

# Renewable Energy Sources in India: A Comprehensive Review

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## Abstract

India has experienced one of the fastest expansions in renewable energy (RE) capacity globally over the last decade. This review synthesizes the literature, policy developments, technology developments, deployment data (through 31 Aug 2025), grid-integration issues, socio-environmental impacts, and pathways for decarbonization through 2030 and beyond. It places special emphasis on solar and wind —the two dominant technologies in India’s RE mix — while covering hydropower, biomass, waste-to-energy, and storage/green hydrogen as enablers. Quantitative data from official sources are used to provide a current snapshot and trend-based analysis. The review concludes with policy and research recommendations to consolidate gains and address critical integration, financing, and sustainability challenges.

**Keywords:** India, renewable energy, solar PV, wind, hydropower, biomass, grid integration, energy policy, storage, green hydrogen

## 1. Introduction

The twin challenges of rising energy demand and the urgent need for greenhouse gas mitigation position renewable energy at the center of India’s energy strategy. Since the early 2010s, India has aggressively ramped up renewable installations through auctions, state programs, and national missions. By 2024–2025 the country reached major milestones in cumulative capacity additions, led by solar photovoltaic (PV) and onshore wind. India's commitments under international climate agreements and domestic goals for energy access, pollution reduction, and industrial modernization have further incentivized renewable deployment.

This review provides a comprehensive, evidence-based examination of renewable energy sources in India. It documents recent capacity and generation trends (data through 31 Aug 2025), technology-specific developments, policy instruments and market mechanisms, grid-integration and storage requirements, socio-environmental considerations, financing and industrial strategy, and recommended pathways to meet 2030 and mid-century goals. Wherever possible, official data (primarily MNRE and CEA) and reputable international analyses are used for quantitative statements.

## 2. Methodology and Scope

This paper is a structured narrative review combining: (a) primary official statistics and fact-sheets (Ministry of New & Renewable Energy MNRE; Central Electricity Authority CEA; Press Information Bureau PIB), (b) international agency analyses (International Energy Agency IEA; International Renewable Energy Agency IRENA), (c) peer-reviewed literature for technical, environmental and economic perspectives, and (d) leading market/industry reports for recent auction, manufacturing and cost-trend information. Numerical snapshots

(installed capacity by technology) were drawn from MNRE’s cumulative physical progress as of **31 Aug 2025** and used to create the figure and data table in Appendix A. The review limits itself to electricity-sector renewable deployment and related enabling technologies (storage, electrolyzers), with discussion of biofuels where they intersect with power and waste management.

**3. Historical Context and Policy Evolution**

India’s modern renewable journey accelerated after 2010 with national targets, the establishment and scaling of the Jawaharlal Nehru National Solar Mission (later integrated into broader MNRE programs), and the shift to large-scale competitive auctions. Important policy milestones include:

- Large-scale reverse-auction procurement frameworks (utility-scale solar and wind).
- Rooftop solar policies and incentives for distributed generation.
- State-level renewable purchase obligations (RPOs) and feed-in mechanisms in earlier phases.
- National initiatives for battery storage and green hydrogen (post-2020).

These instruments, together with falling module and turbine costs, catalysed rapid additions. Auction-driven procurement reduced levelized costs of electricity (LCOE) for utility-scale solar and wind, while hybrid project tenders (solar + wind and storage-enabled bids) have become more common in 2023–2025.

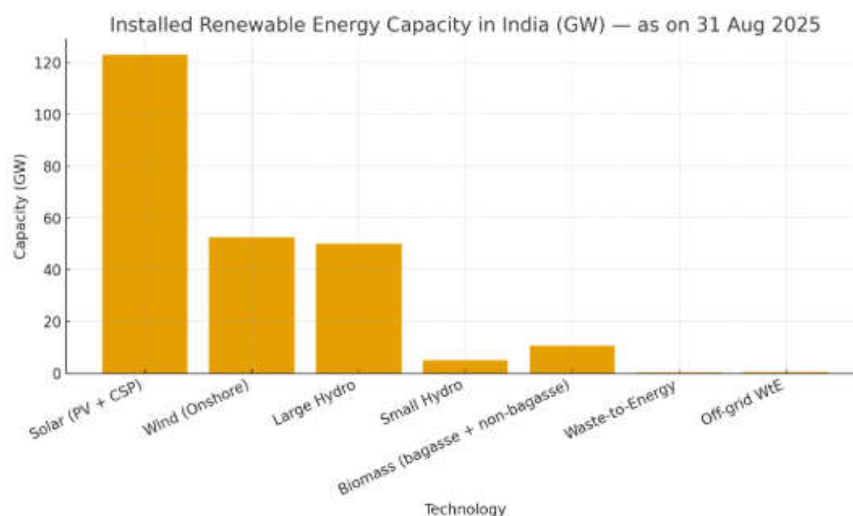
**4. Status and Quantitative Snapshot (as on 31 Aug 2025)**

