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A Review of Solar Energy Multi-level Synergistic Utilization Systems Based on Spectral Splitting

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Abstract. Full-spectrum use of solar energy should be achieved efficiently to address the efficiency limitations of single photovoltaic (PV) or photothermal conversion. Spectral splitting technology splits sunlight into various bands and directs them to PV, photothermal and photochemical processes for cascade use. Based on the previous studies, this paper will systematically organize the theoretical foundation of full-spectrum utilization, review spectral splitting methods, discuss integration modes for multi-level synergistic systems, and explore application prospects in building integrated PV (BIPV) and ecological restoration. It also explores the main problems of optical efficiency, system integration and cost control, and puts forward some research directions. Research has shown that spectral-splitting multi-level synergistic systems are emerging as necessary directions for development, but new problems still need to be solved in splitter design, thermal management and life-cycle economic analysis. Future studies should integrate technical performance, economic feasibility, and environmental impacts into a unified life-cycle assessment framework to identify optimal system configurations. Overall, spectral-splitting multi-level synergistic systems represent a promising pathway toward full-spectrum solar energy utilization, but their practical development requires simultaneous improvements in optical components, thermal management, system integration, and economic performance.

Keywords: Spectral Splitting, Solar Energy, Synergistic Utilization, Photovoltaics

1. Introduction

Given the problems of climate change and carbon neutrality in the world, the shift to a carbon-neutral society must be implemented efficiently. Wei et al. have highlighted that the IPCC's Sixth Assessment Report emphasizes that a large-scale reorganization of the energy system is required to achieve the 1.5°C goal [1]. Huang and Xie [2] further argue that the primary path is zero-carbon electricity and fuels . Li and Kong [3] have reported that China is endowed with abundant solar resources and has reduced PV costs. Single PV or photothermal technologies have bandgap and thermodynamic losses. Mu et al. [4] mentioned that no standardized carbon accounting systems currently exist for new-energy power generation . Liu et al. [5] have demonstrated that large-scale PV plants change the surface thermal balance. Band-selective cascade utilization will enhance the economy and environment more evenly at the same time. Therefore, spectral splitting technology

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can be used to divide the solar spectrum into a short-wave band for PV and a long-wave band for photothermal collection to achieve a dual-purpose structure. This review systematically summarizes the principles, applications, problems and future prospects spectral splitting technology, along with the current state of research.

2. Principles, applications, and challenges

2.1. Principles and theoretical basis

Spectral splitting enables the full-spectrum cascaded utilization of solar energy(see figure 1). Crystalline silicon PV cells have a bandgap of about 1.12 eV and only absorb light with a wavelength of 1100 nm or more, while photons with longer wavelengths pass through unabsorbed, resulting in significant spectral mismatch losses. Zhou et al. [6] analyzed solar resource data from 1961 to 2008 in northwestern China and identified that the relatively stable resources were in northern Qinghai. Hu et al. [7] determined that the solar resources in Inner Mongolia (4858-6925 MJ/m²) are suitable for large-scale power plants. Spectral splitting can be implemented through various optical devices, including dichroic filters, dispersive elements (prisms/gratings), and luminescent materials. Furthermore, Han et al. [8] used Innography and Rao-Stirling indices to identify breakthrough innovation topics in solar PV.

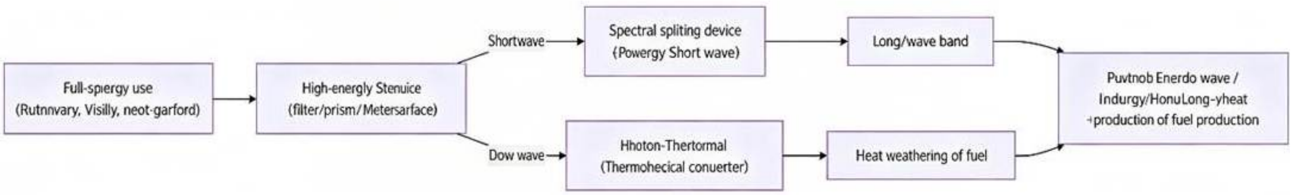

Figure 1. Working principle of spectral splitting multi-level synergistic system

2.2. Main application scenarios

Spectral splitting systems are mainly applied in PV/T integrated systems, CPV/T systems, PV with photocatalysis/thermochemistry, and "PV+" ecological restoration. In the building-integrated photovoltaics (BIPV), Chu et al. [9] proposed a design framework for near-zero energy BIPV, and Qin and Li indicated BIPV as a leading market direction [10]. Zhang et al. presented the "C-House" as a case of low-carbon, energy-producing building that integrates advanced photovoltaic technologies [11]. And, Yao et al. mentioned that life-cycle assessment is essential for solar thermal [12]. Liu et al. [5] demonstrated that desert-based PV plants can be used for power generation and sand control.

