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Green Power and Chemical Foundations: Evolution and Bottlenecks of Core Materials for Solar Electric Vehicles

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Abstract: Solar electric vehicles (SEVs) depend on material breakthroughs in three core components: photovoltaic conversion, energy storage batteries, and lightweight bodies. This paper systematically analyzes the material evolution and key bottlenecks of these three technical routes. In photovoltaics, perovskite single-junction cells have exceeded 26% in efficiency, whereas large-area fabrication and long-term stability remain major barriers to industrialization. For power batteries, solid-state electrolytes are promising for improving the safety of liquid systems, yet solid-solid interfacial impedance and process compatibility are still unresolved. In lightweighting, carbon fiber composites significantly reduce weight, whereas thermosetting matrices are difficult to recycle and thermoplastic matrices often exhibit weak interfacial bonding. These bottlenecks differ in nature: some arise from intrinsic material properties, others from process scaling. Therefore, differentiated R&D strategies must be formulated accordingly.

Keywords: Solar electric vehicles, Perovskite solar cells, Solid-state batteries, Carbon fiber composites, Material bottlenecks.

1. Introduction

Limited by the available illumination area on a vehicle, SEVs must push photovoltaic conversion, energy storage, and weight reduction to their material limits to achieve practical ranges. Their technical feasibility relies on synergistic breakthroughs in three core components: the photovoltaic conversion efficiency of solar panels, the energy density and safety of power batteries, and the lightweight level of the body structure. Advances in all three areas strongly depend on innovations in materials science and chemical engineering.

This paper focuses on these three components, reviews their material evolution, identifies core bottlenecks, and classifies representative solutions.

2. Photovoltaic Materials: From Crystalline Silicon to Perovskites and the Stability Dilemma

SEVs are powered by photovoltaic panels mounted on the roof or body. Photovoltaic technology is currently transitioning from first-generation crystalline silicon cells to next-generation thin-film cells based on perovskites.

Crystalline silicon cells are technologically mature but tend to be heavy, brittle, and costly to manufacture. In contrast, perovskite solar cells (general formula ABX_3, e.g., $CH_3NH_3PbI_3$) have attracted wide attention because of their excellent optoelectronic properties. Their crystal structure features a periodic network of $[PbI_6]^{4-}$ octahedra, which provides efficient pathways for charge transport. According to the National Renewable Energy Laboratory (NREL), the certified efficiency of perovskite single-junction cells increased from 3.8% in 2009 to over 26% by 2025 (Figure 1) [1], approaching that of crystalline silicon. In addition, solution-based fabrication gives perovskites cost advantages and flexible potential.

Stability remains the primary bottleneck for perovskite industrialization. These materials readily degrade under humidity, heat, light, and electric fields. Researchers have therefore explored composition engineering and structural regulation. For example, Kong et al. used a perovskitoid template to form a 1D@3D heterostructure and introduced large organic amine cations to passivate micro-scale defects, substantially improving environmental stability [2]. Another team developed a gas-quenching-assisted in-situ coating strategy that dynamically controls crystallization by applying additives to wet films during continuous quenching. On flexible PET substrates, they prepared 30 × 40 cm2 wide-bandgap perovskite films and obtained flexible all-perovskite tandem cells (0.049 cm^2) with 27.5% efficiency and large-area modules (20.26 cm^2) with a certified 23.0% efficiency. The modules retained 97.2% of their initial efficiency after 10,000 bending cycles at a 10 mm radius (Figure 2) [3].

