Summer Internship Project Report
On
"Grid-Scale Challenges & Solutions for Integrating 500 GW Renewable Energy into the Indian Power System by 2030"

Undertaken By

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Declaration

I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/ data/ fact/ source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Company and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

CERTIFICATE

It is to certify that the work contained in this report titled **"Grid-Scale Challenges & Solutions for Integrating 500 GW Renewable Energy into the Indian Power System by 2030"** is submitted by **Sunny Kumar** of the Department of Electrical Engineering in Indian Institute of Technology(ISM) Dhanbad to Grid Controller of India Limited, for the completion of Summer Internship.

Signature Of Industry Mentor

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(Manager)

Grid Controller Of India Limited
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ABSTRACT

- India has set an ambitious target of integrating 500 GW of non-fossil fuel-based renewable energy (RE) capacity by 2030 into its power system, in alignment with its commitments under the Paris Agreement and its growing energy demand.

- This project report examines the grid-scale challenges and corresponding solutions associated with integrating such a massive quantum of variable and intermittent RE, primarily from solar and wind sources, into the Indian grid.

- The key challenges addressed include grid stability, frequency and voltage control, transmission infrastructure constraints, energy storage limitations, and forecasting accuracy. The report also explores the impacts of renewable variability on system reliability and the balancing requirements of thermal and hydro resources.

- To overcome these challenges, the study evaluates technological, regulatory, and policy-based interventions, including expansion of Green Energy Corridors, development of high-capacity HVDC lines, battery energy storage systems (BESS), flexible generation strategies, dynamic reactive power support, and real-time monitoring through renewable energy management centers (REMCs).

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1.Introduction & Rationale

1.1 Context & Goal

India has committed to one of the world's most ambitious clean energy transitions, targeting **500 GW of non-fossil fuel capacity by 2030**, of which approximately **537 GW** is expected to come from **renewable energy (RE)** sources such as solar, wind (onshore and offshore), biomass, and small hydro. This target is not only enshrined in India's Nationally Determined Contributions (NDCs) under the Paris Agreement, but also concretely laid out in planning documents by key Indian agencies including the **Central Electricity Authority (CEA)**, **Ministry of Power (MoP)**, **Central Electricity Regulatory Commission (CERC)**, and the **Central Transmission Utility (CTU)**.

To meet this goal, CEA's December 2022 Transmission Plan has mapped the development of over **50,000 circuit kilometers** of new transmission lines and **433,575 MVA** of substation capacity to integrate the projected 537 GW RE capacity by 2030. Furthermore, **51.5 GW** of **Battery Energy Storage Systems (BESS)** and high-voltage **HVDC corridors** have been planned to ensure system reliability, grid stability, and round-the-clock power supply.

This project focuses on understanding and addressing the **grid-scale challenges and solutions** essential to achieving the 500 GW integration goal—ranging from transmission planning and real-time grid operations to technical, regulatory, and market interventions.

1.2 Why It Matters

Achieving a **50% non-fossil energy share** by 2030 is not just a technical milestone—it is central to India's **energy security, economic competitiveness**, and **climate leadership**:

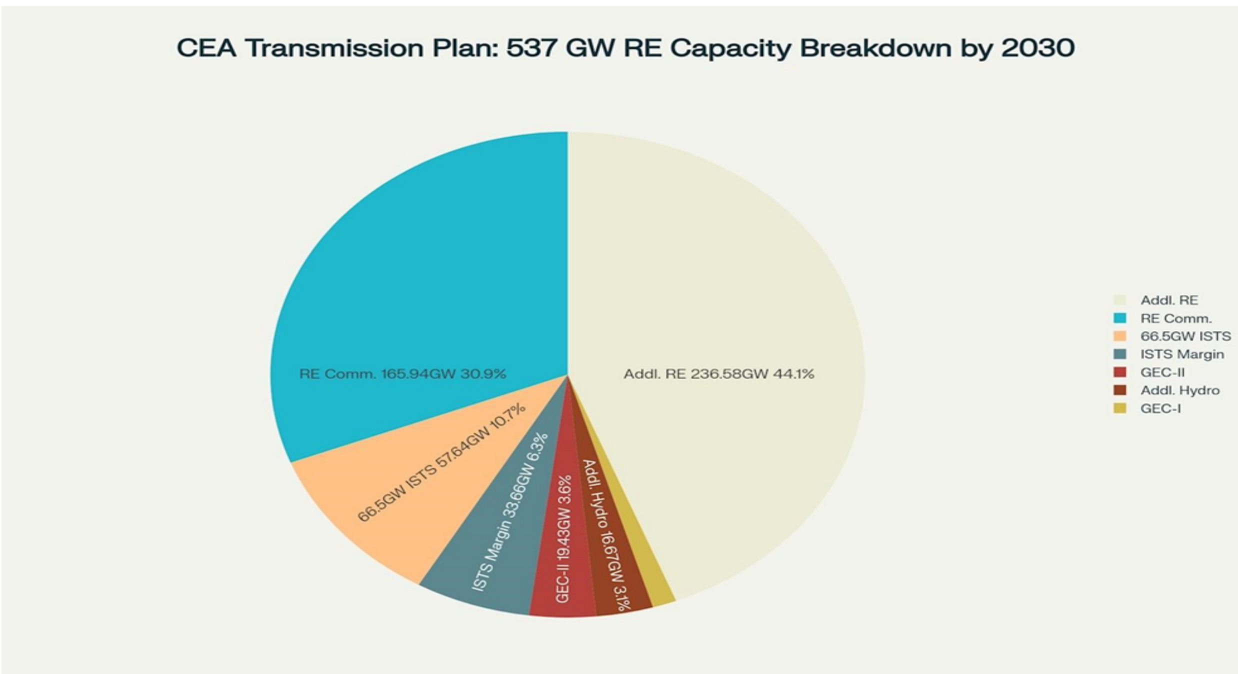
- · **Energy Security & Independence**: Reducing reliance on imported fossil fuels will help India manage geopolitical risks and fuel price volatility, especially given the country's growing electricity demand (forecast to reach 366.4 GW peak by 2031–32).
- · **Climate Commitments**: Integrating 500 GW of renewables is essential to fulfill India's NDCs and its pledge to reduce carbon intensity by 45% by 2030. This aligns India's development path with global climate goals, while promoting environmental sustainability.
- · **Green Investment & Innovation**: The RE transition is expected to drive **₹33.6 trillion** in investments (2022–32), catalyzing economic growth, job creation, and technological innovation in sectors like battery manufacturing, green hydrogen, and smart grids.
- · **Global Renewable Leadership**: India's scale and speed of renewable deployment position it as a leader among developing countries. Flagship projects like the **Bhadla Solar Park** and the **Khavda Hybrid Park** are already attracting global attention.