**4.1 Installed capacity (major technologies — MW)**

The cumulative installed capacities used in this review are taken from MNRE physical progress reporting (31 Aug 2025). They provide the basis for the data table and figure in Appendix A.

- Solar (PV + CSP): **123,130.13 MW**
- Wind (Onshore): **52,681.20 MW**
- Large Hydro: **50,108.17 MW**
- Small Hydro: **5,108.71 MW**
  
- Biomass (bagasse + non-bagasse cogeneration): **10,743.11 MW**
- Waste-to-Energy (utility): **309.34 MW**

- Off-grid Waste-to-Energy: **545.11 MW** Total renewable capacity including large



#### 4.2 Recent additions and trends (2018–2025 overview)

- Solar recorded the fastest growth rate, driven by utility-scale auctions and rooftop programs; module cost declines supported expansion.
- Wind additions regained momentum after policy stabilization and stronger auction design; hybrid tenders bolstered investor interest.
- Biomass and small hydro showed modest, incremental growth; waste-to-energy projects remain limited in scale relative to potential.
- Storage and green hydrogen moved from pilot phases to small commercial roll-outs with supportive policy signals in 2024–2025.

(For year-by-year capacity additions, state-wise breakdowns, and generation-level time series, MNRE and CEA published annual reports and monthly bulletins provide the canonical time series; readers are referred to those sources for raw time-series downloads.)

### 5. Technology-Specific Review

#### 5.1 Solar PV and Concentrating Solar Power (CSP)

Solar PV accounts for the largest portion of capacity in India. Key drivers:

- Utility-scale auctioning lowered LCOE and attracted large developers.
- Rooftop solar programs addressed distributed demand and peak shaving, though rooftop adoption varies by state due to regulatory and billing frameworks.
- Floating solar and agrivoltaics emerged as promising approaches to reduce land conflicts and enhance land-use efficiency.

Challenges include intermittent generation (diurnal & seasonal), grid integration in states with high instantaneous penetration, land acquisition, domestic value-chain constraints, and module supply-chain geopolitics. Storage integration (battery or pumped hydro) is increasingly required to firm solar output for peak management.

#### 5.2 Wind (Onshore and Emerging Offshore)

Onshore wind remains the second-largest RE contributor. Recent trends include repowering older low-capacity-factor sites with modern turbines and hybrid wind-solar projects to optimize utilization of transmission capacity. Offshore wind in India is at an early stage: resource

assessments and pilot auctions are underway but commercialization will need significant transmission investment and supply-chain development.

Technical concerns for wind include site suitability, turbine logistics, and ensuring long-term grid-friendly operations (e.g., low-voltage ride-through, reactive power support).

### **5.3 Hydropower (Large & Small)**

Large hydropower provides seasonal storage-like flexibility (via reservoir storage), and therefore plays a key role in managing system variability. However, large dams have social and ecological impacts that require careful planning and mitigation. Small hydro ( $\leq 25$  MW) contributes to decentralized generation in hilly and rural regions with lower environmental footprint and quicker permitting.

### **5.4 Biomass, Bagasse Cogeneration, and Waste-to-Energy**

Biomass cogeneration (including sugar-cane bagasse) supports grid stability through dispatchable thermal output. Feedstock sustainability, logistics, and seasonality are core challenges. Waste-to-energy projects are limited relative to municipal solid waste volumes due to feedstock heterogeneity and commercial viability constraints; however, they offer co-benefits in waste management.

Additionally, compressed biogas (CBG) programs (SATAT-like schemes) and bio-CNG investments indicate a cross-sectoral approach linking waste management and cleaner fuels.

