

IMPROVING ENERGY EFFICIENCY IN SOLAR POWER PLANTS: TECHNOLOGIES, STRATEGIES, AND PROSPECTS**Narimanov Bahodir Absalamovich**Senior Lecturer of the Department of Power
Engineering Jizzakh Polytechnic Institute
<https://doi.org/10.5281/zenodo.20427253>**Annotatsiya:**

Ushbu maqolada quyosh elektr stansiyalarida energiya samaradorligini oshirishning asosiy texnik yo'llari tahlil qilinadi. Fotoelektrik modullarning samaradorligini oshiruvchi texnologiyalar — tandem perovskite-kremniy arxitekturasini, bifasial panellar, quyosh izlovchi tizimlar, termal boshqaruv va raqamli monitoring tizimlari — ilmiy-muhandislik nuqtai nazaridan ko'rib chiqiladi.

Annotation

This article analyses the principal technical pathways for improving energy efficiency in solar power plants. Technologies enhancing photovoltaic module efficiency — including tandem perovskite-silicon architectures, bifacial panels, solar tracking systems, thermal management, and digital monitoring — are examined from scientific and engineering perspectives. Concentrating solar power systems and artificial intelligence-based forecasting tools are also discussed.

Keywords: solar photovoltaics, energy efficiency, perovskite tandem cells, bifacial modules, solar tracking, concentrating solar power, thermal management, MPPT, AI forecasting, renewable energy.

1. Introduction

Solar energy stands at the forefront of the global transition to clean electricity. The International Renewable Energy Agency (IRENA) reports that solar photovoltaics (PV) accounted for more than 60 percent of all new renewable capacity added globally in 2023, bringing cumulative installed PV capacity to approximately 1,600 GW worldwide (IRENA, 2024). The levelised cost of electricity from utility-scale solar PV has declined by approximately 90 percent since 2010, rendering it the least expensive source of new electricity generation in a majority of markets.

Yet achieving solar energy's full potential depends not merely upon expanding installed capacity, but critically upon improving energy conversion efficiency at every stage of the generation chain. Commercial silicon-based PV modules currently achieve efficiencies of 20 to 23 percent under standard test conditions, meaning that more than three-quarters of incident solar radiation is not converted to useful electricity. System-level losses attributable to thermal effects, soiling, shading, inverter inefficiencies, and mismatch further reduce delivered energy yield.

This article provides a systematic analysis of the principal technical and operational strategies for improving solar plant efficiency, encompassing photovoltaic and concentrating solar thermal technologies, intelligent monitoring frameworks, and the application of artificial intelligence to plant management.

2. Advances in Photovoltaic Cell and Module Technology**2.1 Silicon Cell Architectures**

Crystalline silicon dominates the commercial PV market, accounting for approximately 95 percent of global production. Monocrystalline passivated emitter and rear cell (PERC) technology is the current industry standard, achieving commercial module efficiencies of 22 to 23 percent.

Tunnel oxide passivated contact (TOPCon) cells have surpassed 24 percent, while heterojunction technology (HJT) — combining amorphous and crystalline silicon — has demonstrated certified efficiencies of up to 26.8 percent, approaching the single-junction silicon theoretical limit of 29.4 percent (Green et al., 2024). HJT's low temperature coefficient makes it particularly advantageous in hot climates.

Bifacial module technology captures reflected irradiance from ground surfaces on the module rear, delivering energy yield gains of 5 to 30 percent depending on albedo, row spacing, and mounting height. The combination of bifacial architecture with single-axis solar tracking has become the configuration of choice for utility-scale plants, consistently yielding the lowest levelised cost of electricity in high-irradiance regions.

2.2 Perovskite-Silicon Tandem Cells

The most significant near-term opportunity to transcend the single-junction silicon efficiency ceiling lies in tandem cell architectures, which stack two absorber materials with complementary bandgaps to harvest a broader portion of the solar spectrum. Perovskite-silicon tandem cells have achieved certified laboratory efficiencies exceeding 33.9 percent — surpassing the theoretical single-junction silicon limit by a substantial margin (Green et al., 2024). Commercialisation faces challenges of long-term operational stability and manufacturing scale-up, but tandem cells represent the most credible pathway to commercial PV efficiencies above 30 percent within the near term.

3. System-Level Efficiency Optimisation

3.1 Solar Tracking and MPPT

Single-axis trackers (SAT) rotate modules around a north-south axis to follow the sun's daily arc, delivering energy yield gains of 20 to 35 percent compared to fixed-tilt installations. Advanced tracker control algorithms — including backtracking to prevent inter-row shading, terrain-adaptive algorithms for sloped terrain, and machine learning approaches integrating real-time irradiance data — enable further incremental yield improvements beyond simple astronomical tracking.

