



One National Target, Many State Pathways: Planning Renewable Energy Integration with Equity, Coordination and Demand Flexibility

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Scaling Renewables Without Breaking the Grid

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Motivation

**NATIONAL AMBITION
FOR 2030**

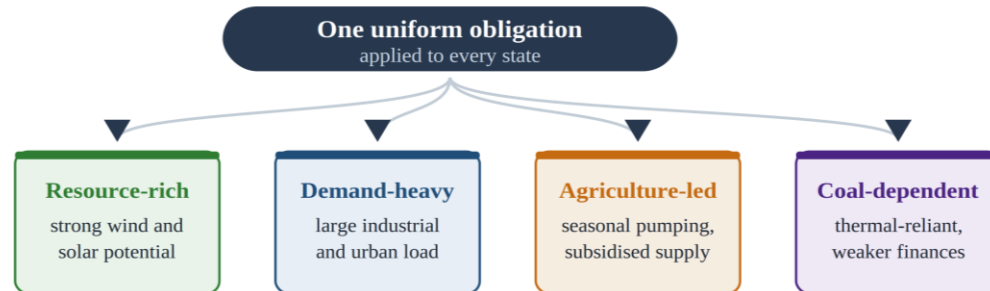
500 GW

non-fossil generation capacity

43.33%

Uniform Renewable Consumption Obligation (RCO) on every obligated utility

Delivery is state-led, and states differ widely

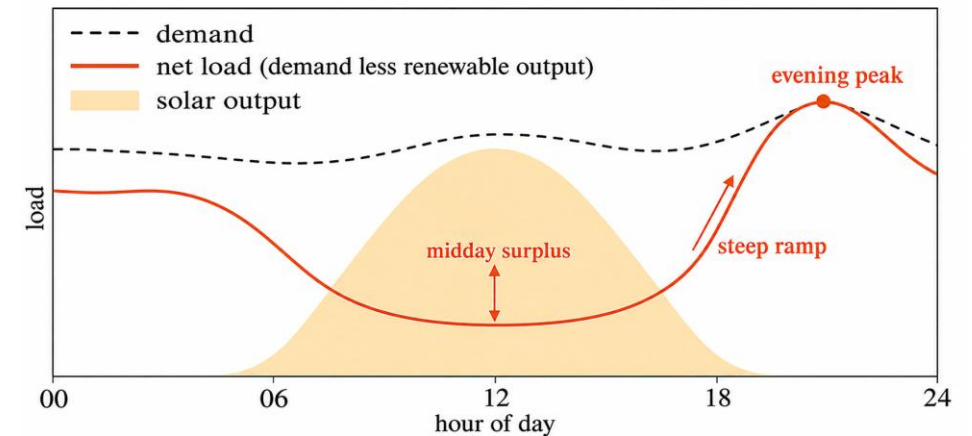


The same percentage means a very different task in each case

A uniform obligation can widen existing gaps

Procurement, demand growth, and operational constraints all sit at the state level.

Integration challenge becomes operational



Curtailement risk

Storage needs

Transmission needs

National ambition must be converted into feasible state-level pathways

A multi-scale framework linking **top-down national targets** to **bottom-up state-level operations**

Gaps in Current Planning Approaches

EQUITY GAP

- **Uniform renewable obligations** overlook large differences in state resources, demand, economic capacity and institutional conditions.
- No **transparent, replicable method** for translating these differences into differentiated state responsibilities.

EFFICIENCY & FEASIBILITY GAP

- Renewable targets are rarely tested using **high-resolution state-level operational models**
- The role of **regional coordination** and **alternative compliance arrangements** in reducing cost and improving feasibility remains underexplored.

FLEXIBILITY GAP

- Demand is often treated as a **fixed or exogenous curve**, rather than as a planning resource
- Demand flexibility is **rarely co-optimized** with generation and storage, partly because granular sectoral and end-use demand data are limited.

Target allocation, operational feasibility, and demand flexibility need to be planned together

Questions the Framework Addresses

1

Allocation:

How should national renewable energy targets be allocated across Indian states with differing capabilities?

2

Implementation:

What planning arrangements enable feasible, least-cost implementation of state-level renewable targets?

3

Demand side:

How can demand flexibility be incorporated as a planning resource in long-term power-system planning?

Base year: FY 2023
Target year: FY 2030

Part 1:

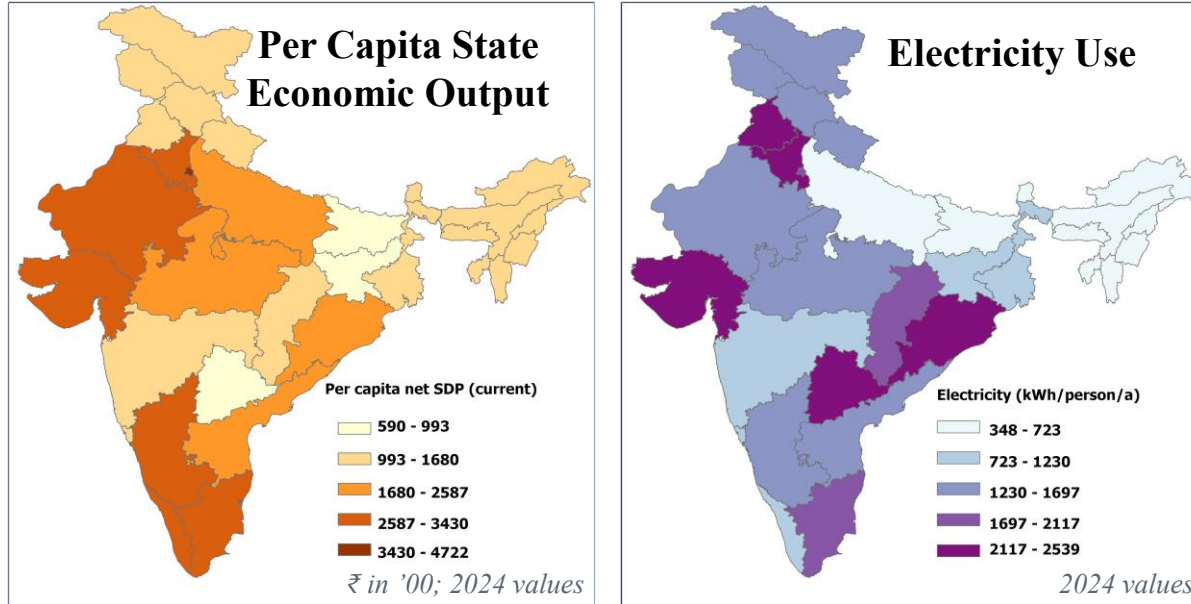
Readiness-Based Target Allocation

Who should carry how much renewable responsibility?

