

Review of the Key Roles and Challenges of PV-CSP Generation Coupling under the Background of Carbon Neutrality

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Abstract: Solar photovoltaic (PV) and concentrated solar power (CSP) hybrid power plants integrate the advantages of both photovoltaic and solar-thermal power generation. This configuration enhances the stability of grid-connected output while simultaneously improving overall power generation efficiency and land-use effectiveness. To further explore the significance of PV/CSP coupling under the dual-carbon goals and to develop its unique strengths, this paper reviews the current research status of PV/CSP hybrid technologies and outlines potential future technological pathways. It's aiming to provide theoretical references for subsequent studies in this field.

Keywords: Solar Energy; Photovoltaic Power Generation; Concentrated Solar Power Generation; Carbon Neutrality.

1. Introduction

Electric energy is indispensable for modern human society. In the 21st century, challenges such as energy shortages and environmental pollution have intensified, making the source of electricity a critical issue. In China, coal-fired power remains the dominant form of power generation. As of April 2025, coal-fired installed capacity reached 1.455 billion kW, accounting for approximately 41.73% of the nation's total installed capacity. Meanwhile, solar and wind power account for 28.45% and 15.52% respectively.

Coal-fired power plants emit large volumes of pollutants, whereas solar energy—being clean and free of pollutant by-products—has gained widespread global attention. Current solar power technologies mainly include PV and CSP. PV generation is highly affected by solar irradiance and shows intermittency and fluctuation, requiring balancing support from other generating units or storage devices[1]. Moreover, PV output typically peaks at noon, while grid load peaks often occur in the evening, creating a temporal mismatch that increases ramping requirements for grid operators. At sunset, the sharp decline in photovoltaic PV output necessitates a rapid and substantial increase in the output of dispatchable generating units to satisfy the remaining load demand, thereby imposing considerable stress on system peak-shaving operations. Moreover, the operational flexibility of conventional thermal power plants remains inherently limited: constraints such as minimum technical output and restricted ramping capability prevent these units from fully responding to such abrupt net-load fluctuations. Consequently, large-scale PV integration significantly heightens both peak-regulation and frequency-regulation challenges, and places more stringent requirements on the secure and stable operation of the power system.

A PV-CSP hybrid power plant is a form of solar energy utilization that combines low cost, high flexibility, and stable power output. By integrating the direct electricity generation of photovoltaics with the high-temperature thermal conversion of concentrated solar power, the system enables controllable, around-the-clock clean power generation.

As early as 1993, Kazuhiko Sakuma and colleagues proposed the concept of hybrid photovoltaic-thermal (PV/T) utilization. In their study, PV modules were mounted on flat-plate solar collectors, and pure PV, pure thermal collectors, and PV/T hybrid panels were compared from the perspectives of electrical, thermal, energy, and entropy efficiency. The results showed that under typical climatic conditions in Tokyo, Japan, PV/T hybrid panels outperformed both pure PV and pure thermal systems in terms of annual entropy efficiency[2]. Subsequently, in 1994, Takumi Takashima et al. proposed an integrated “photovoltaic + thermal recovery” approach, discussing various structural designs and operational modes, and ultimately concluded that the integrated system could enhance overall solar energy utilization [3]. In 2007, Tripanagnostopoulos and colleagues explored the design of a dual-channel heat extraction device for PV/T systems, significantly improving both thermal and electrical output of the collectors [4]. The concept of PV-CSP hybrid power plants, however, was not proposed until 2017. Vossier et al. further summarized the design principles of PV-CSP hybrid power plants, aiming to increase the flexibility of total installed capacity and improve overall system efficiency [5].

This paper aims to review the key technological approaches and existing cases and achievements of highly coordinated and deeply integrated photovoltaic and solar thermal power generation under mainstream technological pathways. It also discusses their significance in the context of China's “dual-carbon” goals.

2. Introduction to PV and CSP

2.1. PV

The basic principle of photovoltaic (PV) power generation is based on the photoelectric effect in semiconductors. When photons strike a material's surface, their energy may be fully absorbed by electrons within the material. If an electron acquires enough energy to overcome the Coulomb forces within the atom, it can escape from the surface and become a free photoelectron. Silicon atoms have four valence electrons; when an atom with five valence electrons (e.g., phosphorus)

is doped into pure silicon, an N-type semiconductor is formed. Conversely, doping with an atom having three valence electrons (e.g., boron) produces a P-type semiconductor. When P-type and N-type semiconductors are combined, a potential difference forms at their interface, creating a solar cell. When sunlight illuminates the P–N junction, the photogenerated carriers move directionally under the influence of the built-in electric field, with current flowing from the P-type region to the N-type region, ultimately generating usable electricity.