2.3. Core challenges

The main problems are the optical efficiency-economy tradeoff for splitters, thermal management and energy matching, and system complexity versus life-cycle costs. Yu et al. [13] employed patent data and the Bass model to determine that thin-film cells are disruptive technologies exhibiting S-curve diffusion . Qu et al. [14] have identified energy storage and transmission as the key constraints for PV in Northwest China, and Deng et al. [15] have put forward the necessity of integrated wind-solar-water-storage systems. Wang et al. [16] used life-cycle assessment for a 500kW PV power plant and found an annual carbon reduction of about 3.05×10^5 kg.

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3. Current research status and classification review of solar energy resources

The precise assessment of solar energy resources is the prerequisite for designing the spectral separation strategy and conducting regional adaptability analysis for the spectral separation system. The research methods in this field have evolved from macroscopic static statistics to microscopic dynamic simulation.

3.1. Research on solar energy resources assessment and utilization potential

3.1.1. Main methods: resource assessment based on site observations and climatic statistics

Traditional research methods mainly rely on long-term meteorological observation station data (such as total radiation, sunshine duration, temperature, etc.) and combine climatic statistical principles (such as linear regression, cluster analysis, peak sunshine duration method, etc.) to quantitatively describe the total solar energy resources, temporal and spatial distribution characteristics, and stability in a specific region. The core logic is to provide basic input for the macro-scale site selection and capacity planning of photovoltaic power stations through static statistics analysis of historical data.

Under this paradigm, Zhao et al. [17] utilized national sunshine duration data and conducted a cluster analysis to classify China into 11 regions. As shown in Figure 2, the findings revealed the long-term evolution trend in sunshine duration, characterized by an overall downward trajectory and a marked transition from significant decrease to slight recovery after 1993. The advantage of this method lies in mature data sources, transparent models, and low computational costs, which can provide stable resource data on a large scale and over a long time scale, especially suitable for national-level strategic planning.

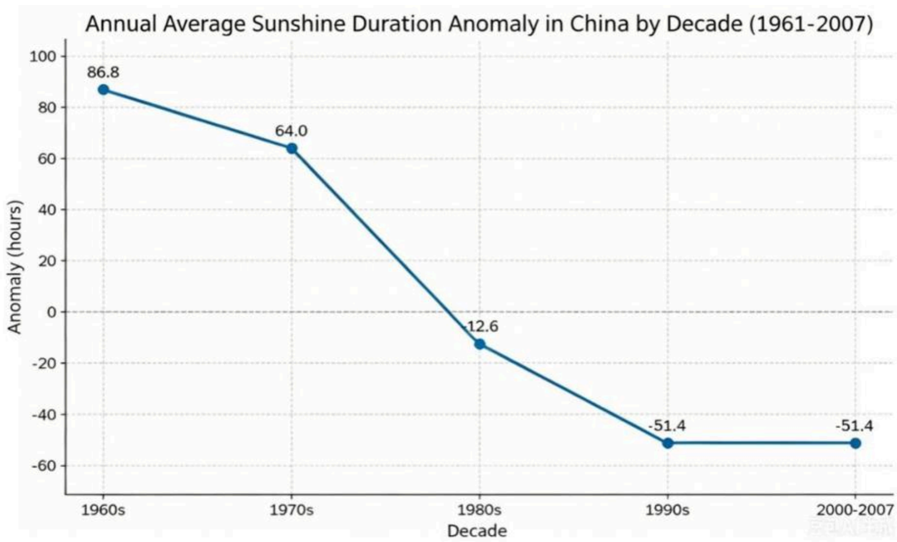

Figure 2. Annual average sunshine duration anomaly in China by decade (1961-2007)