Part 1: Readiness-Based Target Allocation

Why differentiated state targets?

Uniform Targets vs. Diverse Capacities



RCO (43.33%) applies the **same percentage** to all state DISCOMs

States differ widely in resource endowment, demand conditions, and institutional capacity

A uniform RCO can impose uneven burdens across states

RCO = Renewable Consumption Obligation

Major Objectives

1 Disaggregate readiness into two dimensions

Generation readiness $\neq$ consumption readiness

A state's ability to host renewable generation is not the same as its ability to absorb renewable electricity

2 Translate readiness into differentiated state targets

Align national goals with state-level capability

Use readiness scores to design more equitable state-level responsibilities

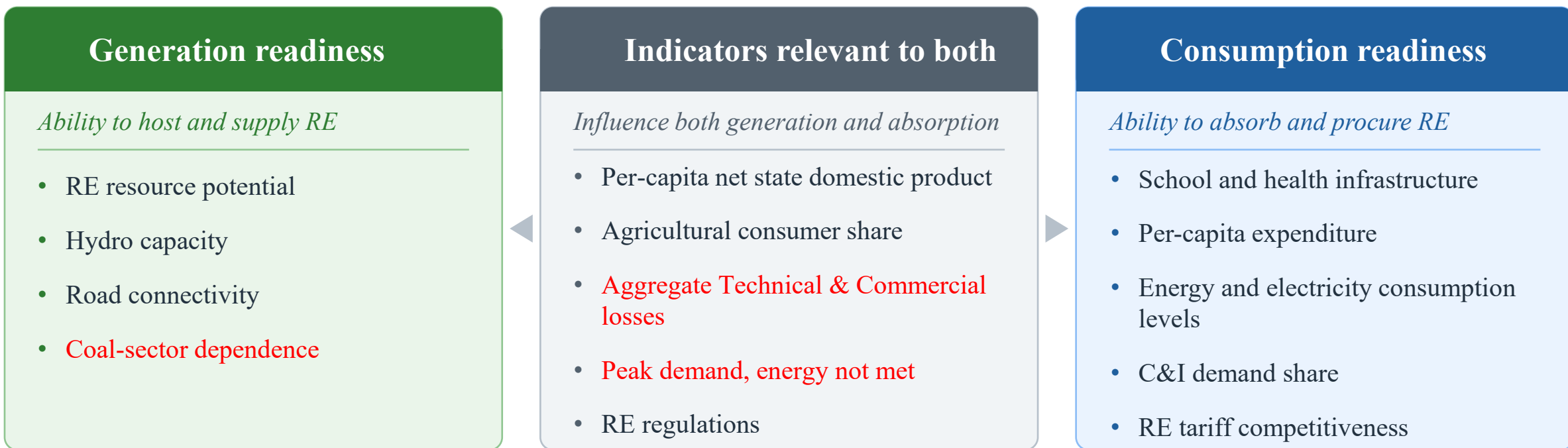
Common but differentiated responsibilities, applied within one national power system

Part 1: FY2023 Methodology

How do we measure state readiness?

Indicator selection

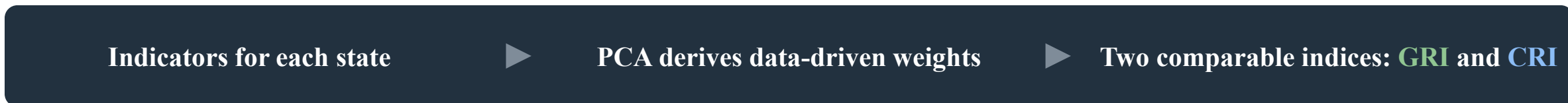
Readiness is treated as two related but distinct capabilities: hosting renewable generation, and absorbing or procuring renewable electricity.



How indicators become readiness scores

PCA= Principal Component Analysis

■ Regressive indicators

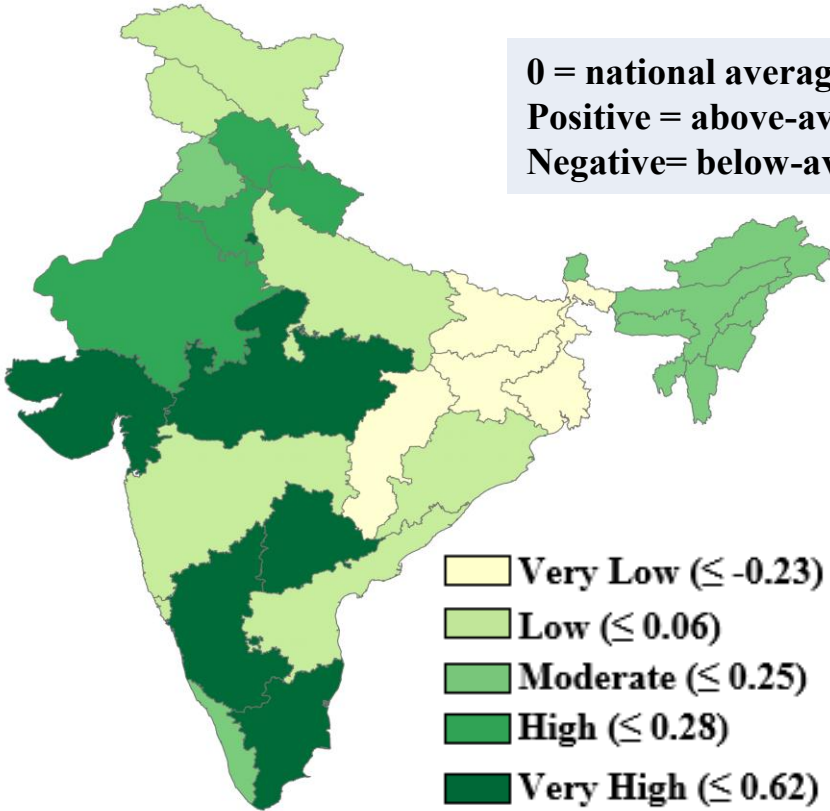


Readiness scores are relative to the national mean: +ve = above average, -ve = below average

