, 505 (2025) 159508.

[32] Z. Peng, J. Song, L. Huai, H. Jia, B. Xiao, L. Zou, G. Zhu, A. Martinez, S. Roy, V. Murugesan, H. Lee, X. Ren, Q. Li, B. Liu, X. Li, D. Wang, W. Xu, J.-G. Zhang, Enhanced Stability of Li Metal Anodes by Synergetic Control of Nucleation and the Solid Electrolyte Interphase, Advanced Energy Materials, 9 (2019) 1901764.

[33] L. Ren, F. Kong, X. Wang, Y. Song, X. Li, F. Zhang, N. Sun, H. An, Z. Jiang, J. Wang, Triggering ambient polymer-based Li-O_2 battery via photo-electro-thermal synergy, Nano Energy, 98 (2022) 107248.

[34] Y. Cheng, H. Wan, E. H. Sargent, D. Ma, Reduced-Dimensional Perovskites: Quantum Well Thickness Distribution and Optoelectronic Properties, Advanced Materials, n/a (2024) 2410633.

[35] N. K. Noel, S. N. Habisreutinger, A. Pellaroque, F. Pulvirenti, B. Wenger, F. Zhang, Y.-H. Lin, O. G. Reid, J. Leisen, Y. Zhang, S. Barlow, S. R. Marder, A. Kahn, H. J. Snaith, C. B. Arnold, B. P. Rand, Interfacial charge-transfer doping of metal halide perovskites for high performance photovoltaics, Energy & Environmental Science, 12 (2019) 3063-3073.

[36] R. Zhang, Z. Chen, X. Li, J. Xu, J. Hui, P. Zhang, M. Liu, J. Tang, Z. Ren, S. Li, Dual-Functional $Cs_3Bi_2Br_9$ for stable all-solid-state photo-rechargeable batteries, Journal of Power Sources, 624 (2024) 235530.

[37] R. Clément, K. Hatzell, Y.-K. Sun, Recent Advances in Battery Safety and Recycling. A Virtual Issue, ACS Energy Letters, 8 (2023) 4524-4527.

[38] A. Balilonda, Q. Li, M. Tebyetekerwa, R. Tusiime, H. Zhang, R. Jose, F. Zabihi, S. Yang, S. Ramakrishna, M. Zhu, Perovskite Solar Fibers: Current Status, Issues and Challenges, Advanced Fiber Materials, 1 (2019) 101-125.

[39] Y. Jiang, Y. Song, X. Chen, H. Wang, L. Deng, G. Yang, In situ formed self-healable quasi-solid hybrid electrolyte network coupled with eutectic mixture towards ultra-long cycle life lithium metal batteries, Energy Storage Materials, 52 (2022) 514-523.

[40] I. Grinberg, D. V. West, M. Torres, G. Gou, D. M. Stein, L. Wu, G. Chen, E. M. Gallo, A. R. Akbashev, P. K. Davies, J. E. Spanier, A. M. Rappe, Perovskite oxides for visible-light-absorbing ferroelectric and photovoltaic materials, Nature, 503 (2013) 509-512.

[41] W. Zhao, J. Yi, P. He, H. Zhou, Solid-State Electrolytes for Lithium-Ion Batteries: Fundamentals, Challenges and Perspectives, Electrochemical Energy Reviews, 2 (2019) 574-605.

[42] A. Manthiram, X. Yu, S. Wang, Lithium battery chemistries enabled by solid-state electrolytes, Nature Reviews Materials, 2 (2017) 16103.

[43] B. Hu, J. Xu, Z. Fan, C. Xu, S. Han, J. Zhang, L. Ma, B. Ding, Z. Zhuang, Q. Kang, X. Zhang, Covalent Organic Framework Based Lithium–Sulfur Batteries: Materials, Interfaces, and Solid-State Electrolytes, Advanced Energy Materials, 13 (2023) 2203540.

[44] L. Cheng, J. Liu, Y. Wang, H. Wang, A. Shao, C. Li, Z. Wang, Y. Zhang, Y. Li, J. Tang, Y. Guo, T. Liu, X. Zhao, Y. Ma, Lithiophilic-Gradient, Li^+ Supplementary Interphase Design for Lean Lithium Metal Batteries, Advanced Materials, 37 (2025) 2420255.

