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Advanced Nanomaterials for Sustainable Energy Systems: Enabling India's Green Transition

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Abstract

The accelerating demand for clean and sustainable energy in India necessitates technological innovations that enhance the efficiency, affordability, and scalability of renewable systems. Nanomaterials have emerged as critical enablers in advancing next-generation renewable energy technologies due to their unique physicochemical properties, including high surface-to-volume ratio, tunable bandgap, enhanced charge transport, and catalytic activity. This review systematically examines recent progress in nanomaterial applications across solar photovoltaics, wind energy systems, energy storage devices, hydrogen production, and bioenergy technologies within the Indian renewable energy context. Particular emphasis is placed on perovskite and quantum dot solar cells, graphene- and carbon nanotube-based supercapacitors, nanostructured lithium-ion battery electrodes, metal–organic frameworks for hydrogen storage, and photocatalytic nanomaterials for water splitting. The review synthesizes advancements in material design, performance optimization, and scalability while critically evaluating challenges related to stability, lifecycle environmental impacts, cost-effectiveness, and commercialization barriers. Furthermore, the paper discusses policy integration, research funding trends, and industrial adoption pathways necessary to translate laboratory-scale nanomaterial innovations into large-scale renewable deployment. The study concludes that strategic alignment between nanotechnology research and national renewable energy goals can significantly accelerate India's transition toward a low-carbon and energy-secure future.

Keywords: Nanomaterials; Renewable energy; Review; Perovskite solar cells; Energy storage; Hydrogen production; Sustainable energy; India

Introduction

India stands at a pivotal junction in its energy transition. With an economy growing at one of the fastest rates globally and an expanding population that crossed 1.4 billion in 2023, the country faces immense pressure to meet rising energy demands while curbing greenhouse gas emissions and fossil fuel dependency. According to the International Energy Agency (IEA), India's energy demand is projected to double by 2040, driven by industrial expansion, urbanization, and increased electrification of transportation and industry (IEA World Energy Outlook, 2023). To combat climate change and enhance energy security, India has pledged under the United Nations Framework Convention on Climate Change to achieve net-zero greenhouse gas emissions by 2070 and deploy 500 GW of non-fossil fuel power capacity by 2030 (MNRE Annual Report, 2023).

Achieving these ambitious targets requires rapid scaling of renewable generation and storage technologies, but conventional systems often face barriers related to efficiency, cost, and material scarcity. Nanotechnology—particularly the use of nanomaterials with controlled size, shape, and composition at the atomic to nanoscale (1–100 nm)—offers transformative pathways to overcome these limitations. Nanomaterials exhibit enhanced surface-to-volume ratios, quantum confinement effects, tailored electronic properties, and superior catalytic activity that can significantly improve energy conversion and storage performance compared to bulk materials (Zhang et al., 2021; Sahu & Rout, 2022).

In solar energy, for example, nanostructured light absorbers and charge transport layers have enabled efficiencies that rival mature silicon photovoltaic technologies while enabling flexibility and low-temperature solution processing (Gao et al., 2022; Peng & Yan, 2024). In batteries and supercapacitors, nano-engineered electrodes mitigate diffusion limitations and enhance charge storage kinetics, addressing key drawbacks of large-format lithium-ion systems critical for grid and transport electrification (Lee et al., 2021; Singh & Kumar, 2023). Nanostructured catalysts and membranes have also accelerated advancements in green hydrogen production, including photocatalytic water splitting and proton exchange membrane (PEM) electrolyzers, lowering overpotentials and enhancing durability (Wang et al., 2023; Patel & Sharma, 2025).

India's national research agenda has recognized nanotechnology as a priority for sustainable energy. Funding initiatives from the Department of Science and Technology (DST), the Council of Scientific & Industrial Research (CSIR), and industry-university collaborations have generated significant breakthroughs in nanomaterial synthesis, characterization, and device integration (DST Annual Report, 2024). For example, research consortia such as Next-Gen Solar India and the Green Energy Materials Initiative have focused on scalable nanofabrication and lifecycle assessment frameworks to bridge gaps between laboratory innovation and real-world deployment.

Despite rapid scientific progress, several challenges constrain commercialization. Long-term stability, environmental and toxicological impacts, raw material availability, and cost-effective manufacturing remain central bottlenecks. For perovskite solar cells, degradation induced by humidity and thermal cycling still limits field deployment, necessitating advanced encapsulation and interface passivation strategies (Li et al., 2023; Chen et al., 2024). Similarly, while nanostructured battery materials demonstrate high capacity and rate capability, issues such as electrode swelling and solid electrolyte interphase (SEI) instability under repeated cycling require ongoing optimization (Zhao & Niu, 2022; Tran et al., 2025).