### **5.5 Storage, Firming, and Green Hydrogen**

Battery energy storage systems (BESS), pumped hydro storage (PHS), and hybrid renewables + storage projects are rising as necessary complements to high renewable penetration. Green hydrogen (electrolyser-based hydrogen produced with renewable electricity) is prioritized as both demand sink and industrial decarbonization vector. India's nascent green hydrogen manufacturing ambitions require cheap renewable power, electrolyser cost reductions, and new downstream demand creation (steel, fertiliser, transport).

## **6. Grid Integration, Flexibility and System Operations**

### **6.1 Intermittency management**

High shares of solar and wind increase the need for operational flexibility. Measures include improved forecasting, ramp-capable thermal plants, demand response, BESS, and grid-scale flexibility products. Ancillary services markets and revised grid codes are being developed to remunerate and incentivize flexibility.

### **6.2 Transmission and Curtailment**

Concentrated capacity additions (solar parks, wind clusters) create bottlenecks; delayed transmission reinforcement has caused curtailment in certain states. Coordinated generation-transmission planning, faster right-of-way clearances, and financial instruments to accelerate interstate corridors are necessary.

### **6.3 Market design and contract structures**

The transition from long-term fixed PPAs to merchant and hybrid risk-sharing contracts affects project bankability. Market reforms to enable day-ahead, intra-day, and ancillary markets—plus firm-renewable contract structures—will influence investment flows.

## 7. Socio-Environmental and Land-Use Considerations

Large-scale RE deployment raises socio-environmental questions:

- Land acquisition and potential competition with agriculture; solutions include prioritizing brownfield sites, rooftop and floating PV, and agrivoltaic systems.
- Biodiversity risks in certain wind and hydro sites; environmental impact assessment (EIA) and mitigation measures are crucial.
- Community engagement and equitable benefit-sharing reduce conflict and support local acceptance.
- Lifecycle impacts, including end-of-life PV module and battery recycling, demand circular-economy planning.

Policies encouraging second-life battery markets, recycling infrastructure, and sustainable biomass sourcing will be necessary to minimize externalities.

## 8. Economics, Costs and Finance

### 8.1 Cost trends

LCOEs for utility-scale solar and onshore wind have declined dramatically in the last decade due to global technology scaling, competitive procurement, and local manufacturing incentives. However, soft costs (land, transmission, finance) still influence final tariffs. Battery costs have fallen, but BESS adds significant incremental capital to projects.

### 8.2 Financing mechanisms and risk mitigation

Key instruments include long-term PPAs, viability gap funding for nascent technologies, sovereign or multilateral credit enhancement, and green bonds. Contract enforcement and timely payment are essential to reduce financing costs. Public-private partnerships and blended finance can accelerate deployment in hard-to-reach regions.

## 9. Manufacturing, Supply Chain and Industrial Policy

India's policy emphasis on domestic manufacturing (modules, inverters, batteries, electrolyzers) aims to capture value and improve energy security. Success requires integrated industrial policy, technology partnerships, and incentives that balance import substitution with competitive scaling. Critical raw material dependencies (lithium, cobalt, certain rare earths) necessitate strategic sourcing, recycling, and alternative chemistries.

## 10. Case Studies & State-Level Progress

This section highlights state-level progress and five case studies (Gujarat, Rajasthan, Tamil Nadu, Karnataka, Maharashtra). The quantitative table and chart show **installed solar capacity (GW)** for selected top states using 2025 sources. Solar is used as the primary state-level metric because it dominates recent additions and state comparisons; where useful I add state-specific total RE context (e.g., Gujarat's overall RE capacity growth).

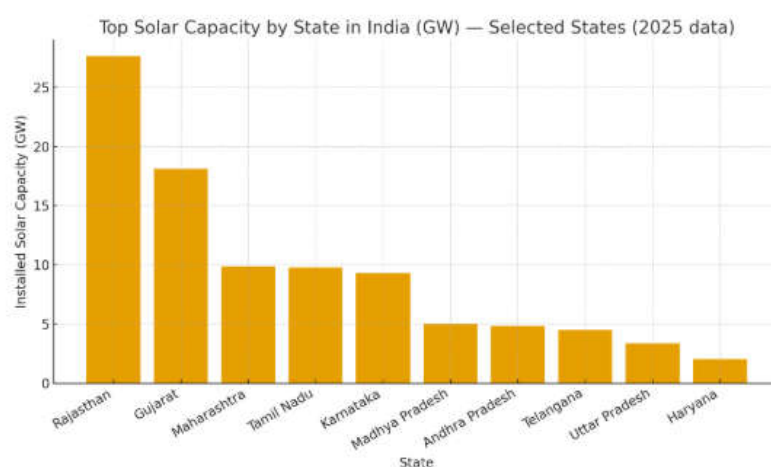
### Data sources

- Ministry of New & Renewable Energy (MNRE) — Physical Progress (cumulative as on 31 Aug 2025). Ministry of New and Renewable Energy
- Times of India (reporting Gujarat state totals, Aug 2025). The Times of India