[45] J. Yu, X. Sun, X. Shen, D. Zhang, Z. Xie, N. Guo, Y. Wang, Stack pressure-A critical strategy and challenge in performance optimization of solid state batteries, Energy Storage Materials, 76 (2025) 104134.

[46] C.-j. Wang, Y.-l. Zhu, T. Zhang, J. Tian, F. Gao, Y. Zhao, X.-y. Bu, T. Quan, Competition between discharge reaction and side reaction for anode's lithium during internal short circuit in lithium-ion batteries, Journal of Cleaner Production, 470 (2024) 143280.

[47] S. Mazumdar, A. J. Bhattacharyya, Dependence of electron recombination time and light to electricity conversion efficiency on shape of the nanocrystal light sensitizer, Energy & Environmental Science, 6 (2013) 1494-1498.

[48] X. Wang, S. R. Kavanagh, D. O. Scanlon, A. Walsh, Upper efficiency limit of Sb_2Se_3 solar cells, Joule, 8 (2024) 2105-2122.

[49] X. Zeng, T. Xu, H. Chen, B. Deng, Q. Yan, X. Wen, Z. Li, H. Zeng, C. Gao, Y. Xiao, J. Liao, H. Liu, B. He, P. Han, G. Zhang, S. Li, Y. Chen, C. Xie, A donor:hole-transport layer alloy for high-efficiency and stable binary organic solar cells with promoted hole collection and suppressed recombination, Energy & Environmental Science, 17 (2024) 9383-9393.

[50] Y. Yan, B. Duan, M. Ru, Q. Gu, S. Li, W. Zhao, Toward Flexible and Stretchable Organic Solar Cells: A Comprehensive Review of

Transparent Conductive Electrodes, Photoactive Materials, and Device Performance, Advanced Energy Materials, 15 (2025) 2404233.

[51] X. Miao, H. Wang, R. Sun, C. Wang, Z. Zhang, Z. Li, L. Yin, Interface engineering of inorganic solid-state electrolytes for high-performance lithium metal batteries, Energy & Environmental Science, 13 (2020) 3780-3822.

[52] B. Tang, P. W. Jaschin, X. Li, S.-H. Bo, Z. Zhou, Critical interface between inorganic solid-state electrolyte and sodium metal, Materials Today, 41 (2020) 200-218.

[53] Y. Yang, H. Chen, J. Wan, R. Xu, P. Zhang, W. Zhang, S. T. Oyakhire, S. C. Kim, D. T. Boyle, Y. Peng, Y. Ma, Y. Cui, An Interdigitated Li-Solid Polymer Electrolyte Framework for Interfacial Stable All-Solid-State Batteries, Advanced Energy Materials, 12 (2022) 2201160.

[54] X. Lin, P. Apostol, H. Xu, V. R. Bakuru, X. Guo, Z. Chen, D. Rambabu, S. Pal, D. Tie, Y. Zhang, X. Xie, S.-G. Kim, Y. Li, Z. Li, M. Du, S. Yan, X. Zhang, R. Yuan, M. Zheng, F. Gauthy, V. Finsy, J. Zou, J.-F. Gohy, Q. Dong, A. Vlad, Design Principles of Quinone Redox Systems for Advanced Sulfide Solid-State Organic Lithium Metal Batteries, Advanced Materials, 36 (2024) 2312908.

[55] B. Ma, R. Li, H. Zhu, T. Zhou, L. Lv, H. Zhang, S. Zhang, L. Chen, J. Wang, X. Xiao, T. Deng, L. Chen, C. Wang, X. Fan, Stable Oxyhalide-Nitride Fast Ionic Conductors for All-Solid-State Li Metal Batteries, Advanced Materials, 36 (2024) 2402324.

[56] S. Qian, H. Zhu, C. Sun, M. Li, M. Zheng, Z. Wu, Y. Liang, C. Yang, S. Zhang, J. Lu, Liquid Metal Loaded Molecular Sieve: Specialized Lithium Dendrite Blocking Filler for Polymeric Solid-State Electrolyte, Advanced Materials, 36 (2024) 2313456.

[57] J. Lv, J. Xie, A. G. A. Mohamed, X. Zhang, Y. Feng, L. Jiao, E. Zhou, D. Yuan, Y. Wang, Solar utilization beyond photosynthesis, Nature Reviews Chemistry, 7 (2023) 91-105.