The simplified power supply process of a PV power

generation system is illustrated in Figure 1 [6]. Following the aforementioned processes, the controller regulates the direction of electrical energy flow according to the load demand. When the load power is lower than the generated power, the surplus electricity is utilized to charge the battery storage system; conversely, when the PV output is insufficient to meet the load demand, the battery supplies supplementary power while the PV modules continue operating. The loads are categorized into direct current (DC) loads and alternating current (AC) loads. DC loads can be supplied directly, whereas AC loads require conversion through an inverter.

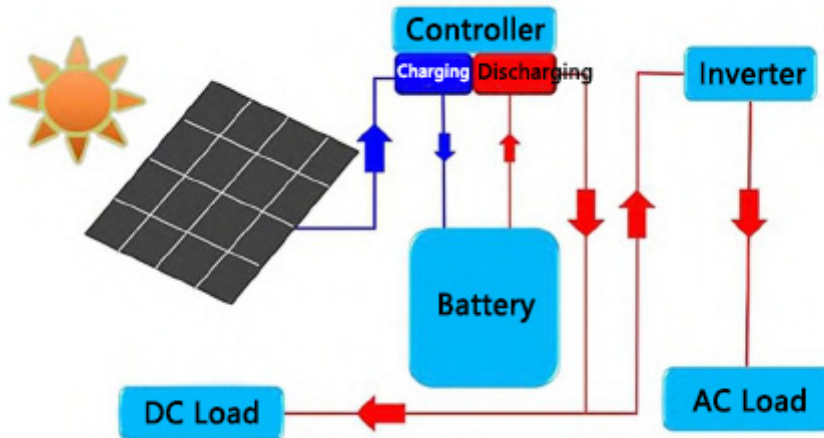


Fig 1. The principle of photovoltaic power generation

Currently, there are multiple technological pathways for PV power generation, mainly including monocrystalline silicon, polycrystalline silicon, amorphous silicon thin films, and perovskite solar cells. Monocrystalline and polycrystalline silicon are the dominant and relatively mature technologies with a longer development history [7]. As an emerging technology, perovskite solar cells differ significantly from conventional solar cells.

Structurally, as illustrated in figure 2, perovskites possess an ABX_3 octahedral crystal framework. By flexibly adjusting the A, B, and X ions—such as through Sn doping or modifying the Br/I ratio to change the B- or X-site ions—their bandgap, lattice stability, and overall performance can be optimized, providing greater space for efficiency enhancement. Moreover, perovskites exhibit stronger absorption of visible and near-infrared light, allowing the absorption layer to be made thinner [6].

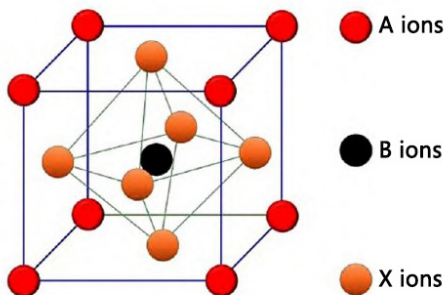


Fig 2. Schematic diagram of perovskite crystal structure

In terms of fabrication, perovskite solar cells can be prepared using solution-based methods or low-temperature processes, which are simple, low-cost, and more suitable for

flexible substrates and large-scale production [8]. However, regarding stability, silicon-based cells offer extremely high long-term reliability, whereas perovskite materials face challenges such as the easy oxidation of Sn^{2+} and the susceptibility of their lattice to humidity and temperature. These issues remain one of the major bottlenecks for the commercialization of perovskite solar cells.