2. Literature & Policy Survey

2.1.CEA Transmission Plan (December 2022)

Executive Summary

India's Central Electricity Authority (CEA) released its comprehensive transmission plan in December 2022, outlining the roadmap for evacuating approximately 537 GW of renewable energy capacity by 2030[1][2]. This ambitious plan encompasses the development of extensive transmission infrastructure including HVDC corridors, 765/400 kV AC lines, and 51.5 GW of Battery Energy Storage Systems (BESS) to support India's renewable energy targets[3][2].



Overall breakdown of 537 GW renewable energy capacity target showing commissioned, planned, and additional capacity categories

Overall Capacity and Investment Framework

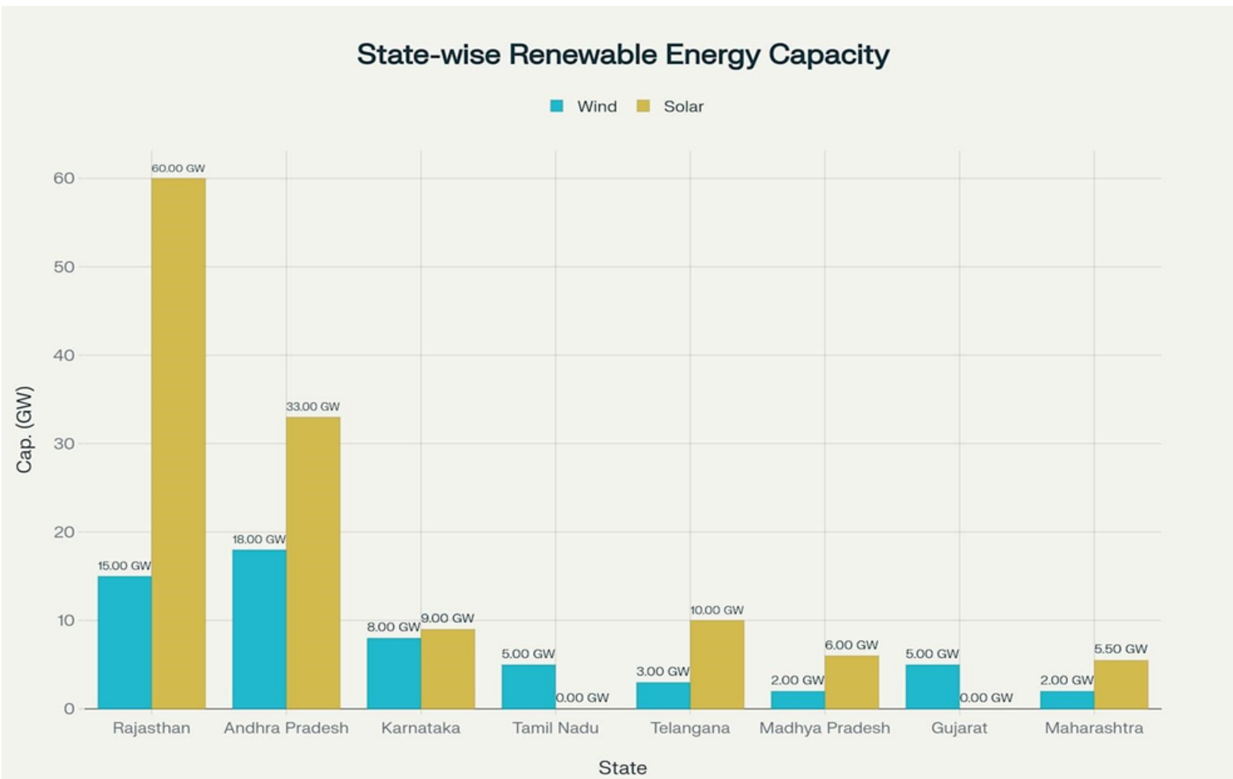
The transmission plan requires a massive investment of **Rs 2,44,200 crores (approximately USD 29.5 billion)** to integrate the targeted renewable energy capacity[3][2][4]. The plan breaks down into several key components:

- **On-shore renewable energy capacity**: 268.68 GW (wind and solar) requiring Rs 2,16,100 crores[5]

- **Offshore wind capacity**: 10 GW requiring Rs 28,100 crores[5]
- **Total additional transmission infrastructure**: 50,890 circuit kilometers (ckm)[5]
- **Additional substation capacity**: 433,575 MVA[5]