[58] C. Ma, N.-G. Park, Paradoxical Approach with a Hydrophilic Passivation Layer for Moisture-Stable, 23% Efficient Perovskite Solar Cells, ACS Energy Letters, 5 (2020) 3268-3275.

[59] H. A. Maddah, V. Berry, S. K. Behura, Biomolecular photosensitizers for dye-sensitized solar cells: Recent developments and critical insights, Renewable and Sustainable Energy Reviews, 121 (2020) 109678.

[60] W. Lu, M. Feng, Z. Li, B. Yan, S. Wang, X. Wen, X. An, S. Liu, J.-S. Hu, D.-J. Xue, Ordering one-dimensional chains enables efficient selenium photovoltaics, Joule, 8 (2024) 1430-1442.

[61] B. Yi, Z. Wei, S. Yao, S. Zhao, Z. Gao, S. Savilov, G. Chen, Z. X. Shen, F. Du, Challenges and prospectives of sodium-containing solid-state electrolyte materials for rechargeable metal batteries, Materials Science and Engineering: R: Reports, 163 (2025) 100949.

[62] X. Rui, D. Ren, X. Liu, X. Wang, K. Wang, Y. Lu, L. Li, P. Wang, G. Zhu, Y. Mao, X. Feng, L. Lu, H. Wang, M. Ouyang, Distinct thermal runaway mechanisms of sulfide-based all-solid-state batteries, Energy & Environmental Science, 16 (2023) 3552-3563.

[63] C. Zhou, W. Guo, J. Fan, N. Shi, Y. Zhao, X. Yang, Z. Ding, M. Han, W. Huang, Recent advances and future perspectives of Ruddlesden–Popper perovskite oxides electrolytes for all-solid-state batteries, InfoMat, 6 (2024) e12563.

[64] D. Wang, H. Shi, S. Wang, X. Wu, W. Jiang, S. Liang, Z. Xu, New insights into Li-argyrodite solid-state electrolytes based on doping strategies, Coordination Chemistry Reviews, 508 (2024) 215776.

[65] F. Ren, Z. Liang, W. Zhao, W. Zuo, M. Lin, Y. Wu, X. Yang, Z. Gong, Y. Yang, The nature and suppression strategies of interfacial reactions in all-solid-state batteries, Energy & Environmental Science, 16 (2023) 2579-2590.

[66] X. Yao, N. Huang, F. Han, Q. Zhang, H. Wan, J. P. Mwizerwa, C. Wang, X. Xu, High-Performance All-Solid-State Lithium–Sulfur Batteries Enabled by Amorphous Sulfur-Coated Reduced Graphene Oxide Cathodes, Advanced Energy Materials, 7 (2017) 1602923.

[67] S. Liu, L. Zhou, T. Zhong, X. Wu, K. Neyts, Sulfide/Polymer Composite Solid-State Electrolytes for All-Solid-State Lithium Batteries, Advanced Energy Materials, 14 (2024) 2403602.

[68] S. Li, W. Zhang, J. Zheng, M. Lv, H. Song, L. Du, Inhibition of Polysulfide Shuttles in Li–S Batteries: Modified Separators and Solid-State Electrolytes, Advanced Energy Materials, 11 (2021) 2000779.

[69] Y.-L. Liao, X.-L. Wang, H. Yuan, Y.-J. Li, C.-M. Xu, S. Li, J.-K. Hu, S.-J. Yang, F. Deng, J. Liu, J.-Q. Huang, Ultrafast Li-Rich Transport in Composite Solid-State Electrolytes, Advanced Materials, 37 (2025) 2419782.

[70] Y. Wang, T. Zhang, M. Kan, Y. Li, T. Wang, Y. Zhao, Efficient α-CsPbI3 Photovoltaics with Surface Terminated Organic Cations, Joule, 2 (2018) 2065-2075.

[71] S. R. G. Balestra, J. M. Vicent-Luna, S. Calero, S. Tao, J. A. Anta, Efficient modelling of ion structure and dynamics in inorganic metal halide perovskites, Journal of Materials Chemistry A, 8 (2020) 11824-11836.