3.1.2. Improved/novel methods: fine assessment coupled with power generation simulation and spatial analysis

To overcome the shortcomings of traditional methods in the insufficient consideration of local heterogeneity and single assessment dimension, researchers began to combine photovoltaic power

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generation physical models (such as peak sunshine duration method, power generation modeling) with high-resolution spatial analysis techniques (such as GIS, remote sensing inversion) and introduce multi-scenario simulation for benefit assessment. The core improvement lies in shifting from "resource total description" to a multi-dimensional explicit assessment of "electricity generation capacity + economic benefits + environmental benefits".

Hu et al. emploued a 5.3 kWp installed capacity as the benchmark, compared the accuracy of the peak sunshine duration method and the sunshine duration modeling method in estimating the solar power generation capacity of rooftops in Inner Mongolia. Combining poverty alleviation and household distributed scenarios, they evaluated economic benefits and linked the resource assessment to specific application scenarios [18]. Qu et al. elevated the assessment to the regional macro strategic level, calculated the photovoltaic power generation potential of the five provinces in northwest China at 2.41×10^{14} kW·h. They further quantified sales revenues and environmental benefits, making the resource assessment results directly serve regional economic decision-making under the "dual carbon" goals [14]. Mao et al. further expanded the assessment object from a single photovoltaic system to a multi-energy complementary system, assessing the comprehensive potential of hydropower, solar energy, wind energy, biomass energy, and geothermal energy in Qinghai Province [19].

3.2. Research on innovation in photovoltaic materials, devices, and system integration

3.2.1. Main methods: "trial and error" mode based on new material exploration and experimental optimization

The traditional research paradigm highly relies on the synthesis, characterization, and device fabrication of new materials (such as perovskites, dye-sensitized agents). The underlying methodology is characterized by a "preparation - testing - analysis" iterative cycle, wherein adjusting the composition, structure, and process parameters of the materials to improve the photoelectric conversion efficiency (PCE).

Under this paradigm, researchers have extensively conducted extensive new systems such as perovskite solar cells and dye-sensitized solar cells. Ma et al. [20] identified TiO_2 semiconductor films, organic dye sensitizers, gel electrolytes, and platinum as key technological forms with development advantages. The advantage of this method lies in its ability to directly produce verifiable experimental results and its role as the source of technological innovation. However, its limitations are also quite prominent: the long research cycle, high cost, and the fact that the understanding of the internal mechanism of performance improvement often lags behind experimental discoveries, thereby hindering systematic prediction of future technological trajectories.

3.2.2. Improved/novel methods: technological path prediction based on big data and semantic mining

To overcome the blindness and lag of the traditional "trial and error" model, researchers have incorporated data-driven analysis methods, especially text mining techniques based on patents and papers, into the research of photovoltaic technological innovation. The core improvement lies in reconceptualizing patent and academic literature not merely as a vehicle for knowledge dissemination, but as a "big data" resource for revealing the inherent laws of technological development.

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Li et al. [21] refined the Subject-Action-Object (SAO) structure semantic mining method by analyzing the "problem-solution" logical chain in patent texts, successfully mapping the technological evolution trajectory of perovskite solar cells and revealing the context of gradual changes in technical performance. Huang et al. and Li et al. [22, 23] further utilized the SAO structure analysis, respectively identifying potential technological opportunities and key solutions in the fields of perovskite and dye-sensitized solar cells. From a macro perspective, Hou and Fan [24] conducted patent family analysis to classify the development of solar photovoltaic cells into three stages: the emergence of new technologies, the improvement of technology, and the adjustment of technology (see figure 3). In parallel, Luan et al. [25] applied technology co-classification analysis to reveal the concurrent evolution trend of divergence and convergence in technology development.