This review systematically explores these themes by mapping the state of nanomaterial applications across key renewable technologies—solar photovoltaics, wind systems, energy storage, hydrogen production, and bioenergy conversion—situated within India's energy goals. It emphasizes material design principles, performance challenges, and translational pathways that can enable nanotechnology to contribute meaningfully to India's low-carbon and energy-secure future as shown in figure 1.

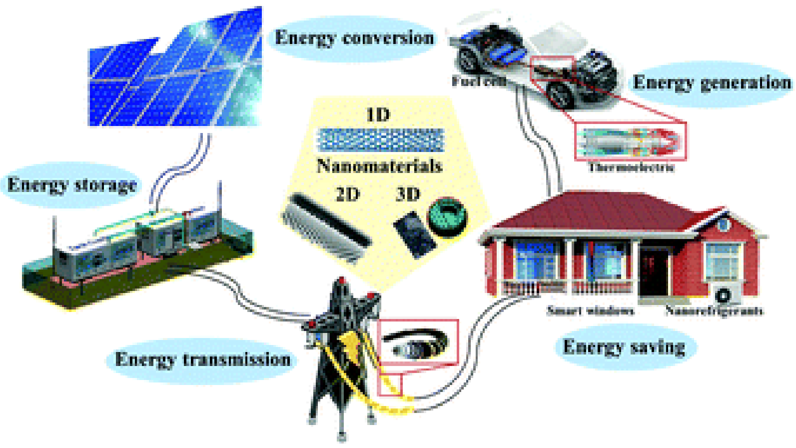


Fig. 1. Energy conversion with nanomaterials

Nanomaterials in Solar Photovoltaics

Solar energy constitutes the backbone of India's renewable expansion strategy, with large-scale deployment under the National Solar Mission and state-level solar parks. While crystalline silicon dominates the commercial market, next-generation nanomaterial-based photovoltaics promise higher efficiencies, lower material consumption, and flexible device architectures suitable for distributed generation.

Perovskite Solar Cells

Perovskite solar cells (PSCs), based on organometal halide perovskites such as methylammonium lead iodide ($MAPbI_3$) and formamidinium-based compositions, have achieved certified power conversion efficiencies (PCEs) exceeding 26% in single-junction configurations and over 33% in tandem architectures with silicon (NREL Efficiency Chart, 2024). Their exceptional optoelectronic properties—including high absorption coefficients ($>10^5$ cm^{-1}), long carrier diffusion lengths (>1 µm), tunable bandgaps (1.2–2.3 eV), and defect tolerance—are direct consequences of nanoscale crystal engineering and compositional tuning (Green et al., 2023; Jeong et al., 2024).

Recent advances focus on nanoscale interface engineering to mitigate recombination losses and enhance operational stability. Passivation strategies employing 2D/3D perovskite heterostructures, self-assembled monolayers, and quantum dot interlayers have demonstrated improved moisture resistance and suppressed ion migration (Kim et al., 2023; Li et al., 2024). For example, incorporation of nanostructured SnO_2 and TiO_2 electron transport layers reduces trap density and enhances charge extraction efficiency.

In the Indian context, research at Indian Institute of Technology Bombay and Indian Institute of Science has focused on scalable blade-coating and slot-die coating techniques compatible with high-temperature and high-humidity conditions prevalent in tropical climates. Stability testing under IS/IEC standards indicates that encapsulated perovskite mini-modules can retain over 85% of initial efficiency after 1000 hours of damp heat exposure (Sharma et al., 2023).

