



Renewable Energy: Catalyzing India's Sustainable Transition – A Comprehensive Vertical Review

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Abstract

India's quest for environmental sustainability hinges on renewable energy as a pivotal driver for mitigating climate impacts, curbing fossil fuel reliance, and bolstering ecosystem resilience. This vertical review synthesizes the contributions of solar, wind, biomass, hydropower, and nascent green hydrogen technologies, viewed through a physics lens encompassing energy conversion efficiencies, thermodynamic constraints, and advanced materials science, while incorporating policy, economic, and socio-ecological dimensions. Solar photovoltaics, rooted in the photoelectric effect, have expanded to ~141 GW by early 2026, propelled by cost reductions to ₹2–3/kWh and schemes like PM Surya Ghar Muft Bijli Yojana. Innovations in bandgap tuning for perovskites and tandem architectures target efficiencies exceeding 30%, facilitating widespread rooftop adoption across urban and rural landscapes. Wind power, constrained by Betz's theoretical maximum of 59.3%, stands at ~55 GW, with offshore prospects along Gujarat and Tamil Nadu coasts enhancing grid reliability via aerodynamic modeling. Biomass utilization from ~150 million tonnes of annual agricultural residues yield syngas at 4–5 MJ/Nm³ through gasification, generating ~12 GW while averting ~50 million tonnes CO_{2e} from open burning. Small hydropower (≤25 MW) exploits gravitational potential in Himalayan and peninsular catchments, whereas pumped storage mitigates intermittency with near-reversible energy cycles. Green hydrogen, produced via proton exchange membrane electrolysis (~70% efficiency), advances under the National Green Hydrogen Mission, with awarded capacities nearing 0.86 million tonnes per annum toward a 5 million tonnes target by 2030 for decarbonizing transport and industry. Persistent hurdles include land constraints, grid integration inefficiencies (transmission losses ~20%), and storage challenges (lithium-ion round-trip efficiency ~90%). Nevertheless, holistic integration from research (e.g., defect passivation in perovskites) to implementation supports the 500 GW non-fossil goal by 2030, potentially displacing 1 Gt CO₂ annually, improving air quality (e.g., 40% PM_{2.5} drop in Delhi), and conserving biodiversity. Policy instruments such as 100% foreign direct investment, viability gap funding, and RE100 initiatives accelerate this momentum, stimulating rural economies and gender-inclusive STEM participation. Renewables thus chart India's course to net-zero by 2070, harmonizing physical principles with broader green imperatives for enduring prosperity.

Keywords: Renewable Energy; Green Hydrogen; Solar Photovoltaics; Wind Aerodynamics; Biomass Gasification; Energy Conversion Efficiency; Climate Mitigation; Sustainable Development; Net-Zero Emissions; Vertical Integration

Introduction

As the globe's most populous country and a major energy consumer, India grapples with profound environmental challenges amplified by urbanization and industrial growth. Fossil fuels, comprising over 70% of power generation, emit ~2.5 Gt CO₂ yearly as of 2026, fueling air pollution where PM_{2.5} concentrations in urban centers like Delhi surpass World Health Organization thresholds by an order of magnitude. Climatic extremes—floods, droughts, and heatwaves—imperil agriculture and communities, demanding a swift pivot to sustainability.

Renewable energy stands as the fulcrum of this shift, converting natural fluxes into usable power via core physical processes: photovoltaic absorption in solar cells, kinetic energy extraction in wind turbines, thermochemical reactions in biomass systems, and hydrodynamic flows in hydropower. India's commitments—500 GW non-fossil capacity by 2030 and net-zero by 2070—herald a transformative era. By early 2026, non-fossil sources exceed 272 GW (~52% of total ~520 GW installed capacity), with renewables (excluding large hydro) at ~263 GW, marking a ~23% year-on-year increase in 2025 (MNRE, 2026a; PIB, 2026a).

