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Optimal Power Dispatch with Renewable Energy Integration Using a MILP Model: A Case Study of Western India[#]

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ABSTRACT

India's power sector is undergoing a rapid transformation towards integrating renewable energy sources to sustainably meet growing electricity demand. To support this transition and achieve India's ambitious renewable energy targets, robust modelling frameworks are essential for guiding the development of a sustainable power system. This study presents a mixed-integer linear programming model assessing optimal capacity expansion and dispatch strategies in Western India for 2030. The model evaluates the feasibility of achieving Renewable Purchase Obligations (RPOs) under different scenarios, considering individual state and combined regional dispatch, with varying constraints on new hydro and coal capacity additions. The analysis is conducted at a 15-minute resolution and includes unit-wise disaggregation for coal and gas sources. Results highlight the comparatively better performance of regional dispatch in integrating renewable energy and reducing investment costs. However, trade-offs between coal and battery storage emerge at higher shares of Renewable energy (RE). The study concludes that regional dispatch, strategic capacity planning, and judicious use of energy storage are crucial for achieving a cost-effective and sustainable energy transition in India. It provides valuable insights for strategic policy decisions and demonstrates a framework adaptable to other regions to optimize renewable energy integration and dispatch strategies.

Keywords: renewable energy integration, renewable purchase obligations, regional dispatch, capacity expansion, economic dispatch.

NOMENCLATURE

Abbreviations	
FY	Financial Year
MoP	Ministry of Power
RE	Renewable Energy
CEA	Central Electricity Authority
DISCOM	Distribution Companies
GW	Gigawatt
INR	Indian Rupee
$MtCO_2$	Million Tonnes of Carbon Dioxide
NDC	Nationally Determined Contributions
RPO	Renewable Purchase Obligations
WR	Western Region
WRLDC	Western Region Load Despatch Centre

1. INTRODUCTION

India’s power sector is undergoing a significant transformation, rapidly integrating renewable energy sources to meet growing electricity demand sustainably. Over the past decade, RE's share in total installed capacity rose from 14% in 2015 to 33% by April 2024 [1]. This impressive progress extends to non-fossil fuel sources overall, including nuclear and large hydro power, which reached a combined installed capacity share of 43% by April 2024 [1], surpassing India's first Nationally Determined Contributions (NDC) target by nine years [2]. The updated NDCs aim for 50% non-fossil capacity by 2030 [2], with the Ministry of Power (MoP) outlining an ambitious trajectory for RE procurement [3]. Despite these advancements, traditional power system planning models often fail to address the complexities involved in integrating RE sources, such as wind and solar, into the grid. These models typically lack the granularity required to capture the temporal and spatial dynamics of renewable energy generation and its integration.

Recent energy modeling studies in India have examined diverse pathways for decarbonization, often focusing on coal transitions and its role in energy system

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evolution [4–7]. Additionally, studies have explored long-term RE integration strategies, assessing different trajectories for wind, solar, and storage technologies [8–12]. Although these studies often project outcomes up to 2050 [13], there is still a critical gap in evaluating high RE integration and storage at more granular temporal and spatial resolutions, particularly for 2030 and beyond.

The MoP's Renewable Purchase Obligations (RPOs) have driven RE adoption since 2010, but state compliance varies significantly [14]. Given the new ambitious trajectory announced by the MoP, it is essential to assess the feasibility of states in meeting diverse RPO targets, considering their current renewable and conventional generation scenarios and future potentials.

This paper addresses these gaps by analyzing the electricity supply in the Western Region (WR) of India, focusing on the target year 2030. The study examines the maximum feasible integration of renewable energy as a share of total generation for each WR state, both with and without storage. It also investigates the feasibility of achieving various RPO targets by 2030, considering scenarios wherein individual states optimize their own state-level dispatch vs scenarios for combined regional dispatch. The analysis includes scenarios that vary the restrictions on new hydro and coal capacity additions: one set where capacity additions are constrained to those under construction, and another where additions are restricted to the remaining potential within the dispatch area.