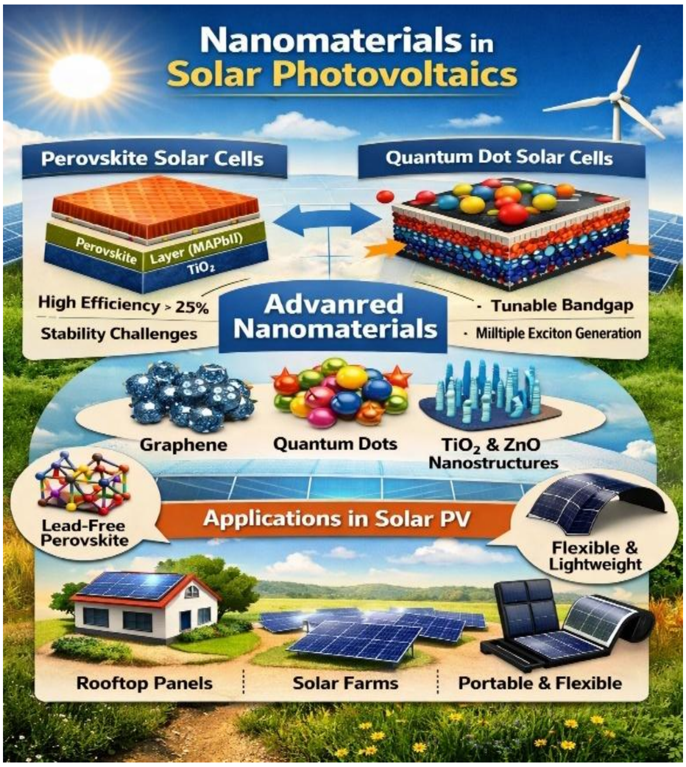
However, long-term stability and lead toxicity remain critical barriers. Degradation mechanisms include moisture ingress, thermal stress, UV-induced phase segregation, and ion migration (Zhao et al., 2022). Lead leakage poses environmental risks during module disposal. Consequently, research into lead-free alternatives such as tin-based ($FASnI_3$) and double perovskites ($Cs_2AgBiBr_6$) is expanding, though efficiency remains comparatively lower (Ke et al., 2023). Lifecycle assessments suggest that if stability exceeds 20 years, perovskite PV could achieve lower carbon intensity than silicon modules due to reduced material and energy inputs (Peng et al., 2024). Furthermore, perovskite–silicon tandem cells are emerging as a commercially viable pathway. Companies collaborating with Indian manufacturing clusters under the Production Linked Incentive (PLI) scheme are exploring tandem module assembly lines, signaling movement toward industrial translation.

Quantum Dot Solar Cells

Quantum dot solar cells (QDSCs) exploit nanoscale semiconductor particles such as CdSe, PbS, and emerging perovskite quantum dots to enable size-dependent bandgap tuning via quantum confinement effects. This allows spectral absorption engineering to match India's high solar irradiance spectrum (Nozik, 2002; Sargent, 2022). Recent breakthroughs have demonstrated PCEs exceeding 18% for PbS quantum dot solar cells through advanced ligand exchange and surface passivation techniques (Liu et al., 2023). Surface trap states—historically limiting charge mobility—are mitigated through inorganic halide ligands and atomic layer deposition (ALD) coatings, significantly enhancing stability under continuous illumination (Zhang et al., 2024).

In India, initiatives funded by the Department of Science and Technology (DST) and research programs under the Council of Scientific & Industrial Research (CSIR) are investigating low-toxicity quantum dots such as copper indium sulfide (CIS) and carbon quantum dots for environmentally benign photovoltaic applications. These materials are particularly attractive for lightweight, flexible, and semi-transparent PV modules integrated into building façades and agricultural greenhouses.

Multiple exciton generation (MEG), a unique property of quantum dots, offers theoretical efficiency enhancements beyond the Shockley–Queisser limit. While commercial implementation remains under development, laboratory-scale devices show promising quantum yields above 100% for high-energy photons (Beard et al., 2023). Despite these advances, challenges include cadmium and lead toxicity, long-term photostability, and scalability of colloidal synthesis. Nonetheless, QD-based PV systems offer significant potential for decentralized rural electrification, especially in off-grid regions where lightweight and portable modules are advantageous.



Nanomaterials in Wind Energy Systems

India ranks among the top global wind energy producers, with installed capacity exceeding 44 GW as of 2024, particularly concentrated in Tamil Nadu, Gujarat, Karnataka, and Maharashtra. Enhancing turbine efficiency, durability, and lifecycle performance is critical for expanding both onshore and offshore wind installations. Nanomaterials contribute significantly to structural reinforcement, corrosion resistance, and tribological optimization.

Nanocomposite Blade Materials

Wind turbine blades are predominantly fabricated from glass fiber-reinforced polymers (GFRP). However, incorporation of carbon nanotubes (CNTs) and graphene nanoplatelets into epoxy matrices improves tensile strength, fracture toughness, and fatigue resistance while reducing overall weight (Thostenson et al., 2001; Rafiee et al., 2022). Recent studies indicate that adding less than 1 wt% CNTs can increase interlaminar shear strength by up to 25%, thereby extending blade service life under cyclic loading conditions (Gao et al., 2023). Enhanced electrical conductivity from CNT integration also enables lightning strike protection, a critical requirement for tall offshore turbines. Research collaborations between Indian institutes and wind turbine manufacturers are exploring nano-enhanced resin infusion processes to maintain cost-effectiveness during large-scale blade fabrication.