State-wise Distribution of Renewable Energy Capacity

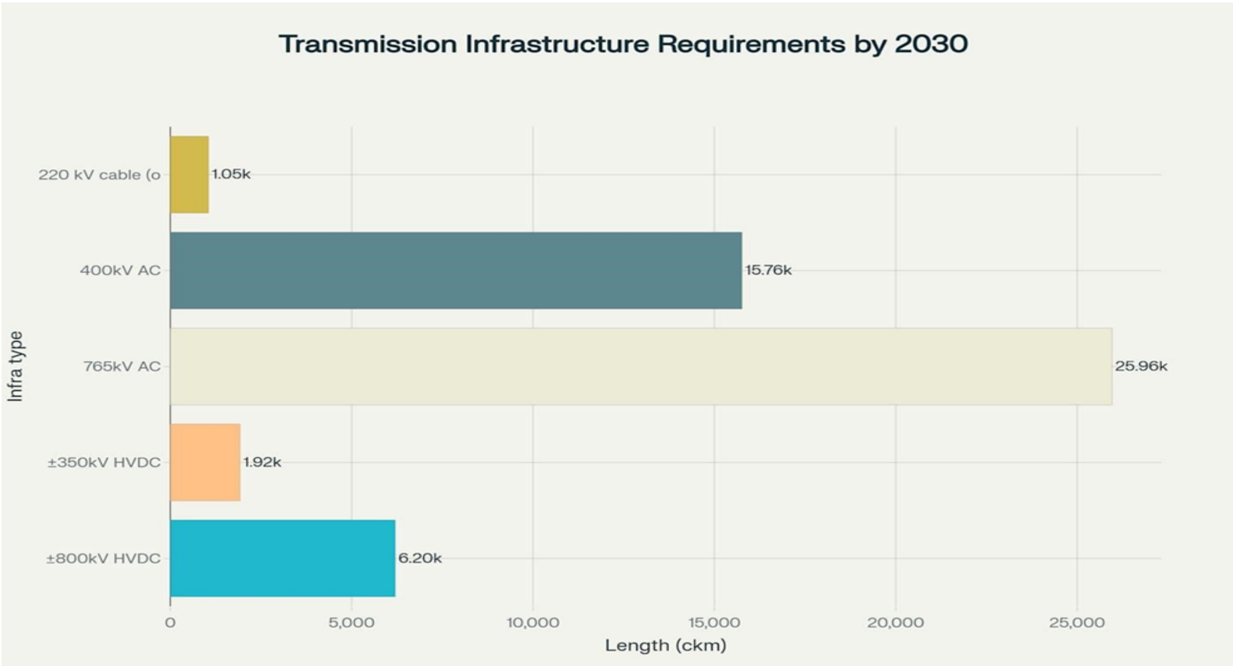
The plan identifies **181.5 GW of additional renewable energy zones** across eight states, with Rajasthan leading the capacity allocation[1][6]. The state-wise breakdown demonstrates India's strategy to leverage diverse geographical advantages for renewable energy development.



State-wise renewable energy capacity distribution showing wind and solar breakdown across 8 states totaling 181.5 GW ISTS connected capacity

Transmission Infrastructure Requirements

The transmission system expansion involves multiple voltage levels and technologies to ensure efficient power evacuation from renewable energy zones to load centers[5]:



Transmission infrastructure requirements showing length of different voltage levels needed by 2030

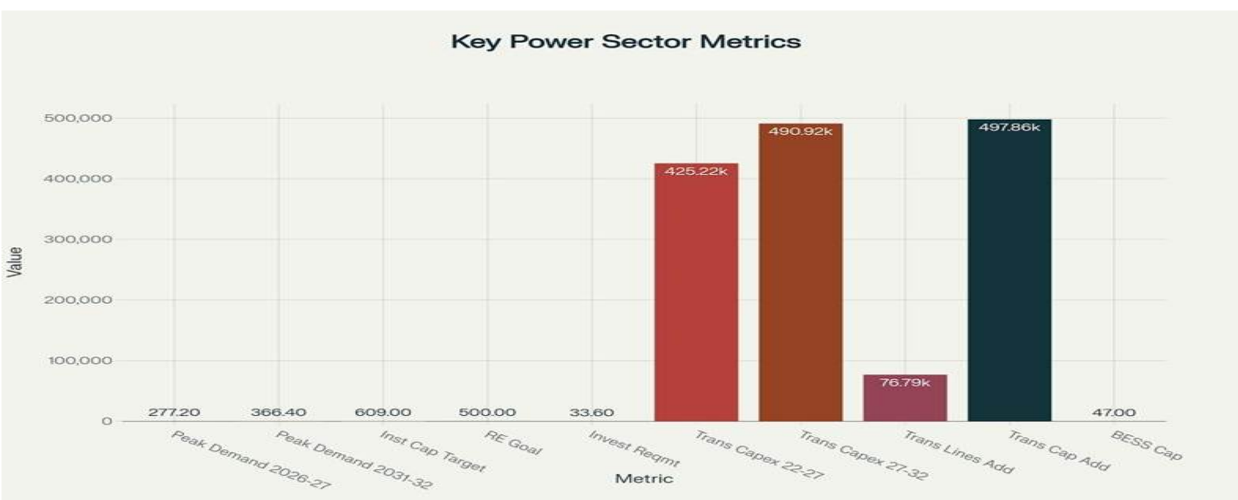
Implementation Timeline and Phasing

The 181.5 GW renewable energy capacity will be deployed in three distinct phases, ensuring systematic grid integration and manageable construction timelines[5]:

- **Phase I (by March 2025)**: 56 GW (24 GW wind + 32 GW solar)
- **Phase II (by December 2027)**: 62.1 GW (17 GW wind + 45.1 GW solar)
- **Phase III (by December 2030)**: 63.4 GW (17 GW wind + 46.4 GW solar)

2.2:National Electricity Plan & CERC Regulations

Metric	Value
Peak Demand Forecast (2026-27)	277.2 GW[1][2][3]
Peak Demand Forecast (2031-32)	366.4 GW[1][2][3]
Installed Capacity Target (2031-32)	609 GW[1][3]
Renewable Energy Goal (by 2030)	500 GW (non-fossil)[1][2][3]
Investment Requirement (2022-32)	₹33.6 trillion[1][3]
Transmission Capex (2022-27)	₹4.25 lakh crore[3]
Transmission Capex (2027-32)	₹4.9 lakh crore[3]
Transmission Lines Addition (2027-32)	76,787 ckm[3]
Transformation Capacity Addition (2027-32)	497,855 MVA[3]
Battery Energy Storage Target (by 2032)	47 GW[3]



Regulatory and Implementation Framework

- **CERC & CEA:** Set, monitor, and enforce technical standards for connectivity, grid operation, and protection[9][10].
- **CTU & Grid-India:** Oversee interconnection studies, system integration, and real-time grid operations.
- **Grid Modernization:** Communication, data exchange, and real-time monitoring systems are prioritized for efficient grid management[9][10].