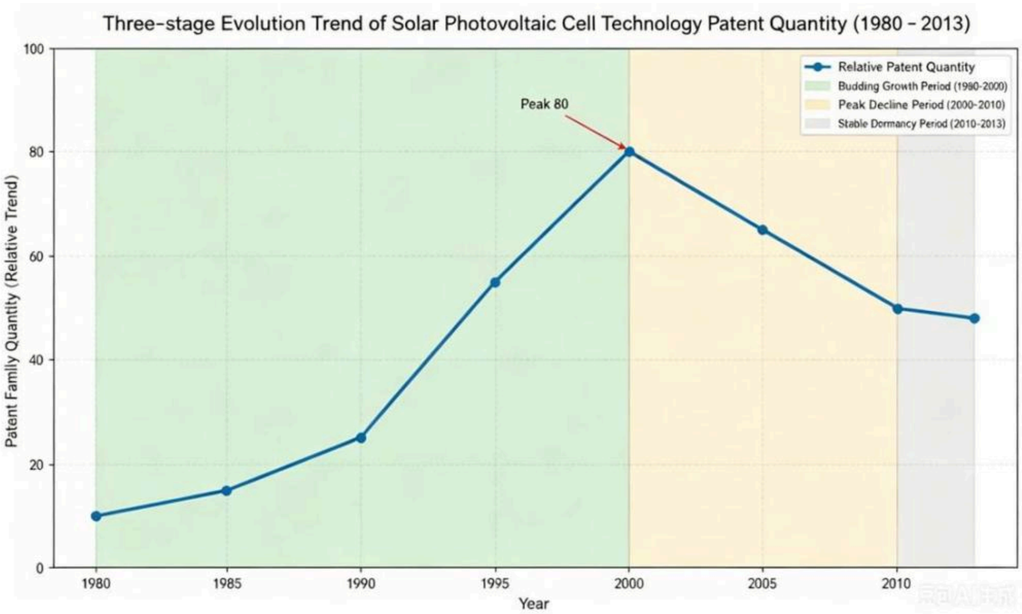

Figure 3. Three-stage evolution trend of solar photovoltaic cell technology patent quantity (1980 -2013)

3.3. Research on the economic performance and policy incentives of photovoltaic systems

3.3.1. Main methods: static economic analysis based on LCOE

Early research mainly focused on calculating the Levelized Cost of Electricity (LCOE) for photovoltaic power generation and comparing it with traditional energy sources to assess the feasibility of "grid parity". The core method was to establish a cost model and calculate the power generation costs under different light resource areas and different installation scales.

After excluding fiscal subsidies, Ma et al. [26] calculated the power generation costs of different-sized photovoltaic systems and predicted the time node (around 2019) for achieving power generation-side grid parity for megawatt-level systems. The advantage of this method lies in its transparent model and intuitive indicators, which can clearly depict the trend of technological cost reduction. However, its limitation is its"static" character, thereby making it difficult to reflect the complex influence of policy intervention, market competition, and uncertainty factors.

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3.3.2. Improved/novel methods: dynamic policy effect evaluation based on econometrics

With the development of the industry, research methods shifted to evaluating the dynamic causal effects of specific policies (such as electricity price subsidies, tax incentives) on enterprise behavior and industrial performance. The core methodology involves employing econometric models (such as two-way fixed effect models, real options models) to identify the net impact of policy shocks from micro data.

Wang et al. [27] used manually collected electricity price subsidy data and empirically found that electricity price subsidies significantly increased the scale, innovation output, and market competitiveness of enterprises in each link of the photovoltaic industry chain. Li and Zhou [28] constructed a real options model to analyse the marginal impact of value-added tax preferential policies on investors' decisions and found that the length of the policy benefit period was more critical than the policy rate itself. In addition, the research perspective expanded from the single effect of policy to the dynamic evolution of the policy system. Yuan and Zhu [29], through social network analysis, divided China's photovoltaic industry policies into five stages, revealing the evolution pattern from cultivating the market to gradual phase-out .

3.4. Photovoltaic ecological benefits and system integration research

3.4.1. Main methods: carbon footprint accounting based on LCA

Early studies mainly applied Life Cycle Assessment (LCA) to quantify the carbon emissions of photovoltaic systems throughout the "cradle-to-grave" (production - operation - disposal) and compare them with fossil energy generation to prove their positive environmental benefits. The core methodology involved compiling LCA of energy consumption and material inputs and outputs.