Additionally, the study assesses the trade-offs between coal-based power generation and battery storage options to meet base-loads, evaluating their respective costs and implications for the power system. The study also evaluates how regional dispatch strategies can exploit the benefits of larger balancing areas, integrating state resources with regional cooperation to develop a cost-effective power system with higher RE integration.

In summary, this research aims to develop a comprehensive supply-side modelling approach for WR states, assessing the feasibility of achieving ambitious renewable energy integration targets and exploring the cost-effectiveness of different dispatch strategies. By incorporating regional dispatch and fostering cooperation across states, the study seeks to inform more efficient power system operations and support policy decisions that align with India's broader renewable energy and climate goals.

2. METHODS

This section outlines the methodologies employed to develop and analyze the capacity expansion and economic dispatch model for the WR of India, targeting the year 2030.

2.1 Model overview

The model presented in this study is a deterministic mixed-integer linear programming (MILP) optimization model developed using the General Algebraic Modeling System (GAMS). It is designed to either minimize total investment and dispatch costs or maximize RE generation, depending on the scenario investigated. The model integrates detailed data inputs and considers operational constraints to simulate and optimize power system performance under various conditions. Fig. 1 illustrates the overall model structure.

2.2 Data inputs

The model utilizes data from state-level DISCOM tariff orders, Central Electricity Authority (CEA) reports, and the National Electricity Plan (NEP). The NEP is a strategic document that outlines the long-term vision and roadmap for India's electricity sector, while the CEA is a statutory body responsible for advising the government and formulating development plans for the electricity systems. These sources provide information on the base year (FY2023) and projected (2030) capacities for various energy sources in the Western Region (WR) states, encompassing both operational and planned projects. Investment costs and emission factors are derived directly from these reports. To forecast future costs, variable costs for existing power plant units are projected using the compound annual growth rate (CAGR) of cost increases observed from 2015 to 2020. This comprehensive data collection ensures that the model is equipped with a robust baseline for evaluating future scenarios.

2.3 *Baseline data and load profiles*

The fiscal year 2022-23 is used as the baseline for this analysis, with comprehensive data sourced from the Western Region Load Dispatch Centre (WRLDC). This dataset includes total generation from all energy sources, power purchases by utilities, and state-wise demand data at 15-minute intervals. Peak days are excluded to prevent overestimation of generation and costs. Two representative days (one weekday and one weekend) for each month are utilized to model typical demand patterns to capture both daily and seasonal variation. These representative days are then scaled to