Part 1: FY2023 Readiness Across States

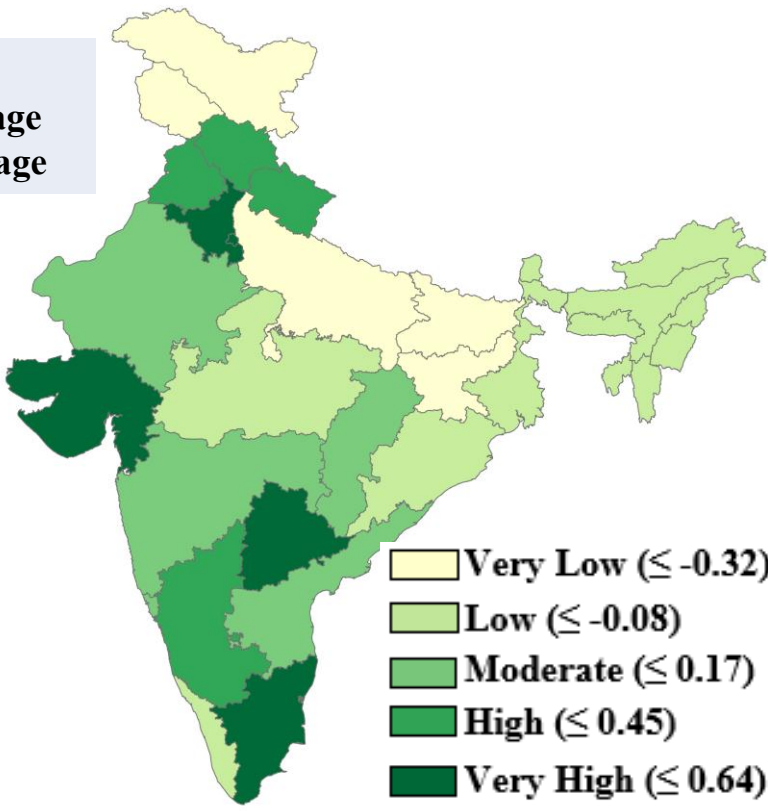
Generation and consumption readiness are distinct dimensions

Generation Readiness Index (GRI)



Range: Jharkhand -1.31 to Karnataka +0.62

Consumption Readiness Index (CRI)



Range: Bihar -1.24 to Haryana +0.64

Top drivers of GRI

- Hydro installed capacity
- Agricultural consumer share

GRI linked to system flexibility

Top drivers of CRI

- Mean per capita expenditure
- Per capita net SDP

CRI linked to economic capacity

The two dimensions do not match

State	GRI	CRI	
Karnataka	+0.62	+0.44	strong in both
Madhya Pradesh	+0.29	-0.18	stronger on generation
Andhra Pradesh	-0.03	+0.17	stronger on consumption

A single readiness score would hide whether a state is better placed to generate renewable electricity, to absorb it, or to do both

Part 1: FY2023 Readiness vs Actual Outcomes

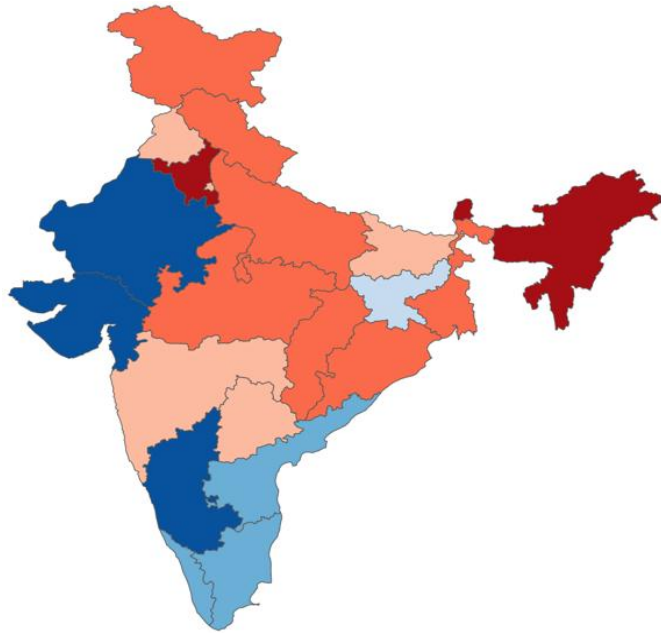
Readiness indicates capability, but realised outcomes can differ substantially

Gap = readiness-based expected share minus actual share

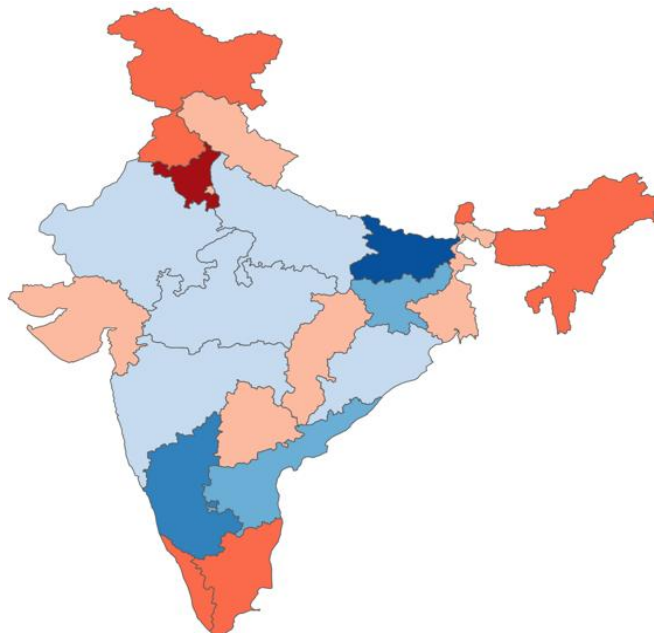
positive gap: shortfall

negative gap: outcome exceeds expectation

RE Deployment Gap



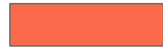
RE Uptake Gap



Shortfall



0 to 5



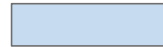
5 to 10



over 10

all values in percentage points

Surplus



0 to -5



-5 to -10



-10 to -15



below -15

darker shade means a larger gap in that direction

Three contrasting states

Rajasthan

Expected 14.4%, actual 38.9%.

Deployment gap -24.4%

*Resource quality & centrally facilitated infrastructure;
part of the output serves other states*

Karnataka

Above expectation on both dimensions.

Deployment -16.9%, uptake -10.4%

*Supportive state policy;
readiness converted into outcomes*

Haryana

Strong readiness, but shortfalls on both.

Deployment +10.1%, uptake +10.8%

Capability not fully realised

Readiness measures underlying capability; actual outcomes also depend on implementation, procurement arrangements and market access

Part 1: FY2030 Projections and Target Allocation

From projected readiness to differentiated state targets

1 Project the indicators to 2030

Business as usual (BAU): recent state-level trends are extended

Convergence (CON): lower-readiness states improve faster under targeted policy support

2 Recompute readiness for 2030

Scenario-specific weights: PCA weights are re-derived from each projected dataset

Readiness scores: FY2030 generation readiness scores are recomputed

3 Allocate the national target

Two inputs: projected readiness and projected electricity demand

Three goals: national non-hydro renewable targets of 20%, 30% and 36.33%

Allocated non-hydro renewable share for four illustrative states

		30% national RE goal		20% national RE goal	
State	Base-year readiness	BAU	CON	BAU	CON
Bihar	Low	8.3%	17.7% ↑	5.5%	11.8% ↑
Jharkhand	Low	0%	1.6% ↑	0%	1.1% ↑
Maharashtra	High	40.2%	32.5% ↓	26.8%	21.7% ↓
Karnataka	High	40.4%	37.1% ↓	26.9%	24.8% ↓
All India		30%	30%	20%	20%

Each value is the state's non-hydro renewable share of its own projected FY2030 demand.