2.2. CSP

Concentrated solar power (CSP) refers to a technology that uses large-scale parabolic or dish-shaped mirror arrays to collect solar thermal energy, which is then converted into steam through heat-exchange devices and subsequently drives conventional steam turbines for electricity generation. Unlike PV power generation that relies on silicon-based materials, CSP does not require costly photovoltaic conversion processes, significantly reducing the overall cost of solar power generation. Moreover, CSP offers advantages that other forms of solar energy utilization cannot easily match: the generated thermal energy can be stored in a working fluid (e.g., water or molten salts) within large insulated tanks, allowing the turbines to continue generating electricity for several hours after sunset and providing grid-load balancing capability, thus ensuring stable power output.

Currently, CSP has achieved practical results across multiple technological pathways.

2.2.1. Solar Power Tower System

Solar power tower technology, also known as a central-receiver concentrated solar power (CSP) system, generates electricity by using a heliostat field to reflect and concentrate sunlight onto a receiver located at the top of a tower. The system is composed of four main components: the heliostat field, the solar tower, the thermal-energy storage unit, and the power-generation block.

As illustrated, a heliostat field is arranged around the tower, where a large number of sun-tracking mirrors continuously follow the solar position and efficiently reflect direct sunlight onto the receiver at the tower's apex[9]. The concentrated

solar flux heats the working fluid—typically generating high-temperature steam—which is then delivered to a steam turbine for power generation or directed into the thermal-energy storage system for later use.

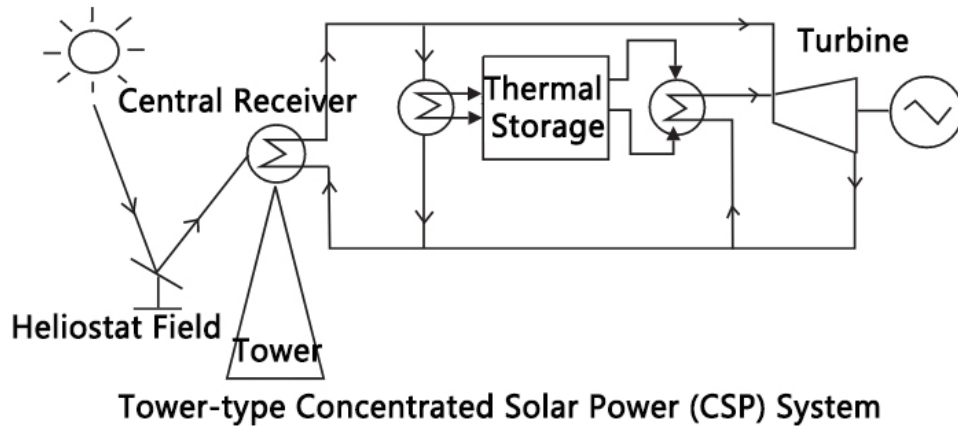


Fig 3. The principle of Solar Power Tower System

2.2.2. Dish Stirling System

The solar dish power generation system, also known as a dish-based CSP system, employs a dish-shaped parabolic concentrator for solar collection. Resembling a large parabolic radar antenna, the system achieves point-focus concentration with a concentration ratio ranging from several hundred to several thousand, generating high-temperature thermal energy for power production.

Similar to the heliostat operation in tower-based CSP systems, the mirrors of a dish system must continuously track the sun to reflect and concentrate sunlight onto the receiver of a Stirling engine. The concentrated radiation heats the working fluid within the receiver under point-focus conditions, and the resulting high-temperature thermal energy drives the Stirling engine to produce electricity.

Professor Mei Shengwei of Tsinghua University has proposed a fourth-generation solar power technology—the novel dish-based thermoacoustic power generation system—which achieves an efficiency of 32%. This system integrates compressed-air energy storage, provides combined cooling–

heating–power supply, and features completely silent operation and zero emissions.

2.2.3. Parabolic Trough Concentrated Solar Power System

Unlike the point-focus configurations used in tower and dish systems, parabolic trough solar power plants adopt a line-focus geometry. A parabolic trough mirror concentrates sunlight onto a linear focal axis, where a tubular receiver (heat-collection element) is installed to absorb the concentrated solar radiation. The heat-transfer fluid flowing inside the tube is heated to high temperatures and then passes through a heat exchanger to produce steam, which subsequently drives a steam turbine for power generation.

This type of system operates continuously throughout the day by tracking the sun from east to west. The collector axis is arranged in the north–south direction, parallel to the focal line. Such a one-dimensional solar-tracking mode is relatively simple to implement and provides high optical efficiency. The principle of parabolic trough concentrated solar power system are illustrated by figure 4 [9].