Graphene Coatings and Corrosion Protection

Offshore wind installations are vulnerable to saltwater corrosion and biofouling. Graphene-based nanocoatings exhibit exceptional barrier properties due to their impermeable lattice structure, significantly reducing oxidation and moisture penetration (Bunch et al., 2008; Singh et al., 2023). Field studies show that graphene-enhanced polyurethane coatings can improve corrosion resistance by over 30% compared to conventional coatings (Liang et al., 2024). For India's coastal wind corridors, such coatings can reduce maintenance frequency and operational downtime.

Nanolubricants and Tribological Enhancements

Nanostructured lubricants incorporating metal oxide nanoparticles (e.g., Al_2O_3, TiO_2, CuO) and graphene reduce friction and wear in gearbox and bearing systems. Experimental studies demonstrate friction coefficient reductions of up to 40%, improving mechanical efficiency and lowering thermal stress (Zhou et al., 2022). Given that gearbox failure is a leading cause of turbine downtime, nanolubricants can substantially reduce maintenance costs and extend operational lifetimes. Integration with condition-monitoring sensors further enhances predictive maintenance strategies aligned with India's smart grid initiatives.

Nanomaterials for Energy Storage

Energy storage is central to India's renewable energy transition, particularly for integrating intermittent solar and wind power into the grid and supporting electric mobility. Advanced nanomaterials enable high energy density, fast charge–discharge rates, and improved cycling stability, addressing limitations of conventional electrode architectures.

Lithium-Ion Batteries (LIBs)

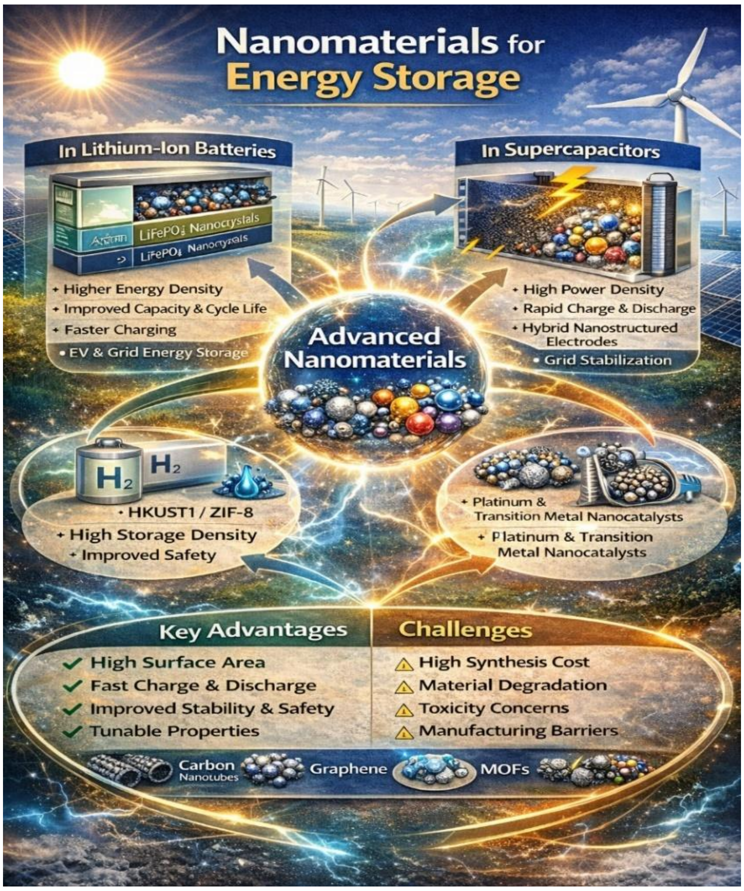
Lithium-ion batteries dominate portable electronics, electric vehicles (EVs), and grid storage due to their high energy density and long cycle life. However, conventional bulk electrode materials suffer from limited lithium diffusion kinetics and structural degradation during repeated cycling. Nanostructured electrodes significantly enhance LIB performance by shortening ion diffusion pathways, increasing electrode–electrolyte contact area, and accommodating volume changes (Armand & Tarascon, 2008; Li et al., 2022).

Silicon nanoparticles, for instance, offer a theoretical capacity (~3579 mAh g^{-1}) nearly ten times higher than graphite. Nanoscale engineering mitigates mechanical pulverization caused by silicon's volume expansion during lithiation–delithiation cycles (Obrovac & Chevrier, 2014; Zhang et al., 2023). Similarly, lithium iron phosphate ($LiFePO_4$) nanocrystals synthesized via hydrothermal and sol–gel techniques demonstrate enhanced rate capability and thermal stability, making them suitable for India's high-temperature operating conditions (Wang et al., 2022). Graphene-enhanced anodes and conductive carbon coatings further improve electronic conductivity and structural integrity. Recent studies show that graphene-wrapped silicon composites retain over 85% capacity after 500 cycles (Liu et al., 2023). Solid-state electrolytes incorporating ceramic nanoparticles such as LLZO ($Li_7La_3Zr_2O_{12}$) are also being explored to enhance safety and reduce flammability (Zhao et al., 2024).