[72] W. Luo, S. Kim, N. Lempesis, L. Merten, E. Kneschaurek, M. Dankl, V. Carnevali, L. Agosta, V. Slama, Z. VanOrman, M. Siczek, W. Bury, B. Gallant, D. J. Kubicki, M. Zalibera, L. Piveteau, M. Deconinck, L. A. Guerrero-León, A. T. Frei, P. A. Gaina, E. Carteau, P. Zimmermann, A. Hinderhofer, F. Schreiber, J.-E. Moser, Y. Vaynzof, S. Feldmann, J.-Y. Seo, U. Rothlisberger, J. V. Milić, From Chalcogen Bonding to S–π Interactions in Hybrid Perovskite Photovoltaics, Advanced Science, 11 (2024) 2405622.

[73] S. Hu, J. Shi, R. Yan, S. Pang, Z. Zhang, J. Wang, M. Zhu, Flexible rechargeable photo-assisted zinc-air batteries based on photo-active pTTh bifunctional oxygen electrocatalyst, Energy Storage Materials, 65 (2024) 103139.

[74] M. Li, X. Wang, F. Li, L. Zheng, J. Xu, J. Yu, A Bifunctional Photo-Assisted Li–O2 Battery Based on a Hierarchical Heterostructured Cathode, Advanced Materials, 32 (2020) 1907098.

[75] M. Yang, D. Wang, Y. Ling, X. Guo, W. Chen, Emerging Advanced Photo-Rechargeable Batteries, Advanced Functional Materials, 34 (2024) 2410398.

[76] S. Upadhyay, S. Narendhiran, M. Balachandran, Cotton-derived carbon fibers and MoS2 hybrids for efficient I3− reduction in bifacial dye-sensitized solar cells, Carbon, 238 (2025) 120248.

[77] B. Wang, G. M. Biesold, M. Zhang, Z. Lin, Amorphous inorganic semiconductors for the development of solar cell, photoelectrocatalytic and photocatalytic applications, Chemical Society Reviews, 50 (2021) 6914-6949.

[78] K. Liang, L. Li, Y. Yang, Inorganic Porous Films for Renewable Energy Storage, ACS Energy Letters, 2 (2017).

[79] Y. Guo, T. Liu, H. He, N. Wang, Bifunctional interface modification for efficient and UV-robust α-Fe2O3-based planar organic–inorganic hybrid perovskite solar cells, Advanced Composites and Hybrid Materials, 5 (2022) 3212-3222.

[80] P. Priyadarshini, S. Senapati, R. Naik, Lead-free organic inorganic hybrid halide perovskites: An emerging candidate for bifunctional applications, Renewable and Sustainable Energy Reviews, 186 (2023) 113649.

[81] F. Liu, Q. Zeng, J. Li, X. Hao, A. Ho-Baillie, J. Tang, M. A. Green, Emerging inorganic compound thin film photovoltaic materials: Progress, challenges and strategies, Materials Today, 41 (2020) 120-142.

[82] W. Chen, X. Li, Y. Li, Y. Li, A review: crystal growth for high-performance all-inorganic perovskite solar cells, Energy & Environmental Science, 13 (2020) 1971-1996.

[83] Y. Zhang, Y. Zhu, J. Sun, M. Hu, J. Chen, B. Duan, S. Hu, P. Hou, W. L. Tan, Z. Ku, W. Yang, J. Lu, Low Pressure Chemical Vapor Deposited Perovskite Enables all Vacuum-Processed Monolithic Perovskite-Silicon Tandem Solar Cells, Advanced Energy Materials, n/a (2025) 2405377.

[84] M. Waqas, D. B. Khadka, A. H. H. Khan, Y.-C. Wang, Fullerene-driven photocarrier processes in perovskite solar cells: recent advances, Nanoscale, 17 (2025) 15648-15675.

[85] A. Wadsworth, M. Moser, A. Marks, M. S. Little, N. Gasparini, C. J. Brabec, D. Baran, I. McCulloch, Critical review of the molecular design progress in non-fullerene electron acceptors towards commercially viable organic solar cells, Chemical Society Reviews, 48 (2019) 1596-1625.

[86] Y. Lu, J. Chen, Prospects of organic electrode materials for practical lithium batteries, Nature Reviews Chemistry, 4 (2020) 127-142.

[87] P. Poizot, J. Gaubicher, S. Renault, L. Dubois, Y. Liang, Y. Yao, Opportunities and Challenges for Organic Electrodes in Electrochemical Energy Storage, Chemical Reviews, 120 (2020) 6490-6557.