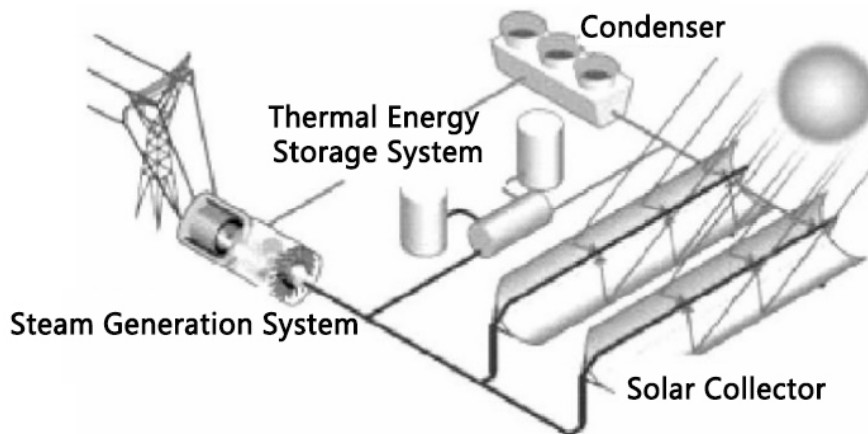


Fig 4. The principle of Parabolic Trough Concentrated Solar Power System

3. Pattern Analysis

3.1. Co-Located, Distributed Arrangement

As shown in the figure 5, a co-located, distributed PV–CSP coupling mode (also known as series coupling) is illustrated

using a tower-type CSP system combined with a supercritical CO₂ Brayton cycle as the power cycle [10]. In this system, the heliostat field concentrates sunlight onto the receiver at the top of the tower, where the solar energy is converted into heat and transferred to the working fluid. The high-temperature fluid then passes through a heat exchanger to charge a thermal

storage tank, storing excess thermal energy when solar irradiance is sufficient. When solar irradiance decreases or the load increases, the thermal storage system releases heat to the working fluid entering the supercritical CO₂ Brayton cycle. In this cycle, CO₂ is compressed, then heated in the receiver,

driving the gas turbine to expand and generate electricity via the generator. The expanded working fluid is cooled and recirculated, completing a closed-loop energy conversion process.

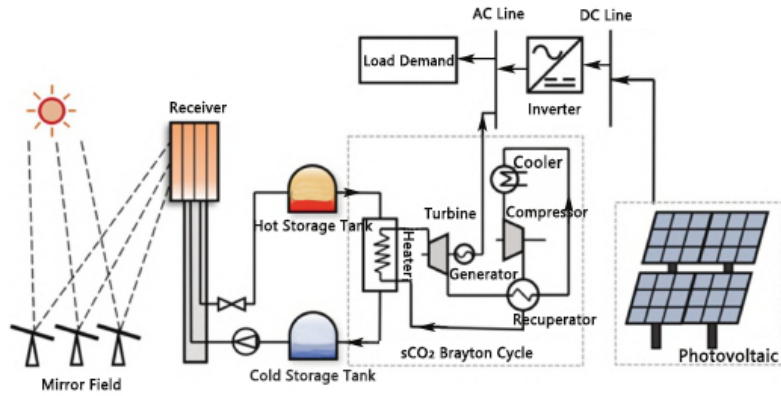


Fig 5. PV-CSP series coupling

Simultaneously, PV modules convert solar radiation directly into DC electricity, which is inverted to AC via inverters. The CSP output is electrically coupled at the DC bus, and both PV and CSP power are unified through the inverter for grid connection.

From a power-generation strategy perspective, the PV system and the CSP-thermal storage system form a temporal complement: PV generates high power during daytime with strong irradiance, while the CSP system can utilize stored heat to generate electricity when PV output is insufficient or during evening hours. This ensures smoother power output and enhances system reliability.

The series-coupled configuration is relatively simple and

easy to control, with coupling occurring only on the electrical side. It offers high system integration and relatively low cost. The introduction of thermal storage provides some dispatchability and delayed power output, partially mitigating PV-induced fluctuations. However, energy interaction between PV and CSP remains limited, and the overall synergy improvement is modest. Therefore, this mode is most suitable for small- to medium-scale grid-connected hybrid power systems aimed at enhancing solar utilization and peak-shaving/load-filling.