- RenewableAffairs / market summaries for state solar rankings (2025 data snapshots). Renewable Affairs
- Central Electricity Authority (CEA) dashboard and installed capacity reports for contextual figures. Central Electricity Authority+1

state-level figures here focus on solar installed capacity (GW) from public summaries and market reports for 2025. For full state-by-state MNRE tabulations (all technologies, location-wise), see MNRE's state-wise cumulative installed capacity page. Ministry of New and Renewable Energy

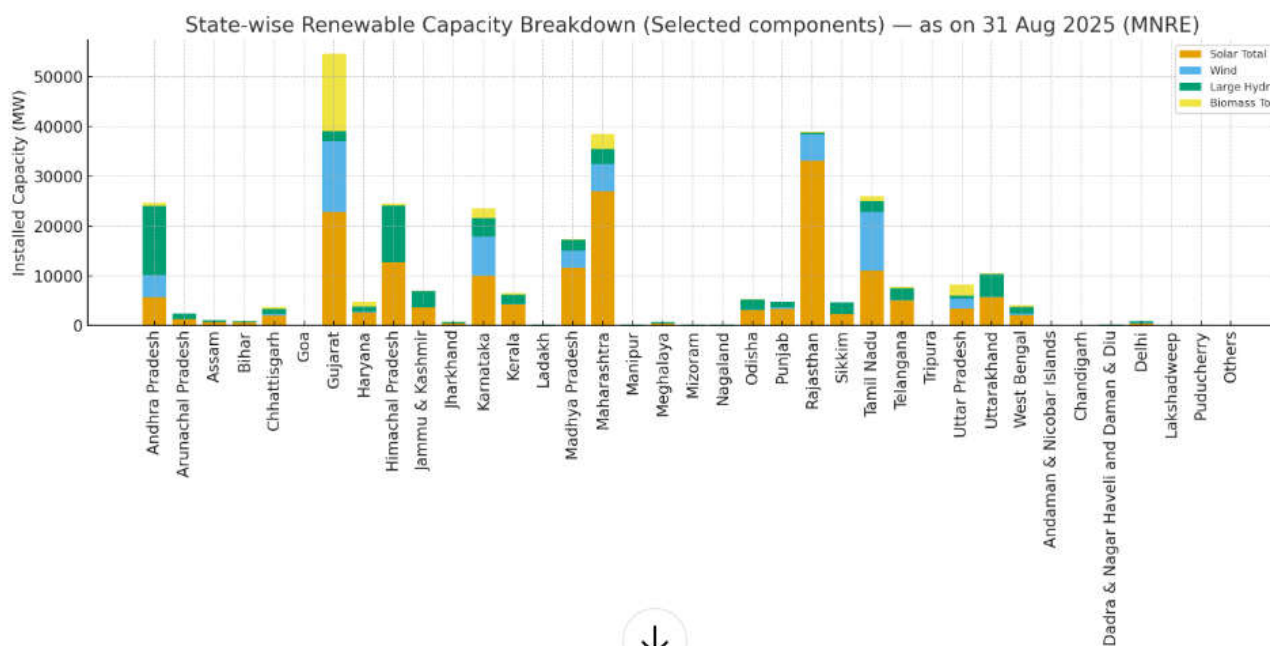
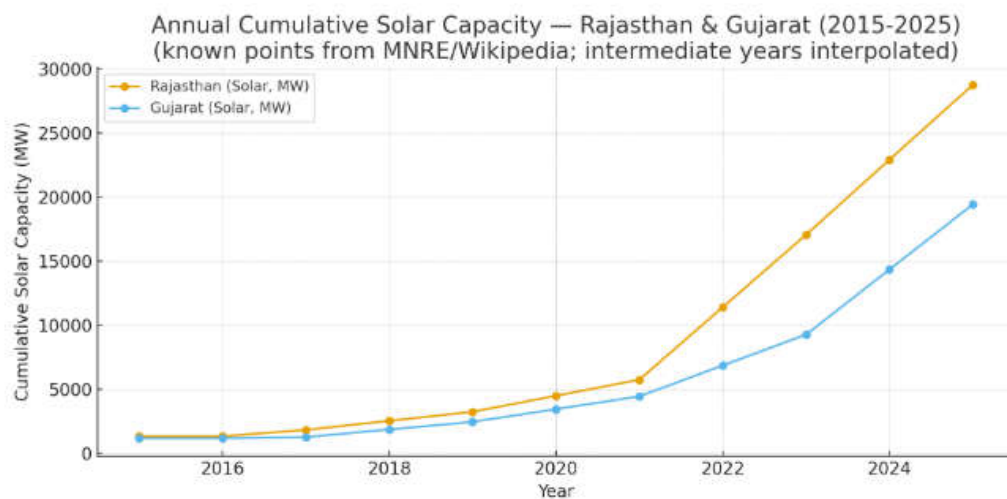
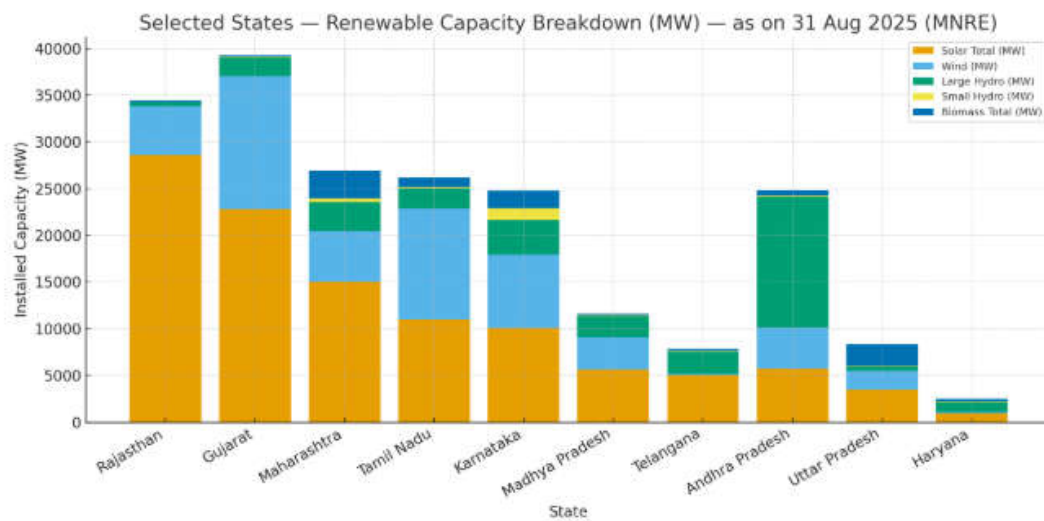
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**State-level Data Table — Selected Top Solar States (2025)**