[88] Y. L. Lin, M. Koch, A. N. Brigeman, D. M. E. Freeman, L. Zhao, H. Bronstein, N. C. Giebink, G. D. Scholes, B. P. Rand, Enhanced sub-bandgap efficiency of a solid-state organic intermediate band solar cell using triplet–triplet annihilation, Energy & Environmental Science, 10 (2017) 1465-1475.

[89] N. Pellet, P. Gao, G. Gregori, T.-Y. Yang, M. K. Nazeeruddin, J. Maier, M. Grätzel, Mixed-Organic-Cation Perovskite Photovoltaics for Enhanced Solar-Light Harvesting, Angewandte Chemie International Edition, 53 (2014) 3151-3157.

[90] F. De Angelis, Modeling Materials and Processes in Hybrid/Organic Photovoltaics: From Dye-Sensitized to Perovskite Solar Cells, Accounts of Chemical Research, 47 (2014) 3349-3360.

[91] B. Ding, M. B. Solomon, C. F. Leong, D. M. D'Alessandro, Redox-active ligands: Recent advances towards their incorporation into coordination polymers and metal-organic frameworks, Coordination Chemistry Reviews, 439 (2021) 213891.

[92] C. Guo, Y. Fu, D. Li, L. Wang, B. Zhou, C. Chen, J. Zhou, Y. Sun, Z. Gan, D. Liu, W. Li, T. Wang, A Polycrystalline Polymer Donor as Pre-Aggregate toward Ordered Molecular Aggregation for 19.3% Efficiency Binary Organic Solar Cells, Advanced Materials, 35 (2023) 2304921.

[93] X. Zhang, C. Li, J. Xu, R. Wang, J. Song, H. Zhang, Y. Li, Y.-N. Jing, S. Li, G. Wu, J. Zhou, X. Li, Y. Zhang, X. Li, J. Zhang, C. Zhang, H. Zhou, Y. Sun, Y. Zhang, High fill factor organic solar cells with increased dielectric constant and molecular packing density, Joule, 6 (2022) 444-457.

[94] L. Xie, P. Vashishtha, T. M. Koh, P. C. Harikesh, N. F. Jamaludin, A. Bruno, T. J. N. Hooper, J. Li, Y. F. Ng, S. G. Mhaisalkar, N. Mathews, Realizing Reduced Imperfections via Quantum Dots Interdiffusion in High Efficiency Perovskite Solar Cells, Advanced Materials, 32 (2020) 2003296.

[95] J. Ho Kim, H. Woo Park, S.-J. Koo, D. Lee, E. Cho, Y.-K. Kim, M. Shin, J. Woo Choi, H. Jung Lee, M. Song, High efficiency and stable solid-state fiber dye-sensitized solar cells obtained using TiO2 photoanodes enhanced with metal organic frameworks, Journal of Energy Chemistry, 67 (2022) 458-466.

[96] L. Schulte, W. White, L. A. Renna, S. Ardo, Turning water into a protonic diode and solar cell via doping and dye sensitization, Joule, 5 (2021) 2380-2394.

[97] M. Kokkonen, P. Talebi, J. Zhou, S. Asgari, S. A. Soomro, F. Elsehrawy, J. Halme, S. Ahmad, A. Hagfeldt, S. G. Hashmi, Advanced research trends in dye-sensitized solar cells, Journal of Materials Chemistry A, 9 (2021) 10527-10545.

[98] J. Halme, P. Vahermaa, K. Miettunen, P. Lund, Device Physics of Dye Solar Cells, Advanced Materials, 22 (2010) E210-E234.

[99] Y. Li, P. Sonar, L. Murphy, W. Hong, High mobility diketopyrrolopyrrole (DPP)-based organic semiconductor materials for organic thin film transistors and photovoltaics, Energy & Environmental Science, 6 (2013) 1684-1710.

[100] S. Kanagaraj, A. Puthanveedu, Y. Choe, Small Molecules in Light-Emitting Electrochemical Cells: Promising Light-Emitting Materials, Advanced Functional Materials, 30 (2020) 1907126.

[101] R. Ji, Z. Zhang, M. Deconinck, Y. J. Hofstetter, J. Shi, F. Paulus, P. Raval, G. N. M. Reddy, Y. Vaynzof, Spontaneous Formation of 1D/3D Perovskite Heterojunctions for Efficient Inverted Perovskite Solar Cells, Advanced Energy Materials, 14 (2024) 2304126.