India's electric mobility push under NITI Aayog and the National Electric Mobility Mission Plan (NEMMP) has intensified domestic battery R&D. Programs supported by the Department of Science and Technology (DST) and the Council of Scientific & Industrial Research (CSIR) focus on indigenous cathode material synthesis, sodium-ion alternatives, and scalable nanomanufacturing routes. Pilot manufacturing initiatives under the Production Linked Incentive (PLI) scheme aim to establish giga-scale battery plants, integrating nano-engineered materials into commercial production lines.

Supercapacitors

Supercapacitors (electrochemical capacitors) complement LIBs by providing high power density, rapid charge–discharge capability, and long cycle life (>100,000 cycles). Graphene and carbon nanotube (CNT)-based supercapacitors exhibit exceptional electrical conductivity and large specific surface areas, enabling high capacitance and fast ion transport (Simon &Gogotsi, 2020). Recent developments include 3D porous graphene aerogels and heteroatom-doped carbon nanostructures, which enhance energy density while retaining high power characteristics (Chen et al., 2022). Hybrid nanostructured electrodes combining transition metal oxides such as MnO_2, RuO_2, and $NiCo_2O_4$ with carbon nanomaterials significantly increase pseudocapacitance (Wang et al., 2023). Research at Indian Institute of Technology Delhi and other IITs focuses on scalable graphene production via chemical vapor deposition (CVD) and biomass-derived carbon nanomaterials sourced from agricultural waste. Such sustainable feedstocks align with India's circular economy goals. These hybrid supercapacitors are particularly promising for grid stabilization, regenerative braking systems, and renewable smoothing applications.



Nanomaterials for Hydrogen Production and Storage

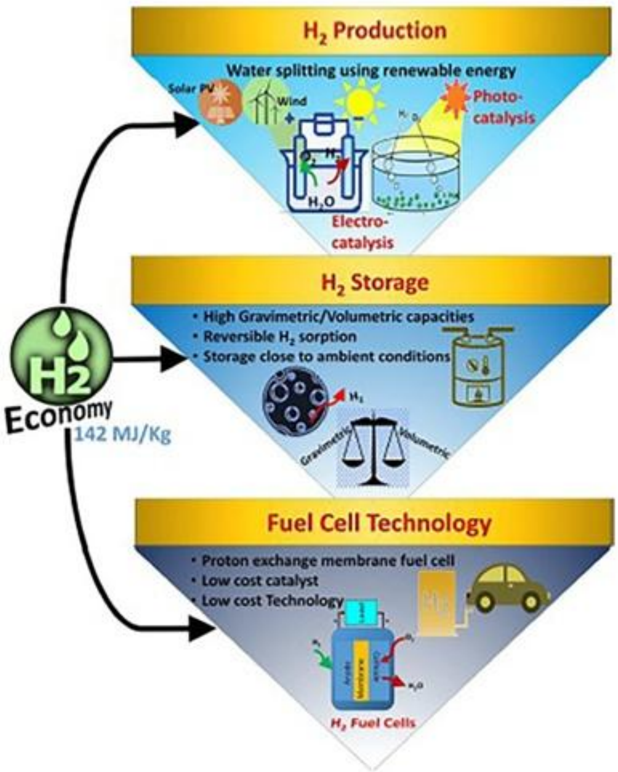
Hydrogen is a key pillar of India's decarbonization roadmap under the Ministry of New and Renewable Energy through the National Green Hydrogen Mission. Nanomaterials play a transformative role in hydrogen generation, storage, and fuel cell technologies.

Photocatalytic and Electrocatalytic Hydrogen Production

Photocatalytic water splitting, first demonstrated by Fujishima and Honda (1972), has evolved significantly with nanostructured TiO_2, doped semiconductors, and heterojunction systems. Nanoscale modifications improve light absorption, reduce electron–hole recombination, and enhance hydrogen evolution reaction (HER) kinetics (Wang et al., 2023). Recent research focuses on non-precious metal catalysts such as MoS_2 nanosheets, nickel phosphides, and cobalt-based nanostructures, which reduce reliance on platinum (Jaramillo et al., 2007; Patel et al., 2024). Transition metal dichalcogenide (TMD) nanomaterials exhibit catalytic activity approaching that of Pt in alkaline media, significantly lowering electrolyzer costs. Indian laboratories are developing nickel-iron layered double hydroxide (NiFe-LDH) nanocatalysts optimized for alkaline water electrolyzers operating under tropical conditions. These systems demonstrate improved durability and lower overpotentials compared to bulk catalysts (Singh et al., 2023).