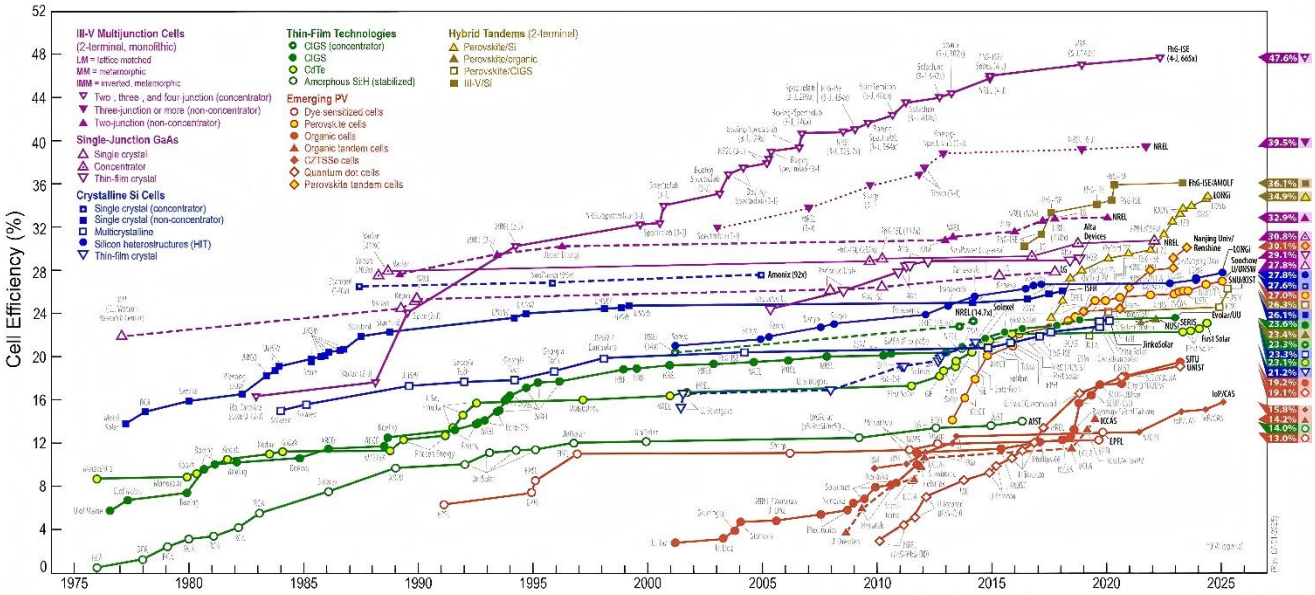

Figure 1. Evolution trend of certified efficiency for perovskite single-junction solar cells (Source: NREL)

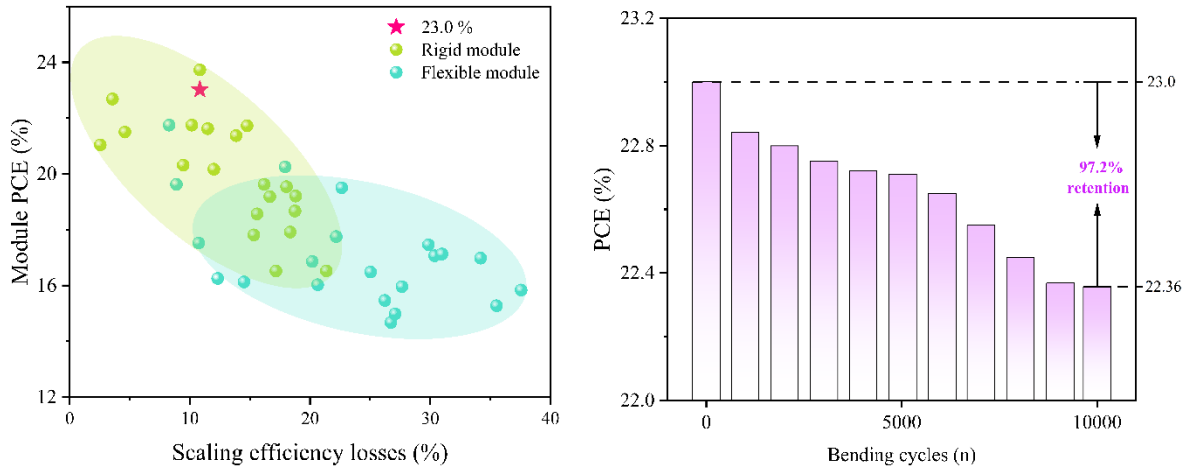

Figure 2. Photovoltaic performance and bending cycle stability of flexible all-perovskite tandem cells and modules (Source: Ref. [3])

Integrating photovoltaic materials onto vehicles requires lightweighting and mechanical durability. Lightweight rigid modules usually adopt honeycomb cores, glass-fiber/epoxy prepregs, and EVA films to maintain high-temperature stiffness and prevent delamination while reducing weight. Flexible photovoltaic components, such as CIGS thin-film cells combined with rolling mechanisms, are also being explored to increase roof-mounted photovoltaic area [4].

3. Power Batteries: From Liquid to Solid State and Interfacial Impedance Challenges

SEVs require high-performance power batteries to handle sunlight intermittency. Lithium-ion batteries are currently mainstream, and their energy density continues to improve through electrode material iteration.

For cathodes, the evolution has progressed from layered $LiCoO_2$ to olivine $LiFePO_4$ and high-nickel ternary $LiNi_xCo_yMn_{1-x-y}O_2$ [5]. High-nickel ternary materials are widely studied because of their high specific capacity, but structural degradation during cycling necessitates doping. Researchers have developed multi-site doping on Li sites, transition-metal sites, O sites, and co-doping to stabilize the crystal structure and suppress phase transitions and cation mixing during charge–discharge (Figure 3). Hou Shunli et al. summarized that multi-site doping can raise 100-cycle capacity retention of high-nickel ternary materials from ~85% to >90% [6]. For anodes, silicon has a much higher theoretical specific capacity than graphite, but it undergoes large volume changes during (de)lithiation, which tends to cause electrode pulverization. Core–shell designs (e.g., Si@C) and porous structures can buffer volume changes and extend cycle life [7].