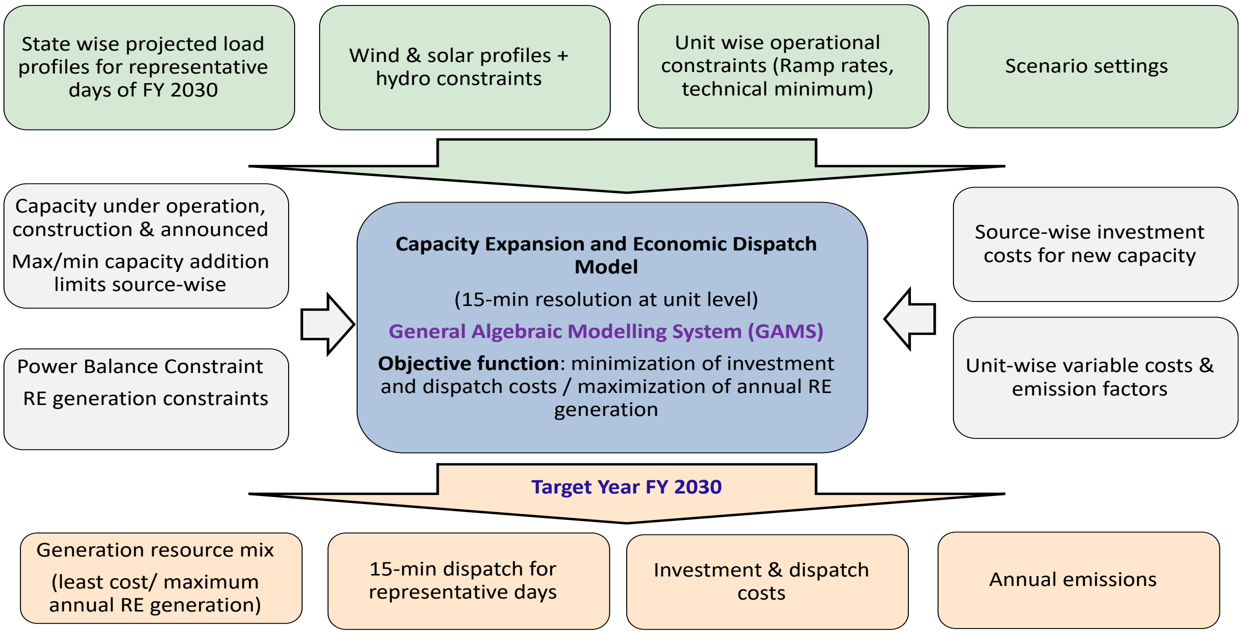

Fig. 1. Model overview

project load profiles for the year 2029-30, based on peak demand and total energy requirements outlined in the 20th Electric Power Survey by CEA [15].

2.4 Model formulation

The model operates at a unit level with a 15-minute resolution, incorporating the following key elements. The primary equations are presented here:

2.4.1 Objective functions

Two objective functions are defined:

Equation 1: minimization of total costs

$$OF1 = Min \sum_{d=1}^{24}\sum_{t=1}^{96}\sum_{s=1}^{S}\sum_{f=1}^{F}\left(INVEST\ (s,f) + VC\ (d,t,s,f)\right)$$

where *INVEST(s,f)* represents the investment costs, and *VC(d,t,s,f)* denotes the variable costs for state *s* and fuel source *f*.

Equation 2: maximization of RE generation

$$OF2 = Max \sum_{d=1}^{24}\sum_{t=1}^{96}\sum_{s=1}^{S}\sum_{f\in R} GEN\ (d,t,s,f)$$

where *GEN(d,t,s,f)* is the energy generation from renewable sources *R*.

2.4.2 Energy generation

The energy generation by each fuel source unit under constraints are modelled as follows:

Equation 3: energy calculation

$$EN(d,t,s,f) = IC(s,f) \times CF(d,t,s,f)$$

where *IC(s,f)* is the installed capacity and *CF(d,t,s,f)* is the capacity factor.

Equation 4: capacity factor limits

$$CFmin(s,f) \leq CF(d,t,s,f) \leq CFmax(s,f)$$

where *CFmin(s,f)* and *CFmax(s,f)* represent the minimum and maximum capacity factors, respectively, for fuel source *f* in state *s*.

Equation 5: ramp rate constraints

$$CF(d,t+1,s,f) \leq (1 + RR(s,f)) \times CF(d,t,s,f)$$

where *RR(s,f)* is the ramp rate limit for fuel source *f*.

2.4.3 RE capacity factors

The capacity factors for RE sources are derived from the base year data and adjusted accordingly for new installations to reflect improved efficiency. Solar and wind capacity factors are based on historical data but are increased to account for the adoption of higher efficiency technologies. For hydro, the plant load factor (PLF) observed on representative days is used to set the upper limit for generation capacity. Additionally, the model incorporates a 4-hour battery storage system characterized by an 88% cycle efficiency and a 1% self-discharge rate in scenarios involving storage.

2.5 Scenario construction

The scenarios in this study are developed by adjusting several critical parameters, including capacity addition constraints, RPO targets, storage options, and dispatch strategies. Capacity constraints are defined as either ‘unconstrained’ or limited to pipeline projects for hydro and coal. RPO targets are tested at 0%, 20%, 25%, 30%, and 43.33%. The analysis also compares cases with and without energy storage options. Two primary objective functions guide the optimization: minimizing total costs or maximizing renewable energy generation. These varied combinations help evaluate the feasibility of achieving optimal dispatch strategies and higher renewable energy integration for Western India in 2030.

2.6 Load dispatch areas

The model examines the dispatch of electricity for both individual states and the combined WR as a whole. This dual approach assesses the potential benefits of larger balancing areas by comparing the cost-effectiveness of state-specific dispatch with a regional dispatch strategy. By integrating state resources and fostering regional cooperation, the model aims to explore how pooling resources across multiple states can enhance the efficiency and balance of the power system, ultimately supporting more cost-effective and reliable power delivery.