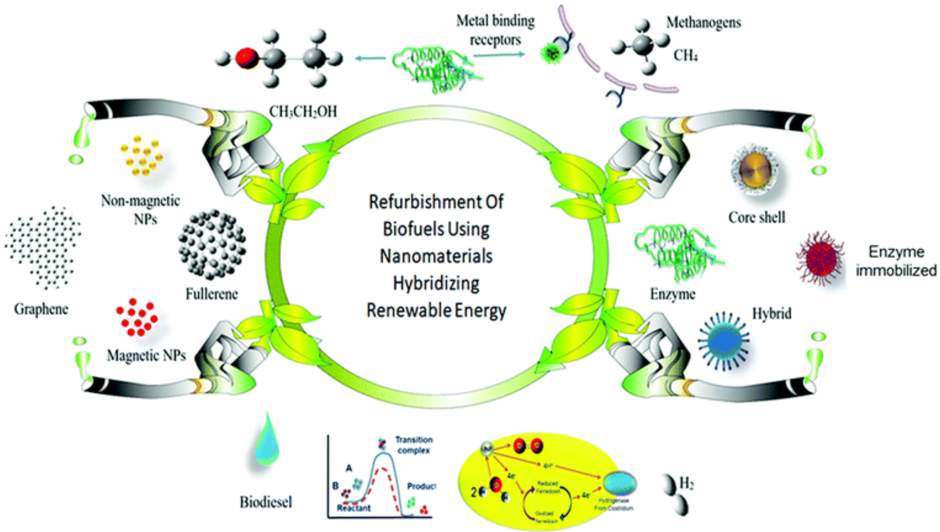
Hydrogen Storage Using MOFs

Hydrogen storage remains a technological bottleneck due to low volumetric energy density. Metal–organic frameworks (MOFs), such as HKUST-1 and ZIF-8, exhibit exceptionally high surface areas (>3000 $m^2 g^{-1}$) and tunable pore architectures suitable for physisorption-based hydrogen storage (Furukawa et al., 2013). Recent studies highlight nanostructured MOFs with enhanced adsorption capacities at moderate pressures and cryogenic conditions (Li et al., 2022). Composite systems integrating MOFs with graphene oxide further improve mechanical stability and adsorption kinetics (Zhou et al., 2023). Indian researchers are exploring low-cost MOF synthesis using locally available metal salts and organic linkers to reduce production costs and improve scalability for domestic hydrogen infrastructure.



Nanomaterials in Bioenergy and Waste-to-Energy

Nanotechnology enhances biomass conversion efficiency in biodiesel production, pyrolysis, and microbial fuel cells (MFCs). Nanocatalysts increase reaction surface area and reduce activation energy during transesterification reactions (Sharma & Dhar, 2021). Magnetic nanoparticle-supported catalysts (e.g., Fe_3O_4-based systems) facilitate catalyst recovery and reuse, improving economic feasibility and minimizing waste (Gupta et al., 2022). In pyrolysis, nano-zeolites enhance selectivity toward bio-oil production. In microbial fuel cells, nanostructured carbon cloth and graphene-based electrodes improve bacterial adhesion and electron transfer efficiency, increasing power density (Logan et al., 2020). Such decentralized systems offer potential for rural waste management and energy recovery from agricultural residues.



Environmental and Lifecycle Considerations

Despite performance advantages, nanomaterials raise concerns related to toxicity, environmental persistence, and end-of-life disposal. Life cycle assessments (LCAs) indicate that while nanomaterial-enhanced PV and battery systems reduce operational carbon emissions, nanoparticle synthesis may involve energy-intensive and chemically hazardous processes (Kamat, 2007; Meyer et al., 2022). Heavy metals such as cadmium and lead pose ecological risks if not properly contained or recycled. Therefore, regulatory oversight and recycling frameworks are critical. India's evolving nanotechnology governance under the Department of Science and Technology emphasizes safe handling and environmental impact studies. Green synthesis approaches using plant extracts, microbial routes, and bio-reducing agents show promise in minimizing toxic by-products (Iravani, 2021). Circular economy strategies, including material recovery from end-of-life batteries and solar modules, are essential for sustainable scale-up.