3.2. Deep Coupling

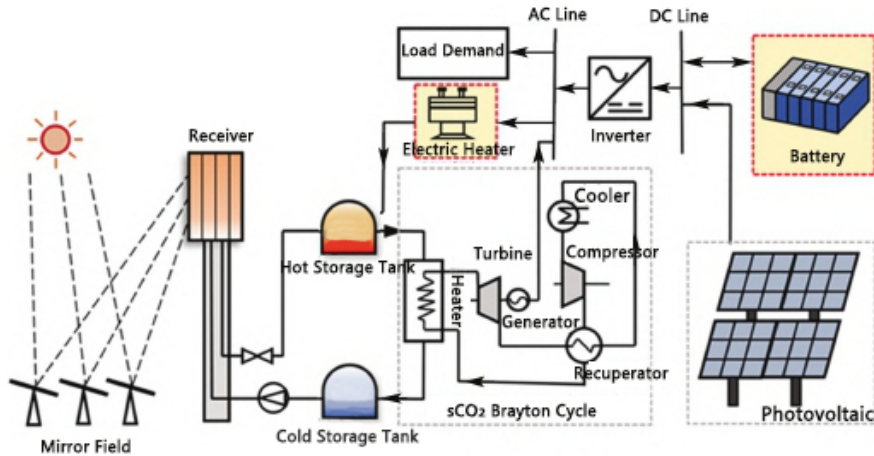


Fig 6. PV-CSP Deep coupling

The system illustrated in figure 6 represents a deep coupling mode between tower-type concentrated solar power (CSP) and photovoltaic (PV) generation (Deep Coupling Mode) [10]. On the original configuration, it introduces an electric heater and a battery energy storage system, enabling bidirectional energy conversion and deep coordination between electricity and heat.

The PV array converts solar radiation directly into DC electricity, which is inverted to AC to meet load demand, with any surplus charging the battery storage system. If the battery is fully charged and PV generation is still in excess, the extra electricity can be converted into heat via the electric heater

and stored in the CSP thermal storage tank. When solar irradiance decreases or load increases, the thermal storage system releases heat to drive the Brayton cycle, while the battery can simultaneously discharge to support the load, achieving dual energy compensation through “electric-heat-electric” and “electric-electric” pathways. Through coordinated optimization of the control system, PV, electric heater, thermal storage, and battery storage form bidirectional energy flows and dynamic balance, constructing a highly efficient and stable multi-energy complementary power system.

Compared with simple coupling modes, the deep coupling

system achieves an organic integration of PV and CSP at the energy level, offering significant advantages: first, surplus PV electricity can be fully absorbed and converted into thermal energy for storage, enhancing PV utilization and overall energy efficiency; second, the combination of battery and thermal storage enables short-term and long-term energy regulation, effectively smoothing power fluctuations and improving peak-shaving and load-following capability; third, the system output is more stable and reliable, with stronger dispatchability and continuous power supply capability [11, 12]. However, this mode involves a more complex system structure, requires sophisticated control strategies, and entails higher initial investment. Overall, the deep-coupled PV–CSP system, through dual electric–thermal storage and bidirectional energy coupling, significantly improves renewable energy utilization and system operational stability, representing a key technical pathway for high-penetration renewable grid integration and around-the-clock power supply.

3.3. Land reuse

In terms of spatial layout, PV modules can be installed in the gaps between heliostats, forming a three-dimensional “PV + heliostat” arrangement. The key to this configuration lies in properly designing the mirror tilt angles and the installation height of PV modules to avoid mutual shading and reflective interference.

This approach enables land reuse and significantly enhances both the spatial utilization efficiency and overall energy capture of the system. Studies have shown that, under optimized layout conditions, this configuration can increase the annual electricity generation per unit area by approximately 25%–35%, substantially improving land energy yield density and overall system benefits [13].

4. Key Technologies

4.1. Fresnel Concentrating Technology

The power generation capabilities of both PV and CSP systems are fundamentally limited by solar irradiance flux density. There are two main approaches to address the issue of low irradiance flux: concentrating sunlight to increase flux density, or expanding the PV panels or heliostat field to collect more solar radiation. The former reduces the land footprint of the power plant but increases equipment investment and thermal load on the system, imposing higher requirements on system reliability. The latter is simpler to implement, requires lower investment, and imposes less stringent reliability requirements, but it increases land use and environmental impact. In the short term, the latter option is more economically favorable; however, in the long term, the former approach is clearly advantageous for improving solar energy utilization and reducing costs.