3. RESULTS

The results from different scenario runs, as summarized in the Fig. 2, are discussed in this section.

3.1. Scenarios of Cost Minimization: 0% RPO Constraints

Under the 0% RPO constraint, individual state dispatch resulted in minimal renewable energy (RE) investment, with only 3.2 GW of new solar capacity added in Maharashtra and no new RE installations in the other states. Regional dispatch increased new solar capacity to 4.7 GW, demonstrating economic efficiencies with lower total installed capacity (144 GW) and investment costs (2995 INR Billion) compared to the aggregate of individual state dispatch (148 GW and 3397 INR Billion, respectively). When hydro gestation period constraints were applied, individual state dispatch saw 2.5 GW of new solar capacity only in Maharashtra, while regional dispatch increased this to 4.9 GW, continuing to show lower investment costs and more efficient RE integration. This highlights the advantages of regional dispatch in pooling resources and better managing generation and load across a larger area.

3.2. Scenarios of Cost Minimization: 20% RPO Constraints

Under a 20% RPO constraint, individual state dispatch resulted in the addition of 18 GW of new solar capacity and 3.2 GW of new wind capacity, while regional dispatch saw a higher solar capacity of 20 GW and wind capacity of 1.7 GW. This reflects the more efficient resource allocation and lower investment costs achievable through regional dispatch, due to the ability to better utilize solar resources within larger balancing areas. When incorporating hydro gestation period constraints, the differences became more pronounced: individual states added 24 GW of solar and 8 GW of wind, whereas regional dispatch increased solar additions to 33 GW and wind additions to 1.7 GW. This underscores the cost-effectiveness and enhanced RE integration capabilities of regional dispatch in managing resources more flexibly and efficiently.

3.3. Scenarios maximizing RE generation

These scenarios investigate the maximum achievable RPO value for individual states and regional dispatch, both with and without new hydro additions. The results are presented in the Table 1.

Load despatch area	**Capacity addition constraints**	
	Unconstrained	**Pipeline only: hydro**
Gujarat	25%	25%
Madhya Pradesh	22%	20%
Chhattisgarh	25%	2%
Maharashtra	34%	32%
Aggregate of individual state despatch	27%	24%
Regional despatch	32.8%	29.6%

Table 1: Maximum RPO values achieved without storage

Regional dispatch reached a 32.8% RPO compared to 27% in individual state dispatch, highlighting regional dispatch's flexibility and efficiency in achieving higher RE penetration.

3.4. Baseline 32.8% RPO Scenarios for Regional Dispatch

Having established that regional dispatch is better for higher RE integration, 32.8% RPO is taken as the baseline and compare the following scenarios with the target of achieving this 32.8% RPO with capacity addition constraints, which would require storage. For the 32.8% RPO scenarios in regional dispatch, Table 2 outlines the