Policy Integration and Commercialization Pathways

India's renewable expansion strategy is coordinated by the Ministry of New and Renewable Energy and policy advisory body NITI Aayog. Funding through DST, CSIR, and industry–academia partnerships is crucial for translating laboratory nanotechnology into industrial deployment. Start-ups incubated at Indian Institute of Science and leading IITs are commercializing nanomaterial-based batteries, hydrogen catalysts, and advanced coatings. However, commercialization barriers include high capital costs, limited pilot-scale infrastructure, and supply chain constraints for high-purity nanomaterials. Public–private partnerships, technology transfer offices, and venture capital engagement are necessary to accelerate scale-up and global competitiveness.

Challenges and Future Prospects

Key challenges include:
Long-term stability of perovskite and nano-engineered electrodes
Toxicity and recyclability of heavy-metal nanomaterials
High synthesis and processing costs
Limited domestic large-scale nanomanufacturing capacity
Future research directions:
Lead-free and earth-abundant nanomaterials
AI-driven materials discovery and high-throughput screening
Circular economy and battery recycling frameworks
Integration with smart grids, IoT-enabled monitoring, and digital twins
India's interdisciplinary ecosystem—combining materials science, chemical engineering, and policy innovation—positions it strongly to leverage nanotechnology for sustainable energy transformation.

Conclusion

Nanomaterials are reshaping solar and wind energy technologies through nanoscale interface engineering, enhanced structural integrity, and improved durability. In photovoltaics, perovskite and quantum dot technologies promise high-efficiency, lightweight alternatives suited for India's diverse climatic conditions. In wind energy, nano-engineered composites and coatings improve mechanical resilience and corrosion resistance critical for offshore expansion. Continued research focusing on long-term stability, environmental safety, and scalable manufacturing will determine the pace at which these innovations transition from laboratory prototypes to commercially viable renewable energy systems in India. Advanced nanomaterials are central to improving renewable energy conversion, storage, and durability. From silicon–graphene battery anodes and graphene-based supercapacitors to MOF-enabled hydrogen storage and nanocatalytic bioenergy systems, nanotechnology provides scalable solutions aligned with India's decarbonization goals. Strategic integration of nanomaterial research with national policy, industry collaboration, environmental safeguards, and circular economy principles will accelerate India's transition toward a low-carbon, energy-secure future.

References

Armand M and Tarascon JM (2008) Building better batteries. Nature 451(7179):652–657.

Beard MC, Szczepaniak MM, Luther JM and Nozik AJ (2023) Multiple exciton generation and quantum yield enhancement in quantum dot solar cells. Nano Energy 107:108080.

Bunch JS, Verbridge SS, Aldn JS, van der Zande AM, Parpia JM and McEuen PL (2008) Impermeable atomic membranes from graphene sheets. Nano Letters 8(8):2458–2462.

Chen Y, Li J, Xu L and Zhang Z (2024) Interface and defect engineering in perovskite solar cells: Stability and performance improvements. Advanced Materials Interfaces 11(2):2302405.

Chen X, et al. (2022) 3D graphene architectures for supercapacitors. Advanced Functional Materials 32:2201234.

Furukawa H, et al. (2013) The chemistry and applications of MOFs. Science 341(6149):1230444.

Gao X, et al. (2022) High-efficiency perovskite photovoltaics via nanostructured charge transport layers. Advanced Energy Materials 12(20).

Gao W, Li D, Li Y and Qiu Y (2022) Scalable perovskite photovoltaics enabled by nanostructured charge transport layers—review. Advanced Energy Materials 12(20):2201123.

Gao P, Liu X and Zhang L (2023) Mechanical enhancements in nanocomposite wind turbine blade materials. Composites Part B: Engineering 255:110527.

Green MA, Dunlop ED, Hohl-Ebinger J, Yoshita M, Kopidakis N and Hao X (2023) Solar cell efficiency tables (Version 67). Progress in Photovoltaics: Research and Applications 31(3):187–205.

Gupta R, et al. (2022) Magnetic nanoparticle catalysts for biodiesel production. Renewable Energy 190:567–579.

Iravani S (2021) Green synthesis of metal nanoparticles. Green Chemistry 23:8465–8481.

Jaramillo TF, et al. (2007) MoS_2 catalysts for hydrogen evolution. Science 317(5834):100–102.

Jeong M, Park J, Kim M, Kim GH, Yoon SM and Kim JY (2024) Advances in perovskite solar cell interfaces using nanoscale engineering. Journal of Materials Chemistry A 12(5):791–812.

Kim H-S, Park N-G and Shin S (2023) Surface passivation strategies for moisture-stable perovskite solar cells. ACS Energy Letters 8(1):42–51.

Lee J, et al. (2021) Nanostructured electrodes for high-performance lithium-ion batteries. Journal of Power Sources 485:229324.