What the allocation shows

- Convergence increases allocations to lower-readiness states
- Higher-readiness states retain larger shares
- Readiness differences persist to 2030

Same national ambition with differentiated state shares based on projected readiness and demand

Part 2:

Operational Feasibility under Coordination

Can those targets be met, and at what cost?

Part 2: Operational Feasibility under Coordination

From target allocation to operational feasibility; scope of study

Part 1 output

Differentiated state renewable targets allocated using readiness and demand



Part 2 question

- Can these targets be translated into feasible capacity and dispatch pathways?
- How the outcome changes when resources can be shared over a wider geographical area?



Model used

A 15-min capacity-expansion and dispatch model

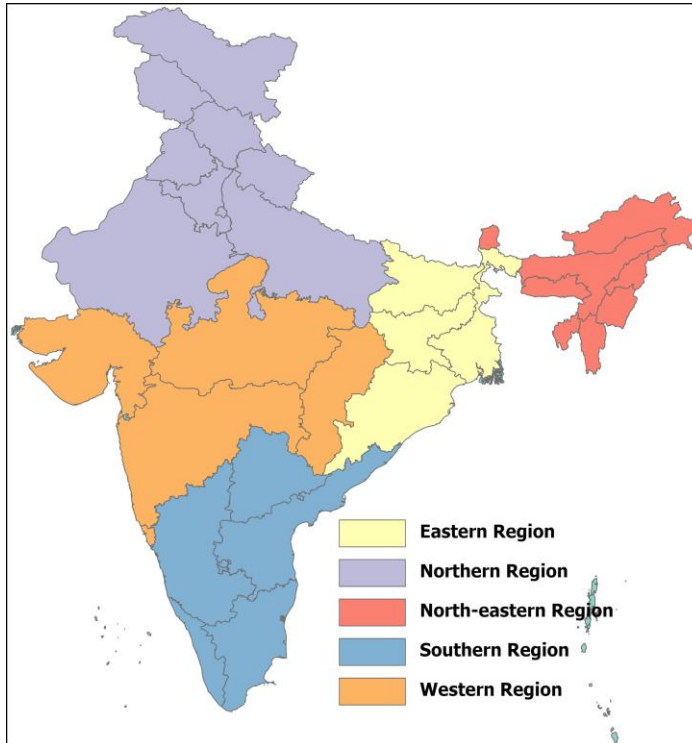
Scope of Study

Southern Region (SR) States

- 1 Andhra Pradesh (AP)
- 2 Tamil Nadu (TN)
- 3 Kerala (KL)
- 4 Karnataka (KAR)
- 5 Telangana (TG)

Western Region (WR) States

- 6 Chhattisgarh (CH)
- 7 Madhya Pradesh (MP)
- 8 Gujarat (GJ)
- 9 Maharashtra (MH)



Projected demand

Covers about 57% of India's projected electricity demand in FY 2030

Resource mix

- MP and CG: pit head coal
- GJ, MH, KA, TN, AP, and TS: solar and wind; KL: hydro

Demand mix and complementarity

- GJ and MH: industrial
- MP, KA, AP, and TS: agriculture
- Diverse seasonal and daily demand patterns create opportunities for resource sharing

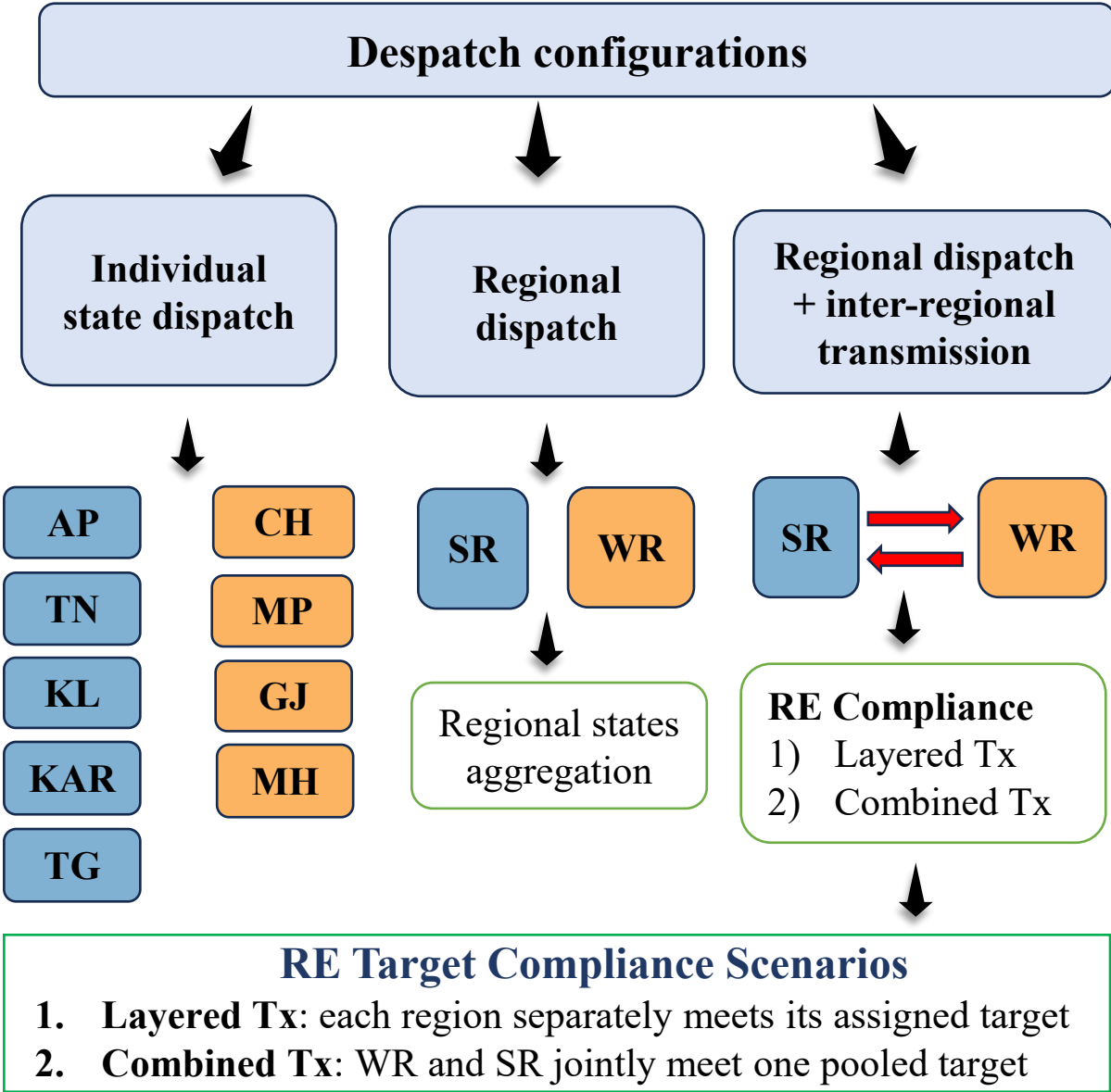
Part 2: Coordination & Compliance Scenarios