[102] X. Liu, J. Zhang, L. Tang, J. Gong, W. Li, Z. Ma, Z. Tu, Y. Li, R. Li, X. Hu, C. Shen, H. Wang, Z. Wang, Q. Lin, G. Fang, S. Wang, C. Liu, Z. Zhang, J. Li, X. Xiao, Over 28% efficiency perovskite/Cu(InGa)Se2 tandem solar cells: highly efficient sub-cells and their bandgap matching, Energy & Environmental Science, 16 (2023) 5029-5042.

[103] R. Lin, Y. Wang, Q. Lu, B. Tang, J. Li, H. Gao, Y. Gao, H. Li, C. Ding, J. Wen, P. Wu, C. Liu, S. Zhao, K. Xiao, Z. Liu, C. Ma, Y. Deng, L. Li, F. Fan, H. Tan, All-perovskite tandem solar cells with 3D/3D bilayer perovskite heterojunction, Nature, 620 (2023) 994-1000.

[104] Y. Bai, M. Hao, S. Ding, P. Chen, L. Wang, Surface Chemistry Engineering of Perovskite Quantum Dots: Strategies, Applications, and Perspectives, Advanced Materials, 34 (2022) 2105958.

[105] C. Yang, W. Hu, J. Liu, C. Han, Q. Gao, A. Mei, Y. Zhou, F. Guo, H. Han, Achievements, challenges, and future prospects for industrialization of perovskite solar cells, Light: Science & Applications, 13 (2024) 227.

[106] J. Bi, S. Li, D. Liu, B. Li, K. Yang, M. Xu, C. Fu, Y. Zhao, W. Zhang, Highly Integrated Perovskite Solar Cells-Based Photorechargeable System with Excellent Photoelectric Conversion and Energy Storage Ability, Energy & Environmental Materials, 7 (2024) e12728.

[107] M. Ashrafuzzaman, A. Kalam, A. G. Al-Sehemi, P. Yadav, M. Dubey, A review of photoanode materials, challenges, and outlook of dye-sensitized solar cells, Journal of Power Sources, 638 (2025) 236636.

[108] Y. Shi, Y. Wang, J. Lin, Y. Li, X. Guo, C. Jin, Y. Wang, X. Zhang, High-performance Cu-based PEO/PVDF-HPF gel polymer electrolyte of semi-transparent dye-sensitized solar cells, Journal of Power Sources, 628 (2025) 235876.

[109] Z. Wu, B. Shi, J. Yu, M. Sha, J. Sun, D. Jiang, X. Liu, W. Wu, Y. Tan, H. Li, S. Huang, J. Wang, J. Liu, C. Zhang, X. Ma, L. Cui, L. Ye, F. Zhang, B. Cao, Y. Chen, Z. Ji, F. Chen, X. Hao, G. Li, H. Yin, Human-friendly semitransparent organic solar cells achieving high performance, Energy & Environmental Science, 17 (2024) 6013-6023.

[110] J. Huang, Z. Zhang, Y. Zhu, H. Yu, X. Li, Z. Liu, S. Kazim, Y. Hu, W. Yang, X. Ma, L. Dai, S. Ahmad, Y. Shen, M. Wang, Modulating Buried Interface to Achieve an Ultra-High Open Circuit Voltage in Triple Cation Perovskite Solar Cells, Advanced Energy Materials, 14 (2024) 2402469.

[111] L. Ren, M. Zheng, F. Kong, Z. Yu, N. Sun, M. Li, Q. Liu, Y. Song, J. Dong, J. Qiao, N. Xu, J. Wang, S. Lou, Z. Jiang, J. Wang, Light Enables

View Article Online
DOI: 10.1039/D5NR02473K

the Cathodic Interface Reaction Reversibility in Solid-State Lithium-Oxygen Batteries, Angewandte Chemie International Edition, 63 (2024) e202319529.

[112] Q. Wang, Q. Sun, Y. Pu, W. Sun, C. Lin, X. Duan, X. Ren, L. Lu, Photo-Thermal Mediated Li-ion Transport for Solid-State Lithium Metal Batteries, Small, 20 (2024) 2309501.

[113] S. H. Kwon, S. Kim, J. Park, M. J. Lee, Y. Byun, H. J. Kim, Y. M. Baek, J. Kim, E. Lee, S. W. Lee, B. J. Kim, In-situ photo-polymerized elastomeric composite electrolytes containing Li6.4La3Zr1.4Ta0.6O12 particles for stable operation in lithium metal batteries, EcoMat, 6 (2024) e12503.