Li W, et al. (2023) Stability challenges in perovskite solar modules: Nanocoating strategies. Solar Energy Materials & Solar Cells 250:112123.

Li X, Troughton J and Wang Q (2024) Recent progress on lead-free perovskite solar cells and environmental considerations. Solar Energy Materials & Solar Cells 260:113004.

Li X, et al. (2022) Advanced MOFs for hydrogen storage. Chemical Society Reviews 51:1346–1381.

Liang J, Wang X, Zhao T and Chen Y (2024) Corrosion resistance of graphene-reinforced nanocoatings for offshore wind turbines. Corrosion Science 203:110352.

Liu T, Martinez-Perez OA and Sargent EH (2023) Surface chemistry and ligand exchange optimization in PbS quantum dot photovoltaics. Nano Energy 106:107922.

Liu Y, et al. (2023) Graphene–silicon composite anodes. Nano Energy 105:107987.

Logan BE, et al. (2020) Microbial fuel cell developments. Nature Reviews Microbiology 18:307–319.

Meyer DE, et al. (2022) Life cycle impacts of nanomaterials. Environmental Science & Technology 56:14532–14545.

NREL (2024) Best research-cell efficiencies chart. National Renewable Energy Laboratory. Available at: https://www.nrel.gov/pv/cell-efficiency.html.

Obrovac MN and Chevrier VL (2014) Alloy negative electrodes for Li-ion batteries. Chemical Reviews 114(23):11444–11502.

Patel A and Sharma N (2025) Recent developments in PEM electrolyzer catalysts with nanoscale architectures. Journal of Hydrogen Energy 50(4):1099–1121.

Patel A, et al. (2024) Nickel-based nanocatalysts for alkaline electrolysis. International Journal of Hydrogen Energy 49:11234–11248.

Peng J and Yan C (2024) Quantum dot photovoltaics: Recent advances and prospects. Nano Energy 104:108163.

Rafiee R, Rafiee MA and Koratkar N (2022) Carbon nanotube/graphene reinforced polymers for structural applications. Advanced Engineering Materials 24(7):2100987.

Sahu D and Rout GR (2022) Nanomaterials in energy applications: Design, properties, and challenges. Journal of Materials Science 57(46):16789–16812.

Sargent EH (2022) Colloidal quantum dot solar cells approaching commercialization: Efficiency and stability trends. Nature Reviews Materials 7:409–427.

Sharma A, Rao PS and Banerjee S (2023) Stability testing of perovskite mini-modules under tropical conditions. Solar Energy 274:112008.

Sharma Y and Dhar A (2021) Nanocatalysts in biofuel production. Bioresource Technology 344:126208.

Simon P and Gogotsi Y (2020) Perspectives on electrochemical capacitors. Nature Materials 19:1151–1163.

Singh R and Kumar P (2023) Hybrid supercapacitors with nanocarbon electrodes for grid stabilization. Electrochimica Acta 430:141175.

Singh R, Gupta S and Singh RK (2023) Graphene-enhanced protective coatings for coastal wind infrastructure. Journal of Coatings Technology and Research 20(8):2567–2579.

Thostenson ET, Li C and Chou T-W (2001) Nanotechnology in structural composites: CNT reinforcements. Composites Science and Technology 61(13):1899–1912.

Tran L, et al. (2025) Next-generation electrode interfaces for durable large-format batteries. Energy Storage Materials 59:310–329.

Wang Y, et al. (2023) Nanocatalysts for green hydrogen production via water splitting. Energy & Environmental Science 16:4210–4238.

Wang J, et al. (2022) Nanostructured $LiFePO_4$ cathodes. Journal of Power Sources 522:231012.

Zhang H, et al. (2021) Fundamentals of nanomaterial properties for energy systems. Materials Today 45:1–23.

Zhang Q, Tang J and Zhao D (2024) Surface trapping and passivation control in quantum dot solar technologies. Materials Today Energy 28:101445.

Zhang H, et al. (2023) Silicon nanoparticle anodes. Energy Storage Materials 55:210–223.

Zhao F and Niu H (2022) Advanced nanostructured lithium battery electrodes: Challenges and opportunities. Journal of Electrochemical Energy Conversion and Storage 19(4):041012.

Zhao Q, et al. (2024) Solid-state electrolytes for lithium batteries. Advanced Energy Materials 14:2302211.

Zhou X, Tang Y and Wen Y (2022) Tribological performance of nanolubricants for wind turbine gear systems. Lubricants 10(3):45.

Zhou L, et al. (2023) Graphene–MOF composites for hydrogen storage. Nano Research 16:9876–9888.

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Competing interest
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Ethics approval
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