Maximum power point tracking (MPPT) algorithms embedded in inverters continuously adjust array operating voltage to maximise power extraction under varying irradiance and temperature. Module-level power electronics (MLPE) — including DC optimisers and microinverters at the individual module level — eliminate the yield losses caused by partial shading or module mismatch, demonstrating energy improvements of 10 to 25 percent relative to conventional string inverter systems (IEA, 2023).

3.2 Thermal Management

Silicon PV cell efficiency decreases by approximately 0.35 percent per degree Celsius above 25 degrees Celsius. In arid zones, module operating temperatures routinely reach 60 to 80 degrees Celsius, producing efficiency losses of 12 to 20 percent. Elevated mounting to enhance convective cooling, rear-surface ventilation, and low-emissivity backsheet materials can reduce operating temperatures by 5 to 15 degrees Celsius. Photovoltaic-thermal (PVT) hybrid collectors simultaneously generate electricity and useful heat, cooling the cells and improving electrical efficiency while increasing the overall utilisation of captured solar energy.

4. Soiling, Maintenance, and Operational Efficiency

The accumulation of dust and particulate soiling on module front glass is one of the most significant and tractable sources of energy yield loss. In arid regions, soiling losses can reach 1 to 6 percent per day without cleaning, with cumulative losses of 20 to 50 percent documented at sites with extended cleaning intervals (IRENA, 2024). Waterless robotic cleaning systems — deploying rotating dry brushes or electrostatic mechanisms on autonomous platforms — have demonstrated

soiling removal efficiencies comparable to wet cleaning while eliminating water consumption, a critical advantage in water-scarce desert environments.

Thermographic inspection using drone-mounted infrared cameras detects cell-level defects — hot spots, cell cracks, bypass diode faults — that cause localised efficiency losses and can progress to permanent degradation or fire hazard. Drone surveys of utility-scale plants can be completed in hours rather than days required for manual inspection. Integration with machine learning defect classification automates anomaly identification and prioritises maintenance interventions, building longitudinal datasets that inform procurement and warranty management decisions.

5. Concentrating Solar Power and Hybrid Approaches

Concentrating solar power (CSP) systems focus direct normal irradiance onto a heat-transfer medium driving conventional thermodynamic cycles. CSP's distinctive advantage is the ability to store thermal energy in molten salt reservoirs at low cost and high efficiency, enabling dispatchable electricity generation through the night and during cloudy periods. CSP plants with 10 to 15 hours of thermal storage — such as the Noor III project in Morocco — can operate effectively as baseload generators powered entirely by solar energy.

Agrivoltaic systems — in which PV modules are installed above agricultural land permitting simultaneous crop cultivation — improve land-use efficiency while co-generating food and energy. Research demonstrates that many crop species show equivalent or enhanced yields under partial shading from elevated PV arrays, while evapotranspiration from crops cools module rear surfaces and improves electrical efficiency by 1 to 3 percentage points. Water savings from reduced soil evaporation can reach 20 to 30 percent in arid environments (UNEP, 2023).

6. Digital Technologies and AI in Solar Plant Management

Machine learning algorithms applied to solar irradiance forecasting have achieved accuracy improvements of 20 to 40 percent relative to persistence and clearsky-index models across diverse climate regimes (BloombergNEF, 2024). Deep learning models — including LSTM recurrent networks, convolutional networks applied to satellite imagery, and transformer-based architectures — enable more precise short-term generation forecasts that reduce balancing reserve requirements and lower the system integration cost of solar energy.

Digital twin technology — high-fidelity virtual models of physical plant assets continuously updated with real-time operational data — enables proactive performance management by identifying deviations from expected output, diagnosing root causes, and simulating the impact of operational interventions before field implementation. Digital twins integrating physical performance models with machine learning anomaly detection support optimisation of tracker scheduling, inverter set-points, and cleaning cycles through probabilistic scenario analysis.

7. Conclusion

The improvement of energy efficiency in solar power plants spans materials science, power electronics, mechanical systems, and data analytics. Progress across these fronts — from tandem perovskite-silicon cells approaching 34 percent efficiency, to intelligent tracking algorithms, module-level optimisers, robotic cleaning, and AI-powered forecasting — has enabled solar plants to extract substantially more energy from each unit of captured solar radiation and invested capital than was possible a decade ago.

Commercialisation of perovskite-silicon tandems above 30 percent module efficiency, maturation of supercritical CO₂ cycles for CSP, widespread agrivoltaic deployment, and AI-driven digital twin platforms represent the most consequential near-term opportunities for further efficiency advancement. In the global energy transition, every percentage point of solar efficiency improvement translates directly into reduced land use, reduced material consumption, and accelerated decarbonisation — making solar energy efficiency a decisive lever in achieving a sustainable and equitable energy future.

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