[114] P. Wen, Y. Liu, J. Mao, X. Liu, W. Li, Y. Ren, Y. Zhou, F. Shao, M. Chen, J. Lin, X. Lin, Tuning desolvation kinetics of in-situ weakly solvating polyacetal electrolytes for dendrite-free lithium metal batteries, Journal of Energy Chemistry, 79 (2023) 340-347.

[115] G. G. Serbessa, Y. Nikodimos, B. W. Taklu, S. K. Merso, Z. B. Muche, B. D. Dandena, S. A. Vallal, T.-I. Yeh, F. Valencia, Y.-F. Hung, J.-H. Hsu, C.-M. Lee, S.-H. Wu, W.-N. Su, C.-C. Yang, B. J. Hwang, Stabilizing the interface between Li6PS5Cl argyrodite sulfide solid electrolyte and Li via in situ formed LiF-Li3Bi lithiophobic-lithiophilic bifunctional layer, Energy Storage Materials, 76 (2025) 104103.

[116] P. P. Puthiyaveetil, A. Torris, S. Dilwale, F. Kanheerampockil, S. Kurungot, Cathode|Electrolyte Interface Engineering by a Hydrogel Polymer Electrolyte for a 3D Porous High-Voltage Cathode Material in a Quasi-Solid-State Zinc Metal Battery by In Situ Polymerization, Small, 20 (2024) 2403158.

[117] J. H. Kim, J. U. Lee, L. Zheng, J. Li, K. Sivula, M. Grätzel, J. S. Lee, J. H. Kim, Low-temperature thermite reaction to form oxygen vacancies in metal-oxide semiconductors: A case study of photoelectrochemical cells, Chem, 11 (2025) 102388.

[118] W. Zhang, Y. Wu, H. W. Bahng, Y. Cao, C. Yi, Y. Saygili, J. Luo, Y. Liu, L. Kavan, J.-E. Moser, A. Hagfeldt, H. Tian, S. M. Zakeeruddin, W.-H. Zhu, M. Grätzel, Comprehensive control of voltage loss enables 11.7% efficient solid-state dye-sensitized solar cells, Energy & Environmental Science, 11 (2018) 1779-1787.

[119] J. Song, Y. Gu, Z. Lin, J. Liu, X. Kang, X. Gong, P. Liu, Y. Yang, H. Jiang, J. Wang, S. Cao, Z. Zhu, H. Peng, Integrating Light Diffusion and Conversion Layers for Highly Efficient Multicolored Fiber-Dye-Sensitized Solar Cells, Advanced Materials, 36 (2024) 2312590.

[120] F. Kwaku Asiam, A. Kumar Kaliamurthy, M. Mahbubur Rahman, B. Yadagiri, C. Chen, H. Cheol Kang, M. Sadiq, J. Ryu, A. Ewusi Mensah, M. Zain Qamar, K. Yoo, J.-J. Lee, Direct charge-transfer mechanism (Type-II) in coordination complexes for sensitization in solar cells: A comprehensive review, Coordination Chemistry Reviews, 514 (2024) 215908.

[121] X. Dong, X. Li, X. Wang, Y. Zhao, W. Song, F. Wang, S. Xu, Z. Miao, Z. Wu, Improve the Charge Carrier Transporting in Two-Dimensional Ruddlesden–Popper Perovskite Solar Cells, Advanced Materials, 36 (2024) 2313056.

[122] Ultralightweight perovskite solar cells for use in drones, Nature Energy, 9 (2024) 641-642.

[123] Y.-H. Lin, V. null, F. Yang, X.-L. Cao, A. Dasgupta, R. D. J. Oliver, A. M. Ulatowski, M. M. McCarthy, X. Shen, Q. Yuan, M. G. Christoforo, F. S. Y. Yeung, M. B. Johnston, N. K. Noel, L. M. Herz, M. S. Islam, H. J. Snaith, Bandgap-universal passivation enables stable perovskite solar cells with low photovoltage loss, Science, 384 (2024) 767-775.

[124] J. Han, K. Park, S. Tan, Y. Vaynzof, J. Xue, E. W.-G. Diau, M. G. Bawendi, J.-W. Lee, I. Jeon, Perovskite solar cells, Nature Reviews Methods Primers, 5 (2025) 3.

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DOI: 10.1039/D5NR02473K

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.