SR and WR target allocations and dispatch configurations

No	State	National RE 36.33% Goal	National RE 30% Goal	National RE 20% Goal
1	AP	35.6%	29.4%	19.6%
2	TN	46.7%	38.5%	25.7%
3	KL	24.7%	20.4%	13.6%
4	KAR	48.9%	40.4%	26.9%
5	TG	42.2%	34.8%	23.2%
SR (total)		42.1%	34.7%	23.2%
6	CH	28.5%	23.5%	15.7%
7	MP	43.2%	35.6%	23.8%
8	GJ	42.9%	35.4%	23.6%
9	MH	48.7%	40.2%	26.8%
WR (total)		43.9%	36.2%	24.2%
Combined WR+SR		43.1%	35.6%	23.7%

36.33% = non-hydro renewable component of the 43.33% total RCO

- 7% hydro share is assumed based on historical shares.
- excluded because its resource potential is highly location-specific and not equally expandable across states.



Part 2: FY2030 Methodology

Capacity expansion and economic dispatch model architecture

Resolution: 15-minute, 24 representative days **Scope:** Western and Southern Regions **Granularity:** unit-wise coal and gas

Stage 1: Inputs and scenarios

Demand and VRE profiles

Projected load; solar and wind generation profiles

Existing and planned fleet

Capacity in operation, under construction and retiring

Techno-economic data

Costs and emission factors for existing and new units

Policy and dispatch scenarios

Uniform and readiness-allocated targets; Individual state, Regional, Inter regional (Layered & Combined compliance)

Stage 2: Optimisation core

Objective function

Solver: MILP, GAMS with CPLEX

$$\begin{aligned} \rightarrow \min & \sum_{\text{units}} (\text{Annualised investment cost} \times \text{New capacity}) \\ & + \sum_{\text{days}} \text{Day weight} \sum_{\text{intervals}} \sum_{\text{units}} (\text{Operating cost} \times \text{Generation}) \end{aligned}$$

Key constraints *plus storage balance and addition limits*

Power balance *in every 15-minute interval, in every region*

$$\begin{aligned} \rightarrow \text{Generation} + \text{Net imports} + \text{Storage discharge} \\ = \text{Demand} + \text{Storage charge} \end{aligned}$$

Renewable compliance *over the year, against the allocated target*

$$\begin{aligned} \rightarrow \text{Annual renewable generation} \\ \geq \text{Allocated target share} \times \text{Annual demand} \end{aligned}$$

Unit operating limits *for every coal and gas unit when running*

$$\begin{aligned} \rightarrow \text{Minimum level} & \leq \text{Unit output} \leq \text{Maximum level} \\ \rightarrow |\text{Change between intervals}| & \leq \text{Ramp limit} \end{aligned}$$

Stage 3: Outputs and analytics

Optimal capacity mix

Least-cost generation and storage portfolio for 2030

High-resolution dispatch

15-minute generation for every asset on representative days

Techno-economic results

Total investment and dispatch cost; annual carbon dioxide emissions

Scenario-based insights

Pathways to the same target under different coordination modes

A multi-state optimisation links capacity choice, 15-minute dispatch, and coordination scope in one framework

Part 2: Individual vs Regional Dispatch Outcomes

Some allocations cannot be met alone; coordination pools surplus and shortfall across states

1. States acting alone

Each state must meet its allocated target within its own boundary.

At the 30% national RE target:

Madhya Pradesh



Shortfall persists even with BESS additions.

Maharashtra



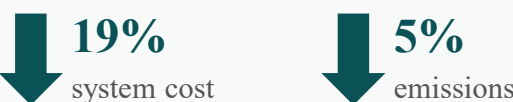
Exceeds its allocation, helping offset MP's shortfall at the regional level.

Feasibility differs substantially across states. Some allocated targets cannot be met in isolation.

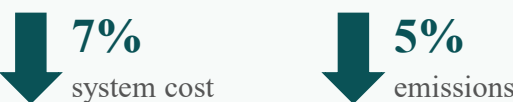
2. Coordinating within a region

At 36.33% national RE target, aggregate of isolated state dispatches is compared with coordinated regional dispatch

Western Region



Southern Region



The same requirement is met with lower cost, emissions and capacity.

A state-level target no longer requires complete state-level self-sufficiency.

3. Wider coordination and compliance

Linking both regions, at the same target:



About 21% lower than states acting alone

How is renewable deployment distributed across regions?

Separate regional targets (Layered)



One pooled target (Combined)



Shares indicate each region's contribution to total WR-SR renewable deployment

Coordination improves feasibility and lowers cost; pooled compliance increases siting flexibility but concentrates deployment

Even with coordination, storage requirements rise as renewable targets become more stringent.

Part 3:

Demand Flexibility Valuation

How can flexibility reduce the remaining integration burden?

Part 3: Adding the Flexibility Dimension

From coordinated supply-side planning to demand-side flexibility

Study area: Maharashtra

What Part 2 showed

Regional coordination reduces the cost of renewable integration.



Remaining challenge

High-renewable pathways still require substantial storage and balancing flexibility.



Part 3 response

Treat demand flexibility as a planning resource alongside generation and storage.

What is demand flexibility in this study?

The ability to shift or temporarily modify electricity demand over time, within defined physical and service constraints.

Two types are modelled. **Load shifting:** energy is moved from one period to another. **Cooling modulation:** demand is temporarily reduced, with part of it returning later as rebound.

Data challenge

15-minute sectoral and end-use demand profiles are not available.

- They must therefore be reconstructed from aggregate demand before flexible loads can be identified and valued.