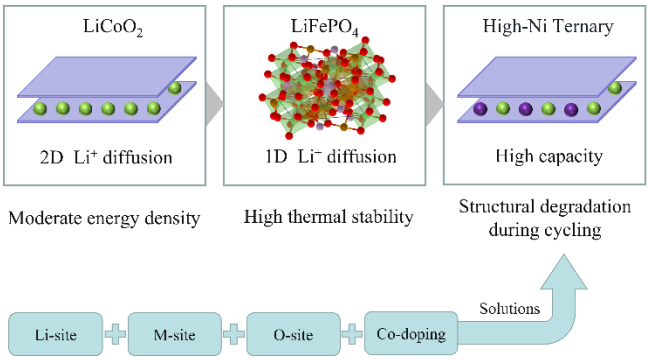

Figure 3. Schematic of crystal structures and doping strategies for Li-ion battery cathodes

To further raise the energy density ceiling and improve safety, solid-state batteries (SSBs) with solid-state electrolytes (SSEs) are regarded as the next-generation technology. SSEs include sulfide systems (e.g., $Li_{10}GeP_2S_{12}$) and oxide systems (e.g., $Li_7La_3Zr_2O_{12}$, LLZO); their

room-temperature ionic conductivities have reached 10^{-4}-10^{-3} S/cm, enabling the use of lithium metal anodes [8]. However, practical application of SSBs is limited by severe interfacial impedance, which originates not from the bulk SSE but from two microscopic mechanisms: (1) Physical "point-contact" failure: volume changes during (de)lithiation turn the solid–solid interface from area contact into point contact, distorting local current density [9]; (2) Chemical "space-charge layer" effects, for example, the Li^+ depletion layer at the oxide SSE-cathode interface driven by chemical potential gradients [10]. Therefore, vague "interface modifications" are insufficient; precise interventions are required, such as 3D continuous ion pathways to relieve stress (e.g., LLZO-composite-based 3D porous current collectors) or in-situ solidified interface layers to block chemical diffusion [11].

Beyond lithium systems, sodium-ion batteries are promising for applications with less stringent energy-density requirements because of abundant resources, lower cost, and better safety. Zhang Ping et al. analyzed the technical feasibility and economics and concluded that sodium-ion batteries have shown initial economic potential for large-scale energy storage [12].

4. Lightweight Bodies: Advantages and Recycling Trade-offs of Carbon Fiber Composites

Lightweighting reduces driving energy consumption and extends range, making it key to efficient SEV operation. Carbon fiber reinforced polymer (CFRP) composites are increasingly replacing metal parts in automotive lightweight design because of their high specific strength and modulus [13].

Carbon fibers are usually made from polyacrylonitrile precursors via pre-oxidation, carbonization, and graphitization, forming a graphite-like layered structure. The resin matrix (e.g., epoxy) forms a 3D cross-linked network that transfers loads and protects fibers. Interfacial bonding strength between fibers and resin strongly affects composite performance. Sizing technology is commonly used to improve bonding; for instance, studies have examined the compatibility of domestic T800-grade carbon fibers with different resins [14].

However, thermosetting matrices such as epoxy are difficult to decompose after curing, complicating CFRP recycling. Thermoplastic matrices such as polyether ether ketone (PEEK) are remeltable and thus potentially recyclable. Teltschik et al. reviewed PEEK-based CFRP recycling routes and showed that, under optimized conditions, thermoplastic composites can largely retain fiber mechanical properties and enable recyclability [15]. Yet thermoplastics usually have high melt viscosity and poor wettability on carbon fibers [16]; molecular design or interfacial modification can mitigate this, but low-cost, industrial-scale interface control remains an open issue.

5. Conclusion

Overall, the three core components of SEVs face distinct material bottlenecks: intrinsic degradation of perovskites, solid-solid interfacial impedance in SSBs, and the matrix selection trade-off in CFRP. Future R&D should move from general trial-and-error to precise, mechanism-driven regulation—for example, micro-defect passivation of the $[PbI_6]^{4-}$ network or interfacial interventions tailored to chemical potential gradients at SSE interfaces. Close collaboration between materials science and chemical engineering remains essential to achieving these differentiated breakthroughs.

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