


Chapter 6

Enhancing Solar Cell Efficiency: AI Solutions for Sustainable Energy

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ABSTRACT

This study explores the integration of nanotechnology and artificial intelligence (AI) to enhance solar photovoltaic (PV) system performance. A simulation-based methodology was applied to a 3 kW rooftop system in Ludhiana, Punjab, using quantum dots and carbon nanotubes to improve light absorption and charge transport. AI models, including artificial neural networks (ANN), were employed for energy forecasting and real-time optimization. Results show a 22% increase in annual energy output for the nano-enhanced system over conventional PV, with improved accuracy under variable weather conditions. The ANN model achieved high prediction accuracy ($R^2 = 0.985$), while AI-assisted MPPT improved power tracking efficiency. This hybrid approach demonstrates significant potential for scalable, efficient, and climate-resilient solar systems suitable for smart grids and decentralized applications in semi-urban regions. The findings support the advancement of intelligent, material-optimized renewable energy systems aligned with sustainability goals.

INTRODUCTION

The global energy landscape is undergoing a rapid transformation as the need for clean, reliable, and sustainable energy sources becomes increasingly urgent.

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Rising carbon emissions, energy insecurity, and climate change have accelerated the transition away from fossil fuels toward renewable energy systems. Among the various renewable options, solar energy stands out for its abundance, scalability, and environmental friendliness. According to the International Energy Agency (IEA,2024), global solar photovoltaic (PV) capacity surpassed 1,200 GW in 2024, making it the fastest-growing renewable energy source. However, despite its promise, conventional silicon-based solar cells are limited by factors such as high production costs, low efficiency under diffused light, and material degradation over time (Di Sabatino et al., 2024).

Improving the efficiency and reliability of solar cells is critical to maximizing energy yield and ensuring widespread adoption. One emerging solution lies in the integration of nanotechnology into PV systems. Nanostructured materials like quantum dots, perovskites, and carbon nanotubes offer superior light absorption, enhanced charge transport, and flexibility in design, allowing solar cells to overcome many of the limitations of traditional technologies, (Yadav & Sharma, 2021; Park et al., 2022). These materials can significantly increase the power conversion efficiency (PCE) of solar modules, making solar energy more cost-effective and practical for large-scale deployment (Green et al., 2023). In parallel, advancements in artificial intelligence (AI) and computational modeling have provided powerful tools for optimizing solar system design and operation. AI algorithms can simulate real-world conditions, predict system performance, and adapt parameters dynamically to maximize energy output (Shaban et al., 2024). When combined with nanomaterials, these intelligent simulations enable researchers and engineers to design next-generation PV systems that are not only more efficient but also more resilient to environmental variability. This chapter explores the combined role of nanotechnology and AI-based simulation in enhancing solar cell efficiency. It presents a simulated case study based on environmental data from Ludhiana, Punjab, and evaluates the system's performance over a one-year period. The study also discusses the environmental and economic impacts of adopting such technologies, highlighting their potential contribution to global sustainability goals (Jathar et al., 2024; Di Sabatino et al., 2024).

Solar cells are categorized into three main generations based on material, technology, and efficiency as shown in figure 1. The first generation consists of crystalline silicon solar cells, including monocrystalline and polycrystalline types (Kazmerski, 2006). These are the most widely used and mature technologies, offering high efficiencies of 15–25% and durability. Monocrystalline cells are more efficient but expensive, while polycrystalline cells are cost-effective but slightly less efficient. The **second generation** includes thin-film solar cells like amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS). These are lightweight, flexible, and cheaper to produce, though they have lower efficiencies (6–20%) compared to first-generation cells. They are commonly used in building-

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