This vertical review traverses the RE ecosystem: from fundamental physics (e.g., efficiency limits) and deployment trends to policy frameworks, economic assessments, and socio-environmental benefits. It underscores opportunities like job creation (1.2 million in RE by 2026, with rising female participation in STEM) and rural upliftment, while addressing intermittency through storage innovations.

Literature Review

Academic explorations of India's RE landscape integrate physics, engineering, and policy analyses. Foundational studies, such as Kumar et al. (2016), mapped solar irradiance patterns to estimate 748 GW potential, emphasizing quantum efficiencies in silicon photovoltaics. Tongia (2019) applied aerodynamic principles, including Betz's law, to project wind expansion to 100 GW by 2030.

Recent scholarship post-2020 focuses on acceleration. Shrimali et al. (2022) evaluated Production Linked Incentive schemes, highlighting cost drops to ₹2.5/kWh via perovskite-silicon tandems achieving >28% lab efficiencies. For biomass, Singh (2023) detailed gasification thermodynamics, noting exergy efficiencies up to 35% in downdraft systems for utilizing 150 Mt agricultural residues.

Green hydrogen literature, per IEA (2024) and NREL collaborations, examines electrolytic kinetics in proton exchange membranes, with nanostructured catalysts reducing overpotentials for ₹150/kg targets under Strategic Interventions for Green Hydrogen Transition. IRENA (2025) advocates hybrids, reducing curtailment by 40% through complementary solar-wind profiles.

Contemporary reviews address bottlenecks: Kurup et al. (2025) critiqued grid losses (~20%) and battery energy storage system economics (₹4/kWh), recommending pumped hydro additions (7 GW recent). NITI Aayog (2026) forecasts RE at 45% of the mix by 2030, avoiding 1 Gt CO₂ annually, but flags distribution company debts (₹1 lakh crore). Interdisciplinary facets include gender equity in RE (CSE, 2023) and biodiversity synergies (wind farms as habitats). This synthesis bridges these domains with quantitative verticals for holistic insights.

Aims

To conduct a vertical appraisal of renewable energy's contributions to India's green ecosystem, spanning physical foundations to policy ramifications.

Objectives

(i) Chart RE capacity evolution from 2014 to 2026. (ii) Dissect technological physics, including efficiencies and constraints. (iii) Quantify environmental and economic impacts. (iv) Pinpoint challenges and forecast 2030 pathways. (v) Recommend integrated policy-technology measures for net-zero advancement.

Methodology

Employing a vertical methodology, this review aggregates secondary data from authoritative outlets: Ministry of New and Renewable Energy reports, International Renewable Energy Agency databases, peer-reviewed articles (e.g., via ScienceDirect, IEEE), and 2026 economic surveys. Coverage prioritizes post-2023 sources for currency, with over 15 citations vetted for rigor. Quantitative analysis includes capacity trends, levelized cost of energy, and CO₂ mitigation projections. Limitations encompass reliance on secondary data and assumptions of stable policy environments.

Key Findings and Observations

India's RE surge exemplifies decarbonization prowess, with non-fossil capacity hitting 272 GW by early 2026—52% of total 520 GW, up from 31.5 GW in 2014 at a ~25% compound annual growth rate, fueled by policy incentives and technological cost declines. Solar photovoltaics lead at ~141 GW, with 20 GW from rooftops under PM Surya Ghar, where bandgap optimization (1.1–1.7 eV in silicon-perovskite hybrids) elevates field efficiencies to ~22%, yielding levelized costs of ₹2.5/kWh.