As the core component of a thermal collection system, the concentrator’s optical performance, structural characteristics, and operational stability directly determine the system’s energy conversion efficiency and economic viability. Solar concentrators should meet the following requirements :

(1). High reflectivity and concentration ratio to maximize effective collection of solar radiation. High-quality reflective materials, such as silvered or aluminized glass mirrors, typically exhibit reflectivity above 0.9, significantly reducing optical losses. Moreover, concentrators must maintain high optical precision, with surface shape errors, installation errors,

and tracking errors controlled within a few milliradians to ensure stable energy density at the focal spot [14].

(2). Sufficient stiffness and wind resistance to withstand long-term deformation caused by wind loads and temperature gradients. The supporting structure should be lightweight, corrosion-resistant, and capable of maintaining optical performance under complex climatic conditions. To improve incidence-angle matching, concentrators must be equipped with high-precision solar tracking systems; for high-concentration systems, tracking errors are generally required to be below 0.1° .

(3). Stable focal position and energy concentration to ensure uniform heating of the receiver or heat-absorption tube, minimizing radiation and convection losses [15]. Additionally, the system should have good thermal matching capability to meet the required temperature levels of different concentrator types, e.g., 300–400 °C for parabolic trough systems and up to 1000 °C for tower systems [14]. Finally, the concentrator’s economic feasibility and maintainability are also critical. The structural design should facilitate manufacturing, transportation, and assembly; mirrors should be easy to clean and resistant to aging, with a design lifetime generally exceeding 20 years.

As shown in the figure 7 is the physical object of the Fresnel lens and a brief introduction to its principle [16].

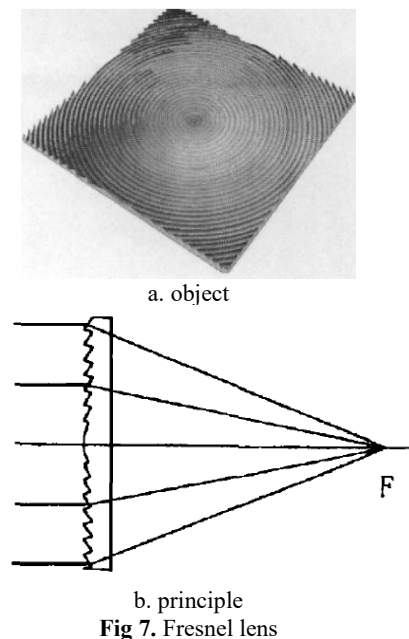


Fig 7. Fresnel lens

Currently, mainstream solar concentrators primarily employ Fresnel lens or mirror technologies. In the 1970s, NASA provided a detailed exposition on Fresnel lens design methods and lens transmittance, laying the groundwork for subsequent research.

In 1979, Kritchman developed a high-concentration, curved-line focusing Fresnel lens through extensive experimentation to improve optical efficiency and concentration ratio [17]. In 1980, he further refined the structure of this technology and, through additional experimental testing and data analysis, demonstrated further improvements in both optical efficiency and concentration performance, paving the way for future applications of Fresnel lenses [18].

Lorenzo summarized methods for optical calculation of Fresnel lenses with various shapes, marking a new beginning

in the field of Fresnel lens optical design and concentrator performance computation [19].

4.2. Spectral Splitting Technology

PV cells can only convert solar radiation within specific spectral bands, while the radiation in other spectral ranges is dissipated as waste heat within the cells, leading to significant thermal load. Moreover, in concentrated PV systems, the concentration ratio often ranges from tens to hundreds, further increasing the cooling demand on the PV cells. Typically, the waste heat from PV cells can be removed and partially utilized by installing a cooling system that transfers heat via a working fluid. However, due to the introduction of the heat transfer medium and the temperature limitations imposed by the PV cell operating range, the thermal utilization efficiency remains low. In addition, the waste heat generated by PV cells is of relatively low quality (low-grade energy).