This concise overview combines the essential data, technical standards, and regulatory framework shaping India's power sector transformation under the National Electricity Plan and CERC regulations.

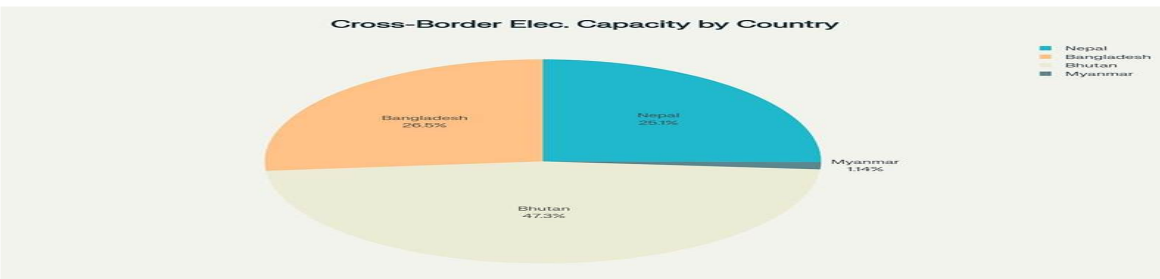
2.3.Green Energy Corridors & OSOWOG

Executive Summary

India's **Green Energy Corridors (GEC)** and **One Sun One World One Grid (OSOWOG)** initiatives represent critical infrastructure programs for renewable energy integration and international grid connectivity. The combined investment across these programs exceeds **Rs 10 lakh crore**, aimed at evacuating over **500 GW of renewable energy** and establishing **global grid interconnections** by 2030-2032.

Cross-Border Infrastructure Development

India currently exchanges **4,100 MW** with neighboring countries through established transmission links[17][14]. This capacity is projected to increase to **7,000 MW by 2026-27** with new interconnections under development.



Current cross-border electricity exchange capacity distribution across neighboring countries

Key existing cross-border connections include:

- **Nepal**: 1,100 MW through Dhalkebar-Muzaffarpur 400 kV line[17][19]
- **Bangladesh**: 1,160 MW via Baharampur-Bheramara 400 kV connection[17]
- **Bhutan**: 2,070 MW from multiple hydroelectric projects[17]
- **Myanmar**: 50 MW through Moreh-Tamu 230 kV line[17]

Planned International Projects

Major cross-border projects under OSOWOG include:

- **India-Sri Lanka HVDC**: 1,000 MW capacity over 285 km with **Rs 3,000 crore investment**[17]
- **India-Oman Undersea Cable**: 3,000 MW capacity over 1,000 km with **Rs 40,000 crore investment**[14][15]
- **India-UAE Grid**: 2,000 MW capacity under discussion[14]
- **India-Saudi Arabia Grid**: 2,000 MW undersea connection being finalized[14][15]

CTUIL Transmission Infrastructure Plan

National Electricity Plan Implementation

The Central Transmission Utility of India Limited (CTUIL) has outlined a **Rs 9.16 lakh crore investment plan** for transmission infrastructure development between **2022-2032**[20][18]. The plan includes **1,91,474 circuit kilometers** of transmission lines and **1,274 GVA transformation capacity**[20][21].

CTUIL transmission infrastructure investment plan showing period-wise allocation from 2022-2032

The investment is phased as:

- **2022-27**: Rs 4.25 lakh crore for **114,687 ckm** transmission lines
- **2027-32**: Rs 4.91 lakh crore for **76,787 ckm** transmission lines
- **Total HVDC capacity**: 33.25 GW bipole links planned[20][21]

Grid Modernization Features

- **Flexible AC Transmission Systems (FACTS)** for grid stability
- **STATCOM and Synchronous Condensers** for reactive power support
- **Dynamic Line Rating** systems for optimized transmission capacity
- **Real-time monitoring** and control infrastructure[2]

Economic and Strategic Impact

Investment and Financing Framework

The combined GEC and OSOWOG programs require **multi-source financing** including central government assistance, multilateral agency funding, and private sector participation[2][5]. The **40% central funding** for GECIII demonstrates government commitment to renewable energy infrastructure[5][7].

Technical and Regulatory Aspects

Key challenges include **right-of-way acquisition**, **environmental clearances**, and **cross-border regulatory harmonization**[18]. Solutions involve **streamlined approval processes**, **advanced technologies** for space optimization, and **international cooperation frameworks**[23][24].

3.Current Status & Gap Analysis

3.1.Installed Capacities

1. As of Feb 2025: ~223 GW Non-Fossil, ~215 GW Renewables; ~24 GW added YTD

🔶 Non-Fossil Fuel Capacity (~223 GW) This includes:
Renewables (Solar, Wind, Biomass, Small Hydro) = ~215 GW
Large Hydro & Nuclear = ~8 GW
Non-fossil capacity refers to energy sources not based on fossil fuels like coal or gas.