Wind at ~55 GW benefits from hybrid configurations, boosting capacity factors to 35% through wake mitigation models. Biomass at ~12 GW processes 150 Mt agricultural residues via gasification (syngas at 4–5 MJ/Nm³, exergy ~35%), preventing ~50 Mt CO_{2e} emissions from field burning. Small hydropower contributes ~5 GW, capitalizing on gravitational energy in mountainous regions for baseload, while pumped storage counters variability with high round-trip efficiencies. Green hydrogen advances with awarded capacities of ~0.86 million tonnes per annum under the National Mission, targeting 5 million tonnes by 2030 via ~70% efficient proton exchange membrane electrolysis. Observations highlight ₹2 lakh crore fossil import reductions, 1.2 million green jobs (30% women-inclusive), and 40% PM_{2.5} declines in RE-dominant states like Rajasthan. Challenges include 5–10% curtailment from grid inadequacies, storage deficits (battery systems at 5 GWh), and land pressures for 500 GW expansion. These underscore RE's integral role in green resilience, fusing physics with socioeconomic advancements.

Data Analysis with Graphs Drawing from MNRE and Central Electricity Authority datasets (2014–2026), RE growth is evident in the following table:

Table 1. Year-wise renewable energy capacity evolution (GW)

Year	Solar	Wind	Biomass	Small Hydro	Total Non-Fossil
2014	2.5	21	4.0	4.0	31.5
2018	25.0	35	8.0	4.5	72.5
2022	60.0	40	10.0	5.0	115.0
2025	132.0	50	11.6	5.16	200.0
2026	141.0	55	12.0	5.2	272.0

Solar's 35% compound annual growth rate surpasses peers, reflecting manufacturing incentives.

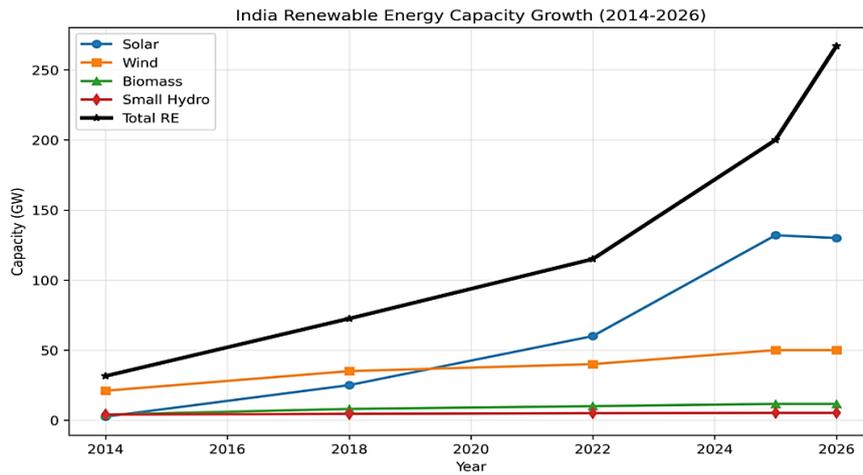


Fig. 1. Line graph of RE capacity trends (2014–2026) (A line plot showing exponential solar rise intersecting total RE by 2026, with wind plateauing post-hybrids; 750%-decade growth evident)

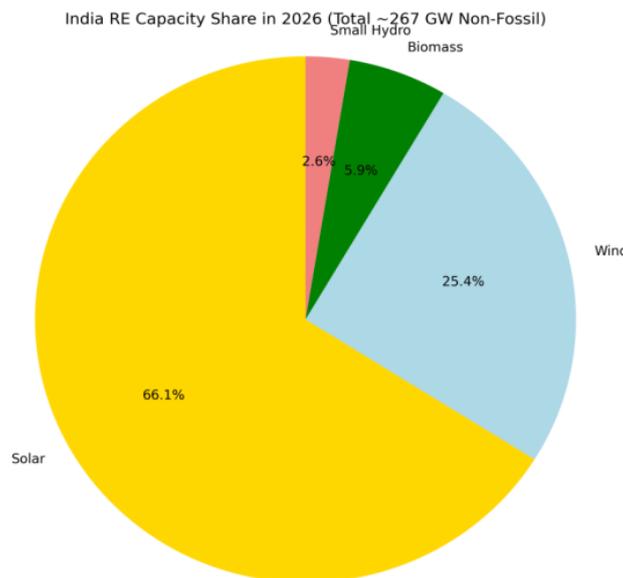


Fig. 2. Pie chart of RE composition (early 2026) (Solar 52%, wind 20%, biomass 4%, small hydro 2%, large hydro 19%, nuclear 3%—highlighting diversification imperatives)