Wang et al. [16] analyzed the carbon emission characteristics of a 500 kW photovoltaic power station throughout its life cycle and calculated the annual carbon reduction compared to standard coal power generation (approximately 3.05×10^5 kg) . The advantage of this method lies in its high standardization, quantifiable results, and ease of horizontal comparison. However, its limitation is that early studies mostly focused on the power generation process itself, ignoring the direct impact of photovoltaic power station construction on local ecosystems (such as soil, vegetation, microclimate).

3.4.2. Improved/novel methods: composite benefit evaluation coupled with ecology and spatial analysis

To overcome the limitations of traditional LCA, researchers began to combine ecological observations and spatial analysis with LCA methods to comprehensively assess the multiple environmental benefits of photovoltaic systems, including carbon reduction, water and soil conservation, and biodiversity, etc. The core improvement was recognizing that the photovoltaic power station is no longer an isolated "power generation equipment", but an "artificial interference factor" embedded in a complex ecosystem.

Liu et al.'s research in the Hexi Corridor pioneered the statement that photovoltaic power plants in desert and Gobi areas can effectively regulate the surface thermal balance and reduce sandstorms, demonstrating the win-win value of photovoltaic power generation and ecological protection [5]. Liu et al. [30] constructed a comprehensive evaluation index system including "topography - meteorology - cost", assessing the emission reduction benefits of photovoltaic development in the

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Beijing-Tianjin-Hebei region and found that large-scale development could contribute nearly half of the region's carbon emissions reduction. Adopting the perspective of zero-carbon villages, Lei et al. [31] evaluated the significant environmental potential of household distributed photovoltaic systems replacing traditional biomass and coal power. These studies elevated the environmental benefits of photovoltaic from a single "carbon reduction" to the level of "ecosystem services".

4. Current challenges: from "feasibility" to "usability"

Although their compelling theoretical advantages, spectral splitting multi-level systems still have many problems before large-scale deployment. The first problem is that the optical efficiency and scalability of the splitters are in conflict. Ideal splitters need high selectivity, wide-angle acceptance and low-cost fabrication. Interference-based optical films are angle-sensitive and show a wavelength shift at large angles of incidence. To achieve high-efficiency splitting in the 0.3-2.5μm band, numerous thin-film layers with precise refractive indices are required, but available material systems remains restricted. Multiple layers of coatings are relatively complex and have a low yield. The second is the problem of poor energy quality and heat management. PV cells generate heat due to non-radiative recombination and are thus less efficient. Low-grade heat (<100 °C) is unsuitable for power generation and industrial heating at present. The optimal operating temperature of PV (25-40 °C) is incompatible with that of thermal collectors (>80 °C), so a trade-off must be made. The third problem is a conflict between the complexity of the system and life-cycle economy. Splitters, dual receivers and control systems are all higher in cost, maintenance and failure risk. Most cost-benefit analyses do not have an all-encompassing 3E (energy-economy-environment) multi-objective optimization model.

5. Future prospects: breakthroughs and new applications

Future research is expected to transition from single-performance optimization to system of intelligent synergy. From a materials perspective, micro- and nanostructured optical devices (metasurfaces, photonic crystals, plasmonics) can be used to overcome the angle-of-incidence constraint and material limitations, and highly compact, efficient, and low-cost splitters have been achieved. AI-based smart energy management systems are anticipated to dynamically optimize splitting strategies according to changes in solar spectrum, temperature and heat demand. Cross-scale simulation platforms that integrate spectral resource data, device physics and thermodynamics and economic models need to be built for early-stage 3E assessment in the design method. In the next 5-10 years, transformative applications will be zero-energy BIPV/T, solar fuel/chemical polygeneration, and "PV+" for ecological restoration and modern agriculture [5, 16].

6. Conclusion

Although their spectral splitting systems spectral splitting multi-level systems still have many problems before large-scale deployment. The first problem is that the optical efficiency and scalability of the splitters are in conflict. Ideal splitters need high selectivity, wide-angle acceptance and low-cost fabrication. Interference-based optical films exhibit angle-sensitive manifesting spectral drift at large angles of incidence. To achieve high-efficiency splitting in the 0.3-2.5μm band, many thin-film layers with precise refractive indices are required, but available material systems are still limited. Multiple layers of coatings are relatively complex and have a low yield. The second is the problem of poor energy quality and heat management. PV cells generate heat due to non-

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