Spectral splitting technology effectively addresses these issues. This approach allows solar radiation to be distributed according to different spectral bands. In a three-dimensional arrangement of PV panels and reflectors, sunlight within the PV-conversion spectrum can be directed to the PV cells, while the remaining spectral components are directed to the thermal reflectors. This reduces the thermal load on PV cells at the source, and decouples the PV conversion process from the thermal conversion process. Consequently, the land footprint of PV-CSP plants can be reduced, and high-grade energy can be utilized more efficiently. The thermal system can also achieve higher temperatures and improved thermal efficiency compared with conventional PV cooling systems.

Wang Botong and colleagues addressed the problem of PV efficiency reduction due to heating by ineffective radiation, proposing a compact, high solar-to-electric conversion efficiency system that integrates spectral splitting PV with concentrated solar thermal utilization [20].

5. Engineering Application

Typical commercial projects include the Noor Energy 1 (DEWA IV) integrated power plant in Dubai, UAE, with a total capacity of 950 MW, comprising 700 MW of CSP (including central tower and parabolic trough configurations with 15-hour molten salt thermal storage) and a 250 MW PV array operating in tandem. It is one of the largest PV-CSP hybrid plants in the world. Another example is the Solgest-1 project by Sener in Spain, where PV modules were added to an existing CSP site to create a peak-shaving system with shared PV and thermal storage. These demonstration projects have validated the theoretical concepts in practice, showing that PV-CSP hybrid schemes can maintain high renewable penetration while providing power output stability comparable to conventional thermal power.

Overall, PV-CSP hybrid generation is emerging as a key development direction for future high-renewable-power systems. With the continuous decline in PV costs and the maturation of CSP thermal storage technologies, the deep integration of the two is expected to enable more efficient and dispatchable renewable energy plants in the future.

6. Prospects and Challenges

6.1. Hydrogen Production from Renewable Energy

In the future, the synergy of PV and CSP can significantly

enhance the efficiency and economic viability of solar-driven hydrogen production systems. PV electricity can directly power electrolyzers, while the waste heat generated by PV panels can be recovered by thermal components or interfacial evaporation devices to preheat water or raise the temperature of the electrolyzer, thereby reducing electrolysis energy consumption. This strategy, known as full-spectrum solar utilization, enables higher solar-to-hydrogen (STH) conversion efficiency [21]. For example, studies have reported that coupling PV panels with thermal distillation devices can achieve an STH efficiency of approximately 12.6%, while simultaneously cooling the PV panels through thermal recovery and distilling seawater for electrolysis [22].

Based on this mechanism, large-scale deployment in the future could enable efficient and low-cost green hydrogen production. By dynamically coordinating PV and thermal systems to respond to solar irradiance fluctuations and varying electrolysis loads, system stability and investment returns can be further improved.

6.2. Seawater Desalination

PV-CSP hybrid systems also offer a sustainable and self-sufficient pathway for seawater desalination and hydrogen production in coastal regions. By integrating concentrated solar power (such as molten salt tower CSP) with multi-stage flash (MSF) or reverse osmosis (RO) desalination units, a combined water-heat-power tri-generation system can be realized [23]. Studies on solar-thermal-seawater desalination coupling have explored flexible design optimization, proposing a two-layer algorithm and a flexibility index evaluation method to minimize annual total costs while ensuring continuous operation under variable weather conditions [24].

When such systems are further integrated with PV generation, PV provides electricity to support desalination and electrolysis-based hydrogen production, while the solar-thermal component supplies heat for distillation and desalination. This coupling not only reduces fossil fuel consumption in desalination processes but also significantly lowers CO₂ emissions. Aligned with national energy policies promoting the integration of renewable energy and green hydrogen (e.g., the “wind-solar-hydrogen-ammonia-alcohol integrated” bases), this synergistic approach holds strong industrialization potential and is expected to serve as a key infrastructure for green energy and freshwater supply in ports, islands, and ecologically sensitive coastal areas.

7. Conclusion

PV/CSP technology integrates the advantages of each individual unit, providing both thermal and electrical energy while enhancing the power generation efficiency of PV cells, thus offering substantial development potential. Moreover, as a clean energy source, solar power generates electricity without producing pollutants or greenhouse gases, contributing to the achievement of “dual carbon” (carbon peak and carbon neutrality) targets. Based on this perspective, this paper reviews the technologies and significance of PV/CSP hybrid power generation under China’s “dual carbon” policy framework.

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