🔶 Renewable Energy Capacity (~215 GW) Breakdown (approximate):
Solar Power: ~85 GW
Wind Power: ~48 GW
Others (biomass, small hydro, waste-to-energy): ~82 GW
Renewables are clean, sustainable, and essential for India's climate commitments.

🔶 YTD Addition (~24 GW)
"YTD" = Year-To-Date – means the amount added from April 2024 to February 2025. This reflects strong project commissioning pace, aided by government support and private investments.

ALL INDIA INSTALLED CAPACITY (IN MW) OF POWER STATIONS
(As on 31.05.2025)
(UTILITIES)

Region	Ownership/ Sector	Mode wise breakup									Grand Total
		Thermal					Nuclear	Renewable			
		Coal	Lignite	Gas	Diesel	Total		Hydro	RES*(MNRE)	Total	
Northern Region	State	20845.00	250.00	2703.90	0.00	23798.90	0.00	6108.24	818.00	6926.24	30725.14
	Private	22084.33	1080.00	664.00	0.00	23828.33	0.00	3241.00	47210.87	50451.87	74280.20
	Central	16368.62	250.00	2344.06	0.00	18962.68	2220.00	12241.51	379.00	12620.51	33803.19
	Sub Total	**59297.95**	**1580.00**	**5711.96**	**0.00**	**66589.91**	**2220.00**	**21590.75**	**48407.87**	**69998.62**	**138808.53**
Western Region	State	21120.00	900.00	2693.72	0.00	24713.72	0.00	5446.50	619.23	6065.73	30779.45
	Private	30217.17	500.00	3425.00	0.00	34142.17	0.00	481.00	63832.01	64313.01	98455.18
	Central	21610.47	0.00	3280.67	0.00	24891.14	3240.00	1676.00	666.30	2342.30	30473.44
	Sub Total	**72947.64**	**1400.00**	**9399.39**	**0.00**	**83747.03**	**3240.00**	**7603.50**	**65117.54**	**72721.04**	**159708.07**
Southern Region	State	22992.50	0.00	1162.03	159.96	24314.49	0.00	11927.48	637.08	12564.56	36879.05
	Private	13636.00	250.00	1834.50	273.70	15994.21	0.00	0.00	60935.20	60935.20	76929.41
	Central	13827.04	3390.00	359.58	0.00	17576.62	3320.00	0.00	541.90	541.90	21438.52
	Sub Total	**50455.54**	**3640.00**	**3356.11**	**433.66**	**57885.31**	**3320.00**	**11927.48**	**62114.18**	**74041.66**	**135246.97**
Eastern Region	State	6970.00	0.00	0.00	0.00	6970.00	0.00	3550.22	278.11	3828.33	10798.33
	Private	5723.00	0.00	0.00	0.00	5723.00	0.00	209.00	2190.45	2399.45	8122.45
	Central	16081.86	0.00	0.00	0.00	16081.86	0.00	1103.20	10.00	1113.20	17195.06
	Sub Total	**28774.86**	**0.00**	**0.00**	**0.00**	**28774.86**	**0.00**	**4862.42**	**2478.56**	**7340.98**	**36115.84**
North Eastern Region	State	0.00	0.00	411.36	36.00	447.36	0.00	422.00	276.25	698.25	1145.61
	Private	0.00	0.00	0.00	0.00	0.00	0.00	0.00	357.36	357.36	357.36
	Central	1242.02	0.00	1253.60	0.00	2495.62	0.00	1522.01	30.00	1552.01	4047.63
	Sub Total	**1242.02**	**0.00**	**1664.96**	**36.00**	**2942.98**	**0.00**	**1944.01**	**663.61**	**2607.62**	**5550.60**
Islands	State	0.00	0.00	0.00	84.35	84.35	0.00	0.00	5.25	5.25	89.60
	Private	0.00	0.00	0.00	35.19	35.19	0.00	0.00	30.49	30.49	65.68
	Central	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.10	5.10	5.10
	Sub Total	**0.00**	**0.00**	**0.00**	**119.54**	**119.54**	**0.00**	**0.00**	**40.84**	**40.84**	**160.38**
ALL INDIA	State	71927.50	1150.00	6971.01	280.31	80328.82	0.00	27454.44	2633.92	30088.36	110417.18
	Private	71660.50	1830.00	5923.50	308.89	79722.90	0.00	3931.00	174556.38	178487.38	258210.28
	Central	69130.00	3640.00	7237.91	0.00	80007.91	8780.00	16542.72	1632.30	18175.02	106962.93
	Total	**212718.00**	**6620.00**	**20132.42**	**589.20**	**240059.62**	**8780.00**	**47928.16**	**178822.60**	**226750.76**	**475590.38**

Figures at decimal may not tally due to rounding off

2. By May 2025: ~232 GW Total Renewables → Halfway to 500 GW

India’s 2030 target is 500 GW of non-fossil capacity.
At 232 GW, India is at ~46% progress — halfway there.
The rate of addition must increase further to meet the goal in the next 5 years.

3.2 Infrastructure Shortfalls

A. Transmission Expansion Lagging (Green Corridors)

🔶 What is Transmission Infrastructure?

It’s the network of high-voltage lines that transport electricity from power plants (e.g., solar farms) to homes, industries, and cities.

🔶 What are Green Energy Corridors (GEC)?

A project initiated to Build dedicated lines for renewable power evacuation.
Ensure grid stability and reduce curtailment (unused RE due to transmission limits).

🔶 Current Issues:

Delays in GEC-II, land acquisition, clearances.
Congestion in RE-rich states like Rajasthan, Gujarat, Tamil Nadu.
Inadequate grid balancing tools for variable solar/
wind.

🔶 Impact:

Even if RE is generated, it can’t be delivered reliably to the grid, leading to loss of clean energy and financial losses for developers.

