

Advancements in Solar Energy Technologies and Their Multifaceted Applications: A Comprehensive Review Towards Sustainable Energy Transition

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Received: 11.06.2026 | Accepted: 06.07.2026 | Published: 16.07.2026

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DOI: [10.5281/zenodo.21387910](https://doi.org/10.5281/zenodo.21387910)

Abstract

Review Article

Solar energy stands as one of the most promising renewable energy sources, offering a clean, abundant, and increasingly cost-effective alternative to fossil fuels. This review paper explores the fundamental principles, technological advancements, and diverse applications of solar energy systems, including photovoltaic (PV) and concentrated solar power (CSP) technologies. It examines global deployment trends, efficiency improvements, integration challenges, and sector-specific applications in electricity generation, heating, agriculture, transportation, desalination, and space exploration. Drawing on recent data (up to 2025-2026), the paper highlights how solar capacity has surged, with global PV installations exceeding 2 TW and record additions in 2025. Key barriers such as intermittency, land use, and grid integration are discussed alongside solutions like energy storage and hybrid systems. The review underscores solar energy's pivotal role in achieving sustainable development goals, projecting continued growth and innovation.

Keywords: Solar energy, Photovoltaic (PV), Concentrated Solar Power (CSP), Renewable applications, Energy storage, Sustainable development, Agrivoltaics, Desalination.

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1. Introduction

The global energy landscape is undergoing a profound transformation driven by the urgent need to mitigate climate change, reduce greenhouse gas emissions, and ensure energy security. Solar energy, derived from the sun's radiation, provides an inexhaustible resource capable of meeting global energy demands many times over. The Earth's surface receives approximately 173,000 terawatts of solar energy continuously, vastly exceeding current

human consumption [1].

Solar technologies are broadly categorized into two main types:

Photovoltaic (PV): Direct conversion of sunlight into electricity using semiconductor materials.

Concentrated Solar Power (CSP): Uses mirrors to concentrate sunlight for thermal energy, which drives turbines for electricity or provides process heat [2]. Recent years have witnessed exponential



Citation: Nimbalagundi, S. M., Poleshi, S. N., & Bagawan, A. S. (2026). Advancements in solar energy technologies and their multifaceted applications: A comprehensive review towards sustainable energy transition. *Global Academic and Scientific Journal of Multidisciplinary Studies (GASJMS)*, 4(7), 25-30.

growth. By the end of 2024-2025, global solar PV capacity surpassed 2 TW, with massive additions in China, India, the US, and Europe. In the first half of 2025 alone, the world added around 380 GW of new solar capacity. This growth is fueled by plummeting costs, policy support (e.g., tax credits, feed-in tariffs), and technological maturation [3]. This paper provides a comprehensive review of solar energy applications, supported by diagrams, tables, and data, while addressing challenges and future prospects.

2. Solar Energy Technologies

2.1 Photovoltaic Systems

PV cells, primarily silicon-based (monocrystalline, polycrystalline), convert photons into electrons via the photovoltaic effect. First-generation crystalline silicon dominates (~90% market share), with efficiencies of 15-22%. Emerging technologies include thin-film (CdTe, CIGS), perovskites, and multi-junction cells for higher efficiencies (up to 25-30% in labs) [4].

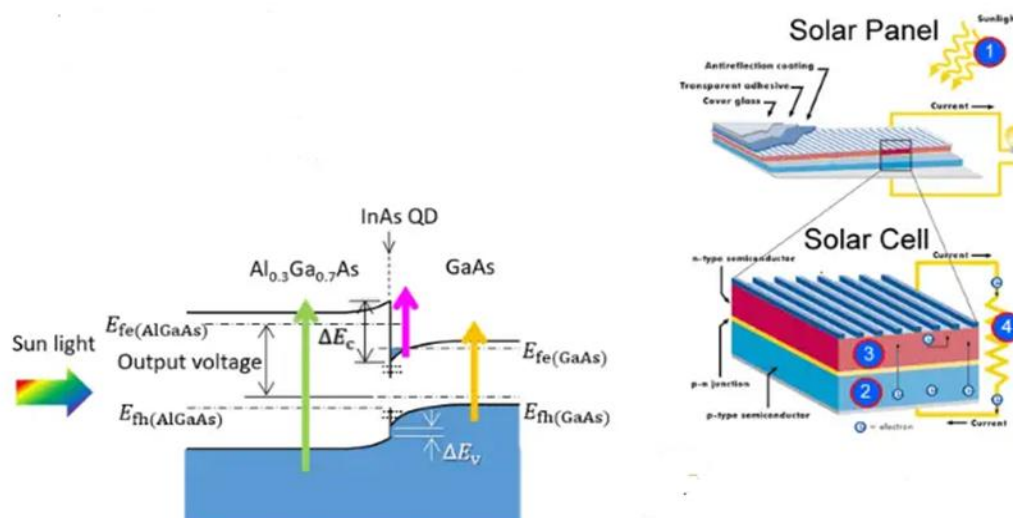


Diagram 1: Working Principle of a Solar PV Cell (Conceptual description; imagine a layered diagram):

- Top: Anti-reflective glass and grid contacts.
- Middle: P-N junction semiconductor where light generates electron-hole pairs.
- Bottom: Back contact.

Sunlight → Excitation → Current flow through external circuit.