| Rank | State          | Installed Solar Capacity (GW) |
|------|----------------|-------------------------------|
| 1    | Rajasthan      | 27.64                         |
| 2    | Gujarat        | 18.13                         |
| 3    | Maharashtra    | 9.88                          |
| 4    | Tamil Nadu     | 9.77                          |
| 5    | Karnataka      | 9.31                          |
| 6    | Madhya Pradesh | 5.01                          |
| 7    | Andhra Pradesh | 4.84                          |
| 8    | Telangana      | 4.5                           |
| 9    | Uttar Pradesh  | 3.36                          |
| 10   | Haryana        | 2.03                          |

Source : RenewableAffairs. (2025)



## Five State Case Studies

### 1) Gujarat — Rapid scale-up and industrial integration

#### Key facts & data

- Reported total RE capacity: ~**39,275.7 MW** (39.28 GW) as of Aug 31, 2025; Gujarat added **6,632 MW** of green power in Apr–Aug 2025 according to state reporting. Gujarat’s solar capacity is ~**18.13 GW** (part of the total). [The Times of India+1](#)

#### Drivers

- Large, policy-driven solar parks and favorable land allocation processes.
- Strong private and industrial demand (corporate offtake, manufacturing cluster power needs).
- Transmission upgrades and proactive state coordination reduced curtailment.