B. Storage Limited (~4.7 GW PHS, 0.22 GWh BESS vs. 60 GW+ Needed)

🔶 Why is Storage Needed?

Renewable sources like solar and wind are intermittent (daytime only / seasonal).
Storage helps:
Store excess power when generation is high.
Release it during peak demand or low RE output.

🔶 Pumped Hydro Storage (PHS) – 4.7

GW Oldest form of grid storage.
Works by pumping water to a height and releasing it to generate power.
India has limited new sites and long approval times.

🔶 Battery Energy Storage Systems (BESS) – 0.22

GWh Newer, fast-responding storage (like large lithium-ion batteries).
Mostly small-scale pilots in India as of 2025.

🔶 Required by 2030: 60 GW+ Storage

As per CEA & NITI Aayog, this is the minimum required to handle 500 GW RE. Need large investments, stable policy support, and viable business models.

4. Technical Challenges in Integrating 500 GW Renewable Energy

4.1. Grid Stability & Flexibility

- Problem: Solar and wind are intermittent sources. Their output is not constant, leading to supply fluctuations.

- Why it matters: These fluctuations cause voltage and frequency instability, risking blackouts.

- Solutions:

- Battery Energy Storage Systems (BESS)

- Flexible hydro and thermal plants

- Demand response mechanisms to balance load in real-time

4.2. Transmission Capacity & Planning

- Problem: RE is generated in remote areas but consumed in urban zones. Long-distance transmission is needed.
- Requirement:
- 8,120 ckm HVDC
- 26,000 ckm 765 kV lines
- 16,000 ckm 400 kV and 1,000 ckm 220 kV
- Challenge: Delays due to land acquisition, cost, and inter-agency coordination.

4.3. Evacuation of Power from Renewable Parks

- Example: Bhadla and Khavda parks generate thousands of MW.
- Problem: Need for dedicated high-capacity corridors.
- Additional Challenge: Requires central and state coordination, land management, and funding.

4.4. Policy and Market Dynamics (Technical Side)

- Financing Issues: High capital cost for storage and grid infrastructure.
- PPA Delays: Developers hesitate without long-term contracts.

5. Case Studies

5.1. Bhadla Solar Park(2245 MW)- evacuation via high-voltage corridors,evolving operational protocols.

- **Location & Capacity**:
  - Situated in Bhadla ,Rajasthan, India.

- One of the world’s largest solar parks with over 2,245 MW installed capacity.

· **Evacuation Infrastructure**:

- Step-up via 220 kV, 400 kV, and 765 kV substations.
- Power evacuated through high voltage corridors built by **PGCIL** and **RVPNL**.

· **Transmission Lines**:

- 765 kV lines connect Bhadla to major grid nodes (Phagi, Jodhpur, Fatehgarh).
- Ensures minimal transmission losses and long-distance evacuation.

· **Operational Protocols**:

- **SCADA** for real-time remote monitoring and control.
- **STATCOMs** for voltage regulation under fluctuating solar output.
- **Synchroscope & PMUs** used for grid synchronization.
- Adherence to **CEA Grid Standards** and IEGC protocols.

· **Grid Coordination**:

- Coordinated with **WRLDC** and **Rajasthan SLDC** for dispatch and load flow.
- Scheduled maintenance and load forecasting improve reliability.

· **Outcome**:

- Efficient, stable, and scalable model for large-scale renewable energy evacuation.
- Sets a benchmark for integrating solar power into India's national grid.

5.2. Khavda Hybrid Renewable Park(30 GW)-multi modal transmission(HVDC+AC) strategies in planning

1. **Location & Capacity**

- Located in Kutch, Gujarat, **Khavda Renewable Park** aims for a massive **30 GW** hybrid capacity (solar + wind).
- It has enough potential to be India's largest renewable energy generation hub.

2. **Evacuation Strategy**:
   - Multi-modal transmission combining **AC and HVDC** systems.
   - Designed to handle large-scale, variable generation with grid stability.
3. **HVDC Corridors**:
   - Planned **HVDC terminals** (±800 kV) at Khavda and key load centers (e.g., Haryana, Rajasthan, Maharashtra).
   - Enables long-distance transmission with reduced losses and improved control.
4. **AC Infrastructure**:
   - 765 kV and 400 kV **AC corridors** for regional evacuation and integration with ISTS.
   - Multiple pooling substations planned at 33/220/400 kV levels.
5. **Operational Planning**:
   - **Phased evacuation** aligned with generation rollout (2025–2030).
   - Smart grid integration with **PMUs, SCADA, EMS** for real-time control.
6. **Grid Synchronization & Flexibility**:
   - Hybrid design allows **load balancing**, **redundancy**, and **dynamic re-routing** during peak generation or faults.
   - FACTS devices (STATCOM, SVC) for voltage regulation.
7. **Outcome**:
   - A scalable, future-ready transmission framework for integrating 30 GW RE reliably into the national grid.

    - Demonstrates India's leadership in large-scale hybrid renewable infrastructure.

5.3. OSOWOG/global Grid learning- potential insights for national level grid synchronization.

- **Concept Overview**:
    - **OSOWOG** is an initiative by the **Government of India** and the **International Solar Alliance (ISA)** to create a globally interconnected **solar power grid**.
    - Objective: Transfer solar energy across borders, time zones, and seasons to enable **round-the-clock clean energy access**.
- **Global Grid Vision**:
    - Envisions a **transnational electricity grid** connecting solar-rich regions (tropics) with energy-deficient zones.
    - Aims to integrate **Africa-Asia-Europe corridors** through coordinated inter-regional links.
- **Learning from Regional Grids**:
    - Builds upon models like **European Super Grid**, **GCC interconnection**, and **SAARC Grid proposals**.
    - Leverages experience from **HVDC interconnections** like China–Europe and North Sea Wind Link.
- **Operational Challenges and Learning**:
    - Synchronization of multiple grid codes, market mechanisms, and time zones.
    - **Cybersecurity**, **data interoperability**, and **sovereignty concerns** are key focus areas.
    - Energy diplomacy and multilateral cooperation are essential for operational success.
- **Planning Approach**:
    - Phased implementation:

   - **Phase 1**: Interconnection within Asia (e.g., India-Middle East)
   - **Phase 2**: Africa–Asia link
   - **Phase 3**: Global scale interconnection

- Pilot projects and **bilateral grid tie-ups** are being developed (e.g., India–Sri Lanka, India–UAE).