(For visual: A standard schematic shows photons striking the cell, separating charges, and generating DC electricity converted to AC via inverters.) PV systems include rooftop (distributed), utility-scale ground-mounted, and floating PV. Agrivoltaics combines PV with farming [5].

2.2 Concentrated Solar Power (CSP)

CSP technologies include parabolic troughs, solar towers (central receivers), linear Fresnel, and parabolic dishes. They achieve higher temperatures (up to 1000°C) for efficient steam generation and include thermal energy

storage (TES) using molten salts for dispatchable power [6].

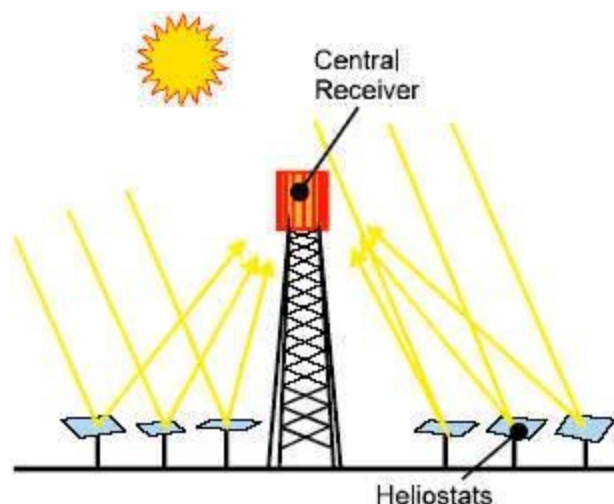


Diagram 2: Types of CSP Systems

- *Parabolic Trough: Curved mirrors focus on a receiver tube.*
- *Solar Tower: Heliostats focus on a central tower.*
- *Others: Fresnel (flat mirrors), Dish (Stirling engine).*

CSP excels in utility-scale with storage, offering capacity factors of 30-55% vs. PV's ~20-25% without storage [7].

2.3 Hybrid and Emerging Systems

PV-T (photovoltaic-thermal) hybrids produce electricity and heat. Perovskite tandems and bifacial modules boost yields. Space applications use high-efficiency multi-junction cells [8].

3. Global Status and Statistics

Table 1: Global Solar PV Capacity and Additions (Approximate, based on recent data)

Year/Period	Cumulative Capacity (GW)	Annual Additions (GW)	Key Regions
End 2024	~2,000+	-	China dominant
H1 2025	-	380	China, India, US, EU
2025 (proj.)	~2,300-2,800	500+	Record growth

Utility-scale dominates new installations, but distributed PV (rooftop) grows rapidly for energy independence.

Table 2: Comparison of PV vs. CSP

Attribute	PV	CSP
Efficiency (system)	15-22%	15-40% (with TES)
Cost (approx. \$/W)	0.5-1.5	Higher (3-8 initially)
Storage Capability	Batteries (expensive)	Thermal (cost-effective)
Land Use	Flexible, agrivoltaics	High DNI deserts preferred
Dispatchability	Intermittent	Excellent with TES

4. Applications of Solar Energy

4.1 Electricity Generation

Primary application: Grid power, off-grid, and microgrids. Utility-scale plants power cities; residential systems reduce bills via net metering.

4.2 Solar Thermal Applications

Water heating, space heating/cooling, industrial process heat (food processing, textiles). Solar cookers and dryers in developing regions [9].

4.3 Agriculture (Agrivoltaics)

Solar-powered irrigation pumps, drying crops, greenhouse climate control, and dual-use land for PV + crops/livestock. Reduces water evaporation and provides shade [10].

- Irrigation pumping
- Solar drying of grains/fruits
- Refrigeration for produce
- Electric fencing and lighting
- Pest control and monitoring sensors

4.4 Transportation

Solar-powered EV charging stations, solar roofs on vehicles, solar buses/trains. Supports sustainable logistics. Solar-powered transportation creates a sustainable future for the automotive industry, addressing climate change and environmental issues.

Integrating solar technology into transportation offers a promising solution. This paradigm shift towards solar-powered vehicles reflects our commitment to reducing carbon footprints and reliance on traditional fuels [11].

4.5 Desalination and Water Treatment

Solar thermal or PV-powered reverse osmosis for fresh water in arid regions. Critical for climate resilience [12].

4.6 Space and Specialized Applications

High-efficiency solar and spacecraft. Radiation-resistant arrays for satellites cells. Understanding the space environment and its effects on space vehicles is of paramount importance for the successful design and operation of SCs for different space missions. According to the NASA Marshall Space Flight Center, the space environment can be described through seven components [13].

4.7 Other: Building-Integrated (BIPV), Portable Systems

Façades, windows, and consumer electronics.

5. Challenges and Explanations

- Intermittency: Addressed by batteries, TES, and hybrid renewables.

- Land Use and Environment: Agrivoltaics and recycling mitigate impacts.
- Grid Integration: Requires smart grids and flexibility.
- Costs and Policy: Declining but upfront investment high; incentives key [14].

Efficiency losses from temperature, dust, shading explained via performance ratio metrics (typically 75-85%).

6. Conclusion:

Solar energy applications have matured into versatile tools for decarbonization across sectors. With continued innovation in materials, storage, and integration, solar will play a central role in the global energy transition. Policymakers, researchers, and industry must collaborate to overcome remaining barriers, ensuring equitable access and maximizing socio-economic benefits. The future is bright, with projections indicating solar could supply a significant portion of world energy by 2050.

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