#### Challenges

- Managing intra-state grid balancing with rapid additions; need for storage and flexible dispatch.
- Ensuring equitable land-use and compensation for affected communities.

#### Notable initiatives

- Gujarat’s emphasis on rooftop solar, hybrid projects and attracting PV manufacturing (local value chain). [The Times of India](#)

### 2) Rajasthan — Highest solar resource exploitation

#### Key facts & data

- Rajasthan leads in solar: ~**27.64 GW** solar installed (2025 snapshot). Vast solar parks (Bhadla, etc.) and desert geography create high resource potential. Renewable Affairs

#### Drivers

- Excellent solar irradiance, availability of large tracts of non-agricultural land, and major utility-scale project development.
- Central and state auctions that leaned towards large solar park development.

#### Challenges

- Long transmission distances to demand centers; need for interstate corridors and transmission upgrades.
- Environmental management in arid ecosystems and local water use for cleaning panels.

**Notable initiatives**

- Large centralised solar parks, and recent moves into floating PV trials on reservoirs to conserve land and reduce evaporation.

**3) Tamil Nadu — Mature wind hub with rising solar****Key facts & data**

- Tamil Nadu is a national leader in wind; by 2025 it also had ~**9.77 GW** solar capacity (selected ranking). Wind remains a large share of its RE portfolio. [Renewable Affairs](#)

**Drivers**

- Strong wind resources (coastal and plateau regions), early developer activity and manufacturing clusters for towers and blades.
- A diversified RE mix (wind + solar) helps smooth temporal generation profiles.

**Challenges**

- Grid curtailment at times due to high instantaneous penetration; coordination with central transmission required.
- Environmental and avian-impact concerns for large wind farms.

**Notable initiatives**

- Hybrid tendering and repowering of older wind farms to increase capacity factor and grid-friendliness.

**4) Karnataka — Balanced growth, industrial uptake****Key facts & data**

- Karnataka's solar capacity near **9.31 GW** (2025 snapshot), and it continues to expand wind and rooftop programs. [Renewable Affairs](#)

**Drivers**

- Proximity to industrial demand centers (Bengaluru & industrial belts) and exporters, policy support for green energy procurement.
- Robust renewable tendering and investments in transmission within the state.

**Challenges**

- Distribution utility financial health and PPA bankability issues in prior years affected developer interest; improving now with reforms.
- Need for more distributed storage to support rooftop schemes.

**Notable initiatives**

- State-driven green energy corridors and support for solar-wind hybrids to improve utilization.

**5) Maharashtra — Scaling up with hybrid projects and storage focus****Key facts & data**

- Maharashtra had **~9.88 GW** solar capacity (2025 snapshot). Recent Cabinet approvals for large joint-venture RE projects (5,000 MW portfolio) aim to boost capacity further. [Renewable Affairs+1](#)

**Drivers**

- Large industrial base, demand centers (Mumbai, Pune), and recent policy push for floating solar and pumped storage.
- Active state-level procurement and joint ventures for large RE portfolios.

**Challenges**

- Land and environmental approvals for large projects; integrating floating solar with reservoirs and improving pumped-hydro timelines.

**Notable initiatives**

- JV approvals for multi-GW projects focusing on hybrids, pumped storage and green hydrogen supply chains. The Times of India

**State-Level Drivers, Common Challenges & Policy Levers****Common drivers across successful states**

- Resource availability (solar irradiance, wind regimes).
- State-level policy clarity and ease of land allocation.
- Transmission investments and corridor development.
- Industrial demand and corporate offtake (open access, captive procurement).

**Common challenges**

- Curtailment and transmission bottlenecks.
- Need for storage, grid flexibility and ancillary services.
- Land-use conflicts and environmental compliance.
- Financing and PPA bankability at scale.

**Policy levers recommended**

- Accelerate transmission and inter-regional corridors.
- Promote hybrid + storage tenders and design firm-renewable contracts.
- Encourage floating PV, rooftop and brownfield deployment to preserve land.
- Use blended finance and credit-enhancement to lower project financing costs.