· **Outcome and Global Significance**:

- OSOWOG promotes **energy equity**, **sustainability**, and **grid resilience** across nations.
- It sets a visionary precedent for **global renewable energy trade**, advancing the UN SDG 7 (Affordable and Clean Energy).

6.Methodology

6.1. Key Outcomes & Derivables from CEA's Transmission Plan for 500 GW Non-Fossil by 2030

1. Executive Summary

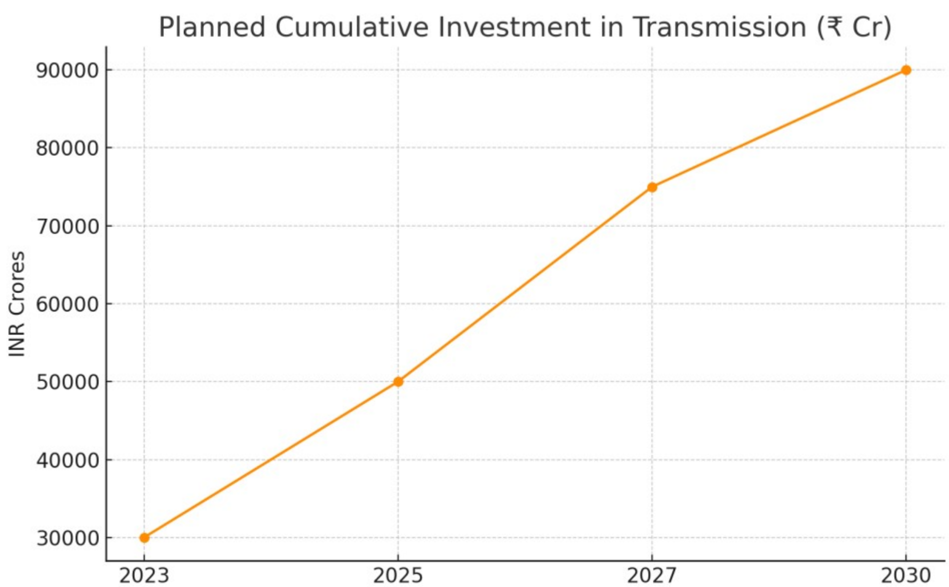
The Central Electricity Authority's (CEA) Transmission Plan for integrating over 500 GW of non-fossil capacity by 2030 outlines the most extensive grid expansion blueprint in Indian history. The plan encompasses over 537 GW of renewable energy (RE), including 181.5 GW from newly identified Renewable Energy Zones (REZs) across 8 states, with substantial roles played by Rajasthan, Andhra Pradesh, and Gujarat. It also integrates offshore wind, green hydrogen zones, and energy storage.

2. Key Targets and Transmission Capacities

- Total RE Capacity Planned: 537 GW
- Transmission lines (ISTS): ~50,890 circuit km
- Substation Capacity: ~433,575 MVA
- Investment: ₹2.44 lakh crores (approx.)
- Phased RE addition: 56 GW by 2025, 62.1 GW by 2027, and 63.4 GW by 2030

- ## 3. Major Outcomes and Derivables

- Transmission phasing is aligned with RE commissioning timelines till 2030
- India to achieve 150,000 MW inter-regional capacity by 2030
- Integration of 5 GW offshore wind (Gujarat, Tamil Nadu) with subsea cables planned
- Prioritization of REZ-linked transmission ahead of generation timelines
- Provisions for green hydrogen hubs and storage-heavy RE clusters



6.2. *comparing RE Developer Practices with CEA Technical Standards & Bottlenecks in PPAs and RPO Enforcement (India – 2025)*

1. Introduction

India aims to install **500 GW of non-fossil fuel capacity** by 2030, with nearly **537 GW renewable energy (RE)**, as detailed by the **Central Electricity Authority (CEA)** in its 2022 Transmission Plan. This massive transition is critical for climate commitments (Paris Agreement), energy security, and economic development.

2. CEA Technical Standards: Summary

The **CEA**, **CERC**, and **CTU** have published the following key requirements for gridconnected renewable developers:

Standard	Requirement
LVRT / HVRT Compliance	Plants must ride-through voltage/frequency disturbances
Ramp Rate Capability	±1.5% of rated capacity per minute (solar & wind)
Forecasting Accuracy	≤10% error in 15-minute block forecasts
Reactive Power Support	0.95 lag to 0.95 lead at interconnection point
Telemetry / SCADA Interface	Real-time data visibility by SLDCs/CTUs

3. Ground Reality: Current Developer Practices

Despite mandates, developers often **fall short** of the above:

Area	Observed Practice (2024–25)	Compliance Gap
LVRT/HVRT Compliance	Only ~55% of plants tuned to handle faults	Moderate

Compliance

Area	Observed Practice (2024–25)	Gap
Forecasting Accuracy	Errors often exceed 15–20% in key states	High

Ramp Rate Management	Many inverters operate without proper ramp control	High
Reactive Power Provision	Static PF used instead of dynamic reactive control	Moderate
SCADA Telemetry	Missing or delayed from ~30–40% of plants	High

This results in grid instability, curtailment, and reduced trust by DISCOMs.