Major objectives

- Reconstruct sectoral and selected end-use demand profiles
- Co-optimize demand flexibility with generation and storage
- Test whether usable flexibility is limited mainly by cost or by physical deliverability

Demand is no longer treated as fixed: selected flexible loads are represented as decision variables in system planning

Part 3: Reconstructing Sectoral Demand

Sectoral load curves do not exist for Indian states, so they are estimated

What is available

- 15-minute total system demand from the load despatch centre
- Annual electricity share of each sector from tariff filings
- Evidence-based time-of-day and monthly patterns by sector from load research

Not available: the 15-minute demand of each sector

Reconstruction optimisation

Estimate the most plausible sectoral curves that stay close to the priors and remain temporally smooth

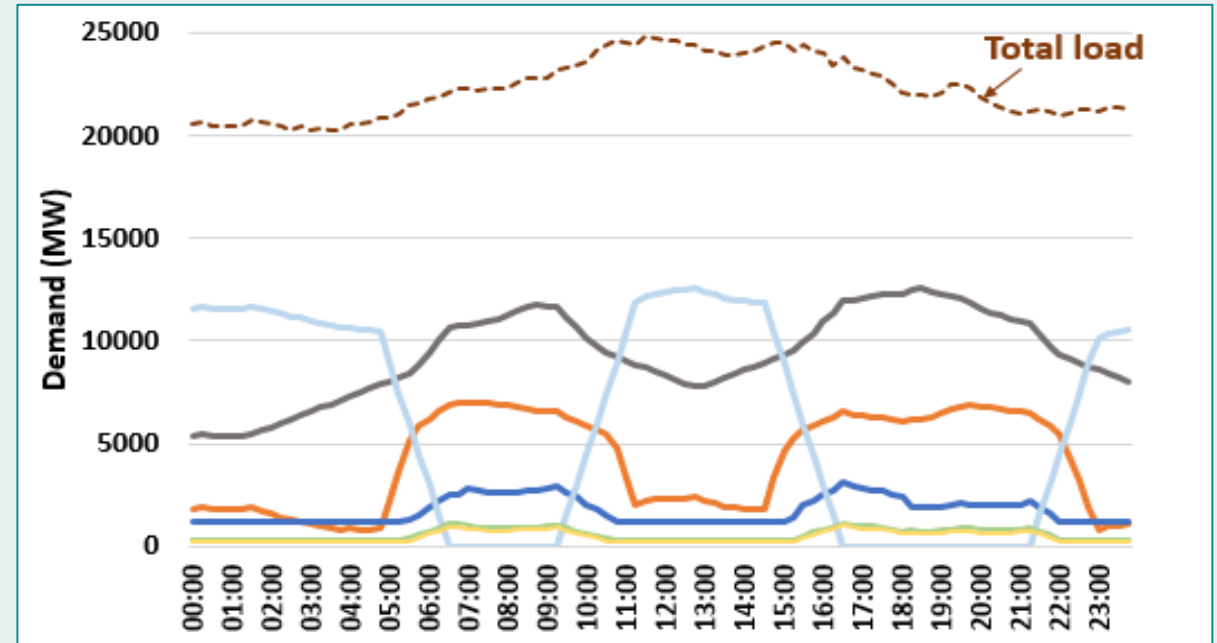
Objective

$$\min \sum \lambda_s (X_{s,t} - \tilde{X}_{s,t})^2 + \Omega$$

closeness to priors + smoothness penalties

Quadratic programme, solved with CPLEX via GAMS

Output: six 15-minute sectoral load profiles



Residential

Commercial

Public services

Industrial

Agriculture

Traction

Projected to FY 2029-30 with demand growth, cooling intensity and EV charging

Part 3: Representing Demand Flexibility

Two flexibility resource classes, each bounded by physical operating limits

A Shiftable loads (energy-neutral)

Energy shifted in time; daily energy conserved



Agriculture



Public Water Works



EV Personal



EV Freight



EV Bus

How much? Maximum share of load that can shift at once

How long? Maximum deferral before the load must be served

At what cost? Procurement or incentive cost per unit shifted

Illustrative values

- **Agriculture:** up to 60% instantaneous shift; up to 8-hour deferral
- **EV charging and public water works:** resource-specific shifting limits

B Cooling modulation (with rebound)

Temporary reduction; part of the load may return later



Residential Cooling



Commercial Cooling

How much? Maximum share of cooling demand that can be temporarily reduced

For how long? Maximum duration of a modulation event

How much returns? Rebound share and recovery period

Illustrative values

- **Residential:** 20% modulation; 1.5-hour event; 50% rebound
- **Commercial:** 30% modulation; 2-hour event; 30% rebound

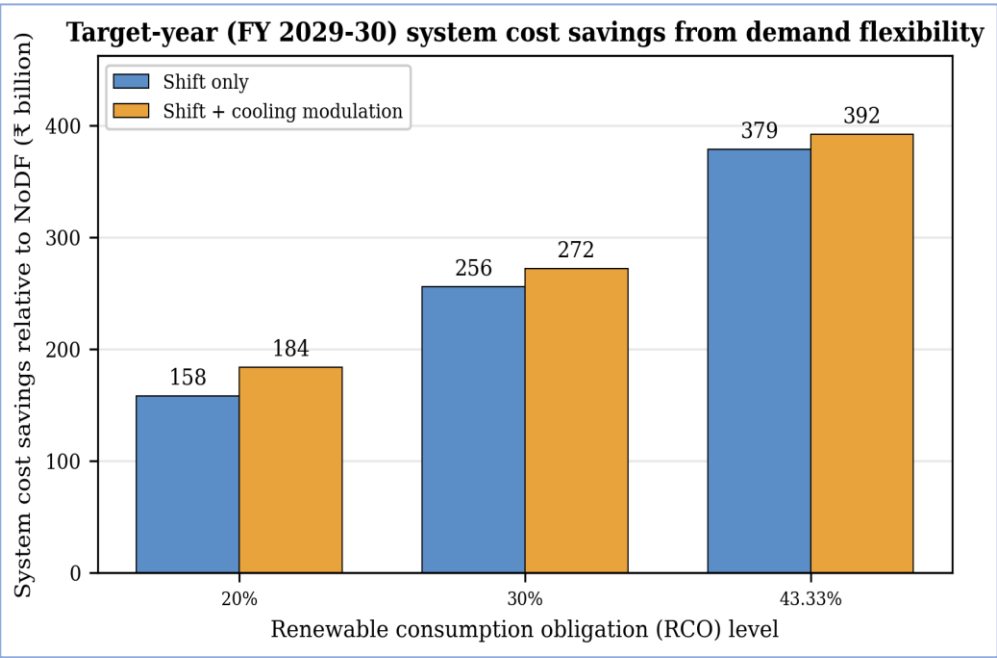
Demand flexibility is physically bounded by how much load can respond, for how long, and how the deferred or reduced demand is recovered.