**11. Pathways to 2030 and Beyond — Scenarios & Policy Priorities**

To meet ambitious climate and development goals, India needs an integrated pathway combining:

1. **Rapid renewable deployment** (continued solar + wind scale-up, plus floating/rooftop expansion).
2. **Storage acceleration** (BESS scale-up, pumped hydro completion, incentives for second-life reuse and recycling).
3. **Market reform** (ancillary markets, firm-renewable contracts, improved PPAs).
4. **Transmission build-out** (inter-regional corridors to move variable generation to demand centers).
5. **Green hydrogen and industrial electrification** (electrolyser roll-out linked to cheap incremental renewable capacity).
6. **Sustainable land & social frameworks** (brownfield use, agrivoltaics, local benefits).
7. **Finance & manufacturing policy** (credit guarantees, blended finance, domestic value chain support).

These steps, coordinated across central and state governments, industry and finance, can enable India to decarbonize power while supporting economic growth.

**12. Research Gaps and Future Work**

Important areas for future technical, policy, and social research include:

- Operational studies on high-renewable grid stability at 50–80% instantaneous penetration.
- Cost-benefit analyses of hybrid and storage-enabled auctions relative to firming options.
- Lifecycle analysis for PV + battery systems in India, including end-of-life pathways.
- Socio-economic impact studies on land-use transitions, and benefit-sharing frameworks.
- Green hydrogen techno-economic studies specific to Indian industrial clusters and feedstock availability.

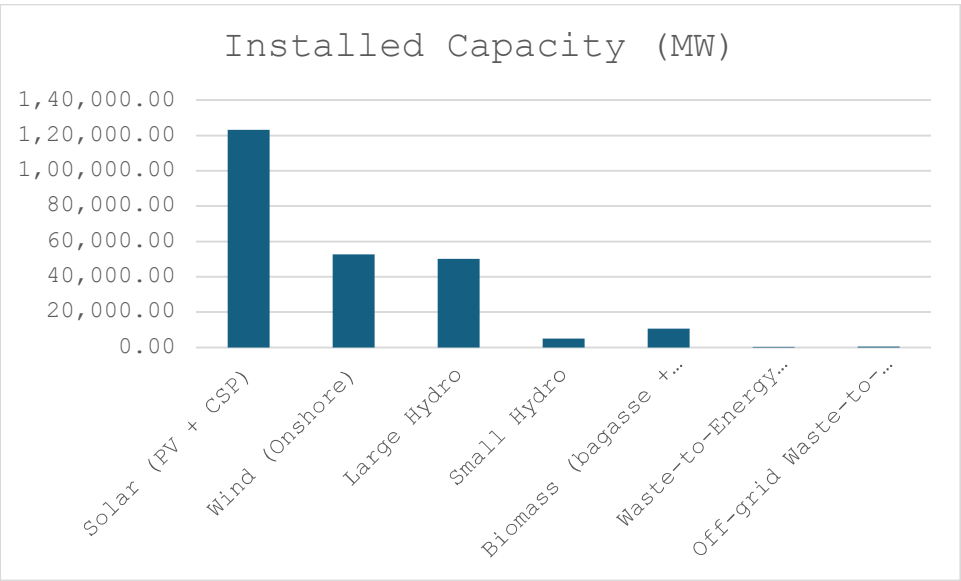
**13. Conclusion**

India's renewable energy story is one of rapid scale-up and experimentation. Solar and wind now occupy the leading roles in the country's RE mix, supported by auctions, falling capital costs, and supportive policy messaging. Yet the transition's next phase — integrating high variable renewable shares while ensuring reliability, affordability, and sustainability —

presents complex technical, regulatory, and social challenges. Addressing grid integration (storage and transmission), creating robust market mechanisms, and building resilient domestic supply chains and recycling systems will be critical. With coordinated policy action and sustained investment, India can transform its power system to meet climate and development objectives.

**Appendix A — Data Table and Figure**  
**Installed Renewable Energy Capacity in India (as on 31 Aug 2025) — MNRE (selected technologies)**

| Technology                      | Installed Capacity (MW) |
|---------------------------------|-------------------------|
| Solar (PV + CSP)                | 123,130.13              |
| Wind (Onshore)                  | 52,681.20               |
| Large Hydro                     | 50,108.17               |
| Small Hydro                     | 5,108.71                |
| Biomass (bagasse + non-bagasse) | 10,743.11               |
| Waste-to-Energy (utility)       | 309.34                  |
| Off-grid Waste-to-Energy        | 545.11                  |
| Total (including large hydro)   | ~242,625.77             |



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