B. Renewable Purchase Obligation (RPO) Enforcement

State	RPO Target (2024–25)	Actual Fulfillment	Gap
Gujarat	17.0%	14.2% Moderate	
Maharashtra	18.5%	12.9%	High
Rajasthan	21.0%	19.8%	Low
Tamil Nadu	18.0%	13.1%	High
Bihar	14.5%	8.7%	Severe

Many states under-procure RE despite availability. Weak enforcement by SERCs is a key issue.

5. Summary Table: CEA Standard vs. Practice

Category	CEA Requirement	Developer Practice	Gap Level
Ramp Rate	±1.5%/min	Often uncontrolled	High

Category	CEA Requirement	Developer Practice	Gap Level
Forecast Accuracy	≤10% error	~15–20% error	High
Reactive Power	Dynamic (0.95 lag–lead)	Static PF in many cases	Moderate

SCADA/Telemetry	Mandatory	Partial/Missing	High
PPA Execution	<6 months post-auction	9–18 months delay	High
RPO Compliance	≥90% compliance	50–80% in many states	High

7.Solutions and Recommendation

7.1. TECHNICAL SOLUTIONS

1.Battery Energy Storage Systems (BESS)

Overview:

BESS refers to grid-connected batteries that store electricity when production exceeds demand and supply it back when demand rises. They play a pivotal role in **flattening the renewable generation curve** and **enhancing grid resilience**.

2. Flexible Hydro and Gas-Based Plants

Overview:

Flexible hydro and gas plants are essential **balancing assets** that provide dispatchable power. Their quick ramping capability allows them to compensate for RE fluctuations.

3. Synchronous Condensers (SCs)

Overview:

Synchronous Condensers are **rotating machines** that provide **non-active services** like **inertia, reactive power**, and **fault current**. They simulate the **electromechanical behavior of traditional generators**.

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4. **Distributed HVDC Nodes**

Overview:

HVDC technology allows bulk power transfer with **lower losses** and **precise control**. Distributed HVDC nodes spread across the grid help transmit renewable power from **remote generation zones** to **distant load centers**.

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5. **Dynamic Control & Forecasting Systems**

Overview:

These systems use **real-time monitoring**, **AI-based forecasting**, and **automated control** to manage RE variability, grid constraints, and dispatch planning.

7.2. INFRASTRUCTURE SOLUTIONS

Green Energy Corridors (GEC)

What it is:

A national transmission infrastructure project to **evacuate renewable energy** (mainly solar and wind) from generation-rich zones to demand centers.

Key Features:

- **Intra-state and inter-state transmission lines**
- Substations, dynamic reactive power compensation (STATCOM/SVC)
- SCADA-enabled smart monitoring

Offshore Wind Integration

What it is:

Harnessing **high-potential offshore wind** (OW) from India's coastal zones (Tamil Nadu, Gujarat) to the grid.

Why It's Important:

- Offshore wind is **more consistent** than onshore wind.
- **Diversifies the RE mix** to reduce solar dependence.
- Brings RE closer to coastal load centers (e.g., Mumbai, Chennai).

Regional Grid Planning

What it is:

Strategic design and coordination of grid assets across **regions, states, and renewable zones** to manage large-scale RE integration.

Why It's Important:

- Avoids **RE oversupply in localized regions**.
- Allows **optimal dispatch** across multiple grids.
- Supports **MBED (Market-Based Economic Dispatch)** vision by CERC.

3.

OSOWOG – "One Sun One World One Grid"

What it is:

India-led global initiative to **interconnect solar and renewable resources across countries**, enabling **transnational electricity exchange**.

Why It's Important:

- Enables **renewable trading across time zones**
- Reduces global RE curtailment and enhances grid security
- Establishes India as a **RE grid hub and power exporter**

7.3. REGULATORY & MARKET SOLUTIONS

1. Renewable Purchase Obligation (RPO)

What It Is:

RPOs are legally binding mandates requiring **discoms, open access consumers, and captive users** to procure a **minimum percentage of electricity** from renewable sources

2. Power Purchase Agreement (PPA) Enforcement

What It Is:

PPAs are long-term contracts signed between **RE developers and discoms** for selling power at a fixed tariff.

3. Tender Process Reform

What It Is:

The tendering mechanism (primarily through SECI and state agencies) allocates RE projects .

4. Incentives for Storage-Backed RE

What It Is:

Encouraging **integration of battery energy storage** with solar/wind to make renewable energy **dispatchable** and **grid-friendly**.

7.4. FINANCIAL SOLUTIONS

1. Blended Public-Private Finance

What It Is:

A financing model that **strategically uses public funds (grants, guarantees, or concessional loans)** to attract and **de-risk private capital** for clean energy projects.

2. Concessional Capital for Storage & Transmission

What It Is:

Low-cost, long-tenure financing for grid-scale **battery energy storage systems (BESS)**, **pumped hydro**, and **transmission infrastructure** that supports RE.

3. Access to Global Climate Funds

What It Is:

India tapping into **international climate finance** mechanisms to fund clean energy transition, especially in areas with **high public benefit but low financial returns**.

8. Conclusion

This project aims to deliver a **comprehensive, data-driven, and multi-stakeholder strategy** to support India's ambitious transition toward **500 GW of renewable energy by 2030**. Grounded in the Central Electricity Authority's (CEA) transmission roadmap and national regulatory frameworks, the study brings together:

- **Technical modeling** of renewable energy integration challenges such as grid stability, transmission congestion, and storage needs.
- **Policy and regulatory analysis** to identify bottlenecks in PPA execution, RPO compliance, and transmission coordination.
- **GIS-enabled spatial diagnostics** to map Renewable Energy Zones (REZs) against transmission buildout and storage deployment.
- **A phased action plan** recommending short-, medium-, and long-term interventions—spanning infrastructure, market mechanisms, and institutional reforms.