Part 3: Demand Flexibility Changes the Least-Cost Resource Mix

System value of demand flexibility across increasing renewable obligations

At varying Renewable Consumption Obligation (RCO) in Maharashtra

System value increases with the RCO level



- **20% RCO:** mainly avoids new conventional capacity
- **30% RCO:** reduces both conventional capacity and storage
- **43.33% RCO:** storage substitution becomes dominant

AT 43.33% RCO

₹3,709 → 3,330 bn

system cost, about 10% lower

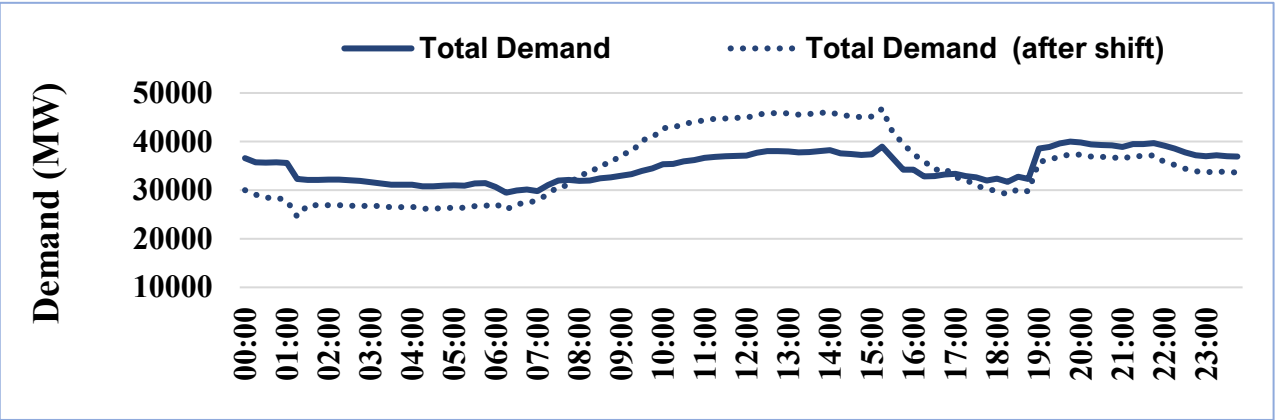
17.6 → 8.9 GW

new 4-hour BESS, about 50% lower

5.7%

of annual energy shifted

How the load reshapes



Midday demand ↑

flexible load moves into solar-rich hours

Evening demand ↓

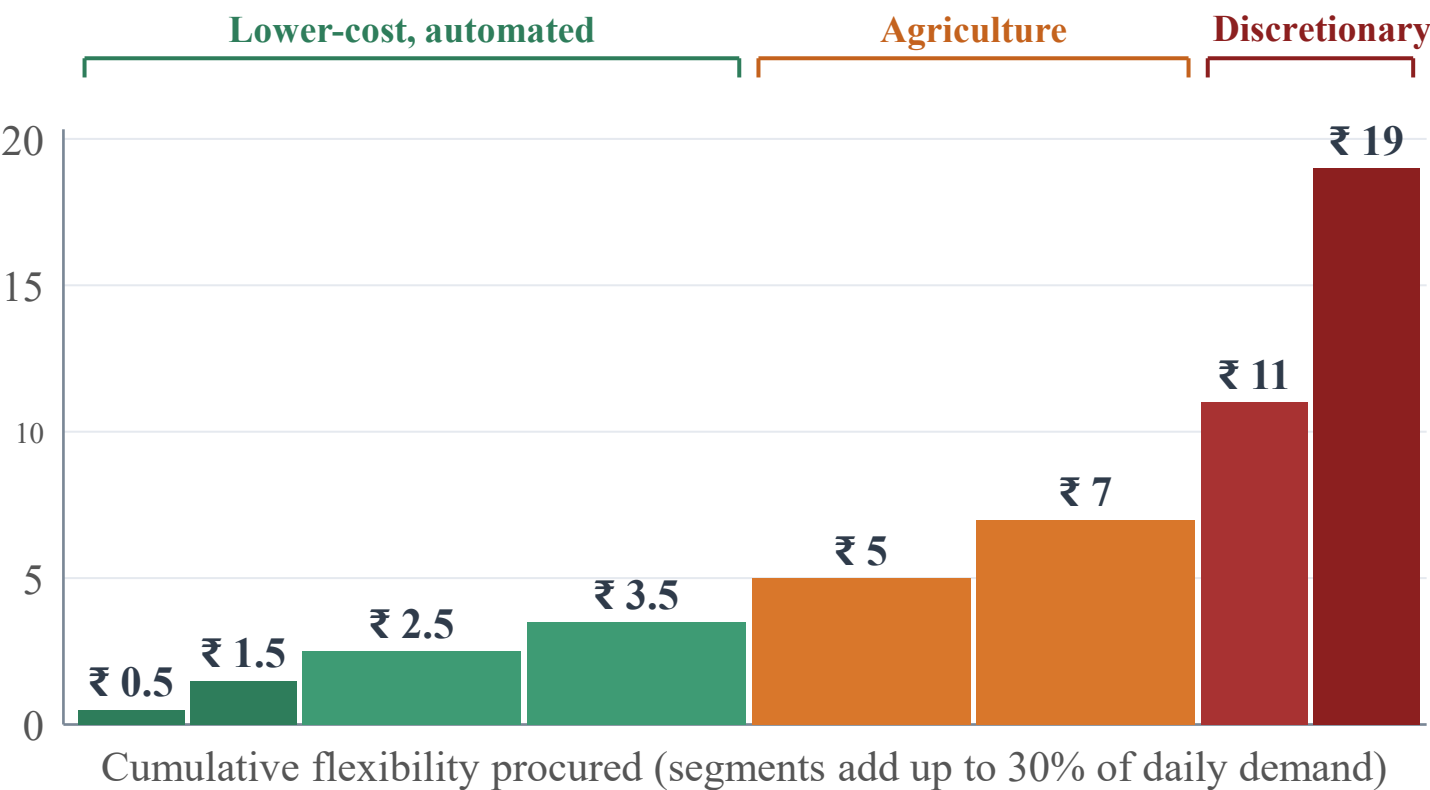
less firming needed at the evening peak

Load shifting provides most of the value; cooling modulation adds a smaller incremental benefit.

Part 3: Cost-Ordered Flexibility Procurement

The first units of flexibility are cheap; deeper participation costs more

Marginal cost of each flexibility segment (Rs/kWh)



Base segment costs are drawn from demand response pilot studies

Why a second model?

The main model gives each sector one flat cost. In practice, the first flexibility is cheap, and the cost rises as more users take part.



Cheapest first

Automated and schedulable loads are used before anything else.



Deeper participation costs more

Each further segment is costlier and more disruptive for users.



Physical limits still apply

How much load can move, and for how long, caps what can be used at any price.