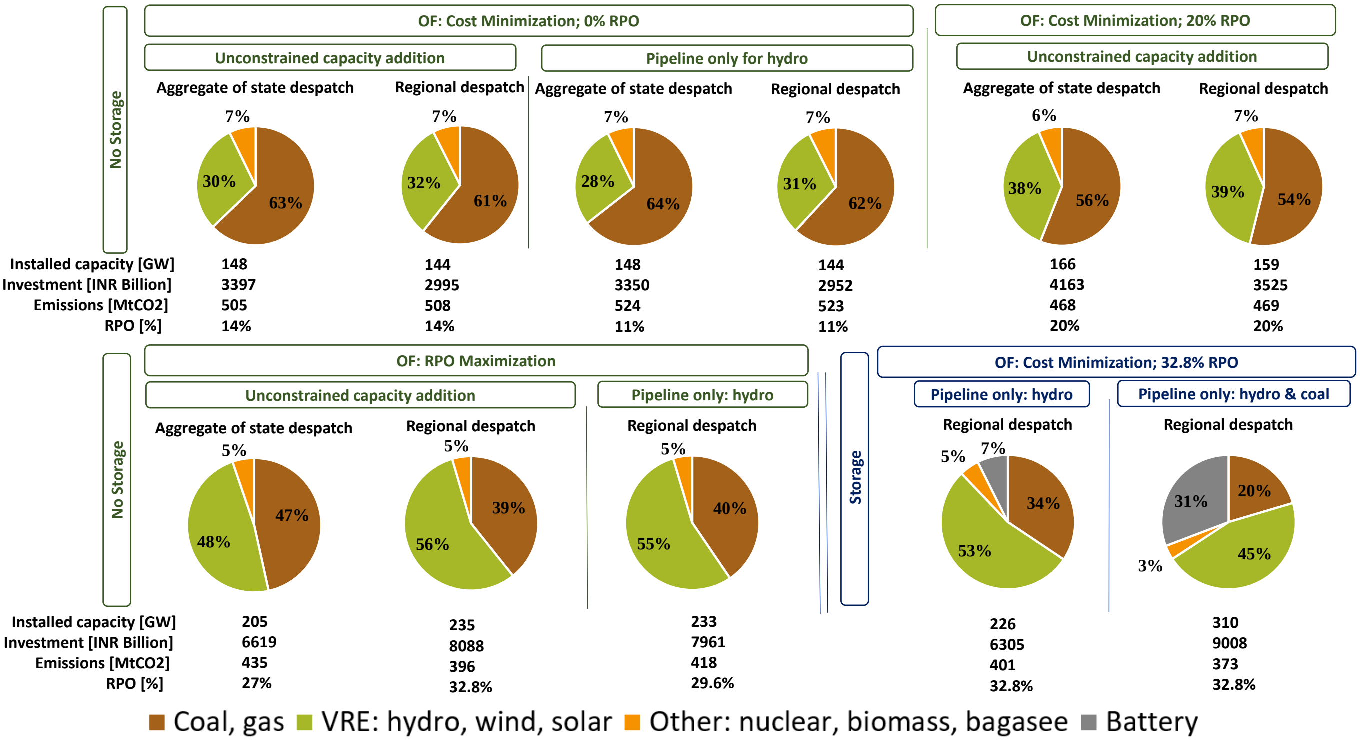

Fig.2. Generation mixes by technology, investment costs, and emissions for WR states in 2030 under various RPO and cost minimization scenarios with and without storage

new capacity additions and investment costs for different capacity addition constraints and objective functions:

New capacity (GW)	**Maximizing RE (No storage)**	**Minimizing cost (storage)**	
	Case1 *Unconstrained*	**Case 2** *Pipeline only (hydro)*	**Case 3** *Pipeline only (hydro & coal)*
Coal	32.6	18	3.52
Solar	35	95	111
Wind	56	1.7	5.5
Hydro	2.3	0.48	0.48
Battery	0	16.7	95.5
Investment (INR Billion)	8088	6305	9008

Table 2: New Capacity Additions and Investment Costs for 32.8% RPO Scenarios

3.4.1. Coal vs battery capacity addition trade-offs

Comparing the 32.8% scenarios reveals that allowing battery storage significantly reduces new coal capacity needs and investment costs. For instance, in Case 1 (no battery storage) 32.6 GW of new coal with an investment cost of 8088 INR Billion. Introducing battery storage in Case 2 lowered new coal to 18 GW and added 16.7 GW of batteries, reducing costs to 6305 INR Billion. However, restricting coal additions further in Case 3 increased required battery storage to 95.5 GW, raising investment costs to 9008 INR Billion. This underscores the importance of finding an optimal balance between coal and battery capacity for cost-effective power system planning in the near term. The situation may change with a reduction in battery costs in the future.

4. CONCLUSION

This study highlights the significant advantages of regional dispatch over individual state dispatch, showcasing improved flexibility and economic efficiency in achieving higher RE integration. The findings emphasize the importance of larger balancing areas for effective resource pooling and cost reduction. Introducing battery storage notably decreases investment costs and reliance on coal to some extent, though overly restricting coal capacity can increase storage needs and costs.

The research underscores the need for strategic planning to balance investments in traditional and storage technologies, providing critical insights for policy decisions and power system management. By focusing on the Western Region of India, the study offers a framework adaptable to other regions, for optimizing renewable energy integration and dispatch strategies.

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