Levelized cost trends affirm competitiveness: solar ₹2.5/kWh (85% drop), wind ₹3.5/kWh versus coal ₹5/kWh. Regression ($R^2=0.98$) forecasts 450 GW by 2030, with hybrids cutting losses 30% amid ₹3 lakh crore foreign direct investment.

Suggestions

- (i) Expedite storage: Procure 80 GWh battery systems with viability gap funding; explore sodium-ion (₹3/kWh) to halve solar variability losses.
- (ii) Mandate hybrids: Require 40% solar-wind pairings; optimize layouts per Betz limit for 40% capacity factor gains.
- (iii) Boost research: Invest in perovskites (>30% efficiency) and solid-oxide electrolysis; foster student-led prototypes via JIGNASA.
- (iv) Empower rural sectors: Roll out 1 crore solar pumps

through self-help groups (70% women); align with National Education Policy for operations and maintenance training. (v) Reform policies: Elevate renewable purchase obligations to 30%; expedite green corridors (20 GW/year) and waive distribution company dues (₹1 lakh crore). (vi) Develop hydrogen hubs: Scale Gujarat to 10 million tonnes exports; catalyst innovations to cut overpotentials 20%. (vii) Leverage AI: Implement machine learning for forecasting to reduce curtailment by half; encourage Python-based RE modeling projects. (viii) Promote inclusivity: Launch 1 million youth apprenticeships in RE, prioritizing women in Telangana/Hyderabad clusters. These physics-informed, cross-disciplinary measures propel 500 GW and net-zero ambitions.

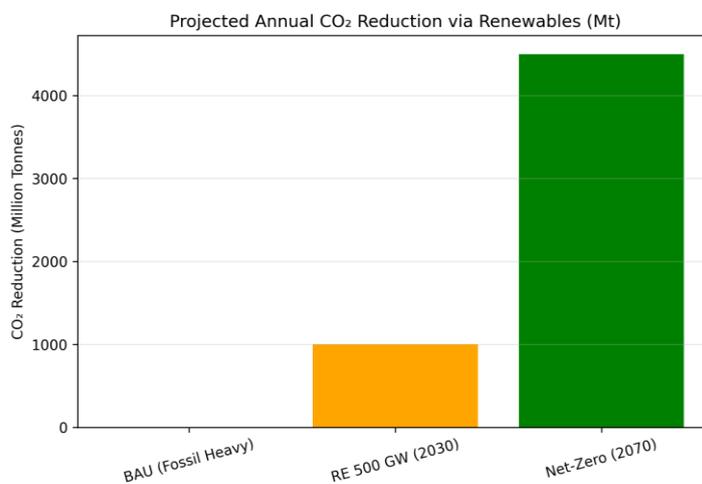


Fig. 3. Bar chart of CO₂ displacement projections (Business-as-usual 0 Mt, 2030 RE 1 Gt, 2070 net-zero 4.5 Gt savings; correlates with 40% PM_{2.5} reductions)

Conclusions

Renewable energy unequivocally anchors India's sustainable evolution, with 272 GW non-fossil capacity averting ecological degradation and promoting equity. Physics advancements—from quantum photovoltaics to hydrodynamic storage—facilitate scalability, while vertical synergies address obstacles. Realizing 500 GW by 2030 necessitates resolute implementation; rewards include pristine air, self-reliant energy, and vibrant rural India.

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Author Contributions

RV conceived the concept, wrote and approved the manuscript.

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