Part 3: What Determines Usable Flexibility?



How much can move at once?

Instantaneous shift cap

15% to 30% of demand

Share of demand that can respond in the same 15-minute interval



How long can it wait?

Deferral window

4, 6 or 8 hours

How long shifted demand can be delayed before it must be served



What does it cost?

Cost curve

Low and high-cost curves

All segment prices scaled up or down by a slope factor



Why agricultural flexibility may carry hidden social costs



Power system view

Shifting farm pumping looks cheap from the grid's side



Farmer's view

Less suitable irrigation timing, extra labour, more water use and higher evaporation losses



In the model

A proxy cost is added to farm segments and tested with and without it, as no reliable estimate exists

In the supply curve, farm segments come after the cheaper automated segments.

Which of these limits decides how much flexibility is actually used?

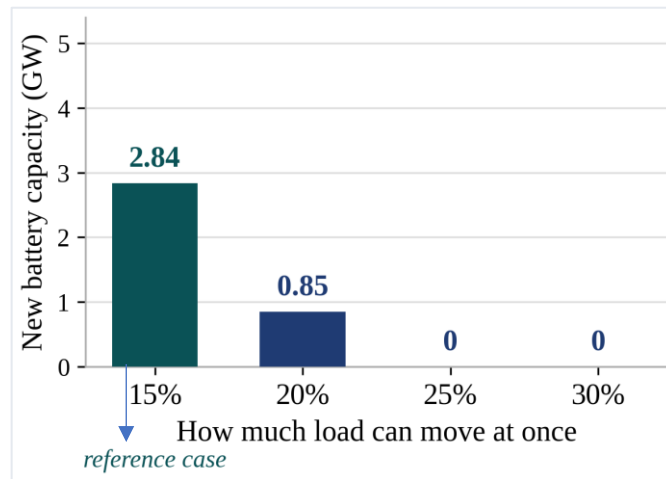
Part 3: Flexibility Supply-Curve Findings

Physical deliverability matters more than the tested cost assumptions

At 43.33% Renewable Consumption Obligation in Maharashtra

1. How much can move at once

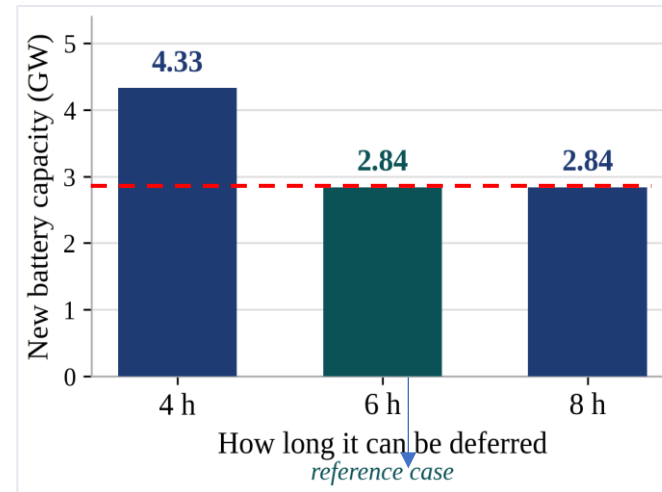
This instantaneous shift limit is the main binding constraint.



Battery additions fall to zero once about 25% of instantaneous demand can respond in these scenarios

2. How long it can be deferred

A six-hour deferral window is sufficient; extending it further adds little value.



Six hours is sufficient to bridge the main midday-solar-surplus to evening-peak period.

3. What it costs

Within the tested range, cost assumptions have limited influence on the amount of flexibility procured.

- Changing the overall cost curve has little effect on procurement.
- The optimiser stops before the higher-cost segments are reached.
- Agricultural segments are not activated, so the social-cost term is non-binding in these runs.

The social-cost term remains important conceptually, even though it is not marginal in these FY2030 scenarios.

Usable flexibility is governed mainly by how much demand can move and for how long, rather than by the tested procurement-cost assumptions.

An Integrated Framework for State-Level Renewable Integration

Flow of analysis: Allocation → Feasibility → Flexibility

National renewable ambition: 43.33% Renewable Consumption Obligation by 2030

EQUITY

Part 1: Dual Readiness and Allocation

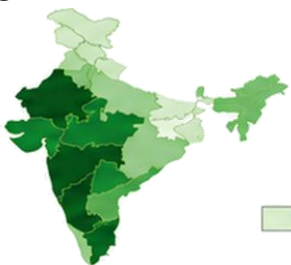
Scale: National → State

Question

Who should carry how much of the national obligation?

Method

Dual-readiness framework (**generation & consumption**) for allocating differentiated state targets.



Base year: 2023
Target year: 2030

Output:

State-level renewable responsibility

EFFICIENCY & FEASIBILITY

Part 2: Coordination and Feasibility

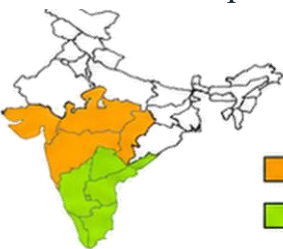
Scale: State → Regional

Question

Can those targets be met feasibly and at what cost?

Method

15-min capacity-expansion and dispatch model for the WR & SR Regions under alternative coordination & compliance structures.



Output:

Feasible least-cost implementation pathways

FLEXIBILITY

Part 3: Demand Flexibility

Scale: Intra-state, demand side

Question

How can the cost of meeting high obligations be reduced?

Method

Sectoral demand-flexibility modelling and cost-ordered flexibility valuation for Maharashtra.



Output:

Value of flexibility and reduced storage burden

One national ambition, implemented through differentiated, coordinated and flexible state pathways

Conclusions

Three findings across allocation, implementation and flexibility

1

Differentiate renewable responsibility

Uniform RCOs overlook substantial differences in state capability.

Projected demand and readiness provide a transparent basis for allocating differentiated state targets.

*Common national ambition,
differentiated state responsibility.*

2

Support allocation through coordination

Some state targets become costly or infeasible in isolation.

Regional and inter-regional coordination improve feasibility and reduce system cost, while pooled compliance can concentrate renewable deployment.

*State-level targets need not require
state-level self-sufficiency.*

3

Treat demand flexibility as a planning resource

Flexible demand can substitute for part of the storage and balancing requirement.

Its value depends mainly on how much load can move and for how long.

*Physical deliverability matters more
than the tested procurement-cost
assumptions.*

National renewable ambition requires differentiated allocation, coordinated implementation, and demand flexibility

Thank You

Optimizing Renewable Energy Integration in India

Equity · *Efficiency* · *Flexibility*

Nikhil Thejesh Venkataramana

Prime Minister's Research Fellow

Department of Energy Science and Engineering, Indian Institute of Technology Bombay