MAHATRANSCO
Maharashtra State Electricity Transmission Co. Ltd.

GRID INTEGRATION LABORATORY
IIT BOMBAY

INTRA-STATE SECURITY CONSTRAINED ECONOMIC DESPATCH ONLINE PILOT IN MAHARASHTRA

INTERIM INSIGHTS FROM SCED REGULATORY SANDBOX EXERCISE



Maharashtra State Load Despatch Centre, MSETCL
January 2026

Disclaimer

The findings and recommendations presented in this interim report are based on the analysis and data available at the time of preparation. While efforts have been made to ensure accuracy, the outcomes of implementing the proposed systems, including any financial savings or operational efficiencies, may vary. Neither the authors nor the institutions involved in the preparation of this interim report shall be held liable for any financial losses or gains resulting from the adoption or non-adoption of the recommendations provided herein. Stakeholders are encouraged to conduct further assessments and consultations to account for specific operational circumstances.



Preface

The operation of the Maharashtra power system is entering a phase of increasing complexity, driven by higher penetration of renewable energy, evolving regulatory mechanisms, changing network conditions and demand characteristics, tighter security requirements, and the need for faster, data-driven operational decisions. In this context, the exploration of Intra-State Security Constrained Economic Despatch (SCED) represents an important step towards strengthening secure, transparent, and economically efficient grid operations at the State level.

This interim report, *"Intra-State Security Constrained Economic Despatch Online Pilot in Maharashtra"*, documents the implementation approach, operational experience, and key insights emerging from the pilot undertaken by the Maharashtra State Load Despatch Centre (MSLDC) in collaboration with the Grid Integration Lab, IIT Bombay, with support from independent domain experts and IT partners. The pilot, taken up as Maharashtra's response to the FOLD (Forum of Load Despatchers) 'MySCED' initiative, has been implemented in parallel mode under a regulatory sandbox framework with the approval of the Hon'ble Maharashtra Electricity Regulatory Commission (MERC), enabling systematic learning without affecting real-time system security.

The intra-state SCED pilot has been undertaken in the context of the evolving regulatory and policy framework governing grid operation and scheduling in India. The Indian Electricity Grid Code (IEGC), 2023 defines SCED and SCUC as optimisation-based approaches for despatch and commitment of generating units, subject to operational and technical constraints, and assigns statutory responsibility to Load Despatch Centres for ensuring optimum scheduling and despatch. The draft National Electricity Policy (2026) recognises the increasing complexity of system operation arising from high renewable energy penetration and states that appropriate Commissions must establish regulatory frameworks for ancillary services, generation reserves, and SCED. In this backdrop, the present pilot has emerged as an important regulatory sandbox initiative aimed at gaining operational experience, strengthening institutional capability at the State Load Despatch Centre level, and generating evidence-based insights to support future regulatory deliberations.

The development of the SCED framework has been a multi-step and iterative process. Multiple versions of the optimisation model were developed and refined to better reflect real system behaviour, operational constraints, contractual structures, and data realities. While this report presents results primarily from the latest version of the model, further refinement remains necessary as system conditions evolve and additional operational requirements are incorporated.

A central objective of this pilot has been capacity building within the system operator. Beyond the development of optimisation tools and dashboards, the initiative has strengthened in-house understanding of optimisation-based despatch, marginal cost signals, ramping coordination, feasibility diagnostics, and system-level trade-offs. Through hands-on engagement and structured training, MSLDC personnel have progressively transitioned from procedural scheduling to analytical interpretation and informed operational judgment. In this process, the Grid Integration Lab, IIT

Bombay has played a key role through continuous technical mentoring and analytical support. This institutional learning is a significant outcome of the pilot and a critical foundation for future scale-up.

The pilot has also reinforced that SCED is not a standalone software deployment but a broader operational reform requiring sustained engagement across technical modelling, data governance, IT workflows, and regulatory alignment. Its continuation is therefore essential to consolidate learning and address emerging challenges such as renewable variability, ramping requirements, and deeper integration of network constraints.

An important insight from the pilot has been the growing interdependence between intra-state and inter-state scheduling and despatch processes. The pilot experience has highlighted how gate-closure timelines, data finalisation practices, and optimisation outcomes at different levels of system operation increasingly influence one another. This highlights the long-term value of calibrated and regulation-aligned harmonisation across State and national levels.

MSLDC gratefully acknowledges the guidance and support of the Hon'ble Maharashtra Electricity Regulatory Commission for permitting this pilot under the regulatory sandbox framework. MSLDC also expresses sincere gratitude to Ms. Abha Shukla, Additional Chief Secretary (Energy), Government of Maharashtra; Shri Ghanshyam Prasad, Chairperson, Central Electricity Authority; Dr. Sanjeev Kumar, CMD, Maharashtra State Electricity Transmission Company Limited; and the management of MSETCL for their continued encouragement, trust, and institutional support. Support received from Grid India and the FOLD authorities is also acknowledged. The technical collaboration with Grid Integration Lab, IIT Bombay, support from the World Bank for GAMS licensing, and the contributions of independent domain experts have been instrumental in shaping the depth and practical relevance of this initiative.

The learnings documented in this interim report are expected to contribute meaningfully to strengthening system operations in Maharashtra and support informed deliberations on the future evolution of intra-state scheduling and despatch practices. This work remains a work in progress, and further insights and learnings will continue to be shared from time to time as the pilot evolves. The experience gained through this pilot places MSLDC on a clear path towards adopting advanced, optimisation-driven operational frameworks based on institutional readiness, evidence, and regulatory intent.



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Acknowledgement

The successful completion of this interim report on the Intra-State Security Constrained Economic Despatch Online Pilot in Maharashtra would not have been possible without the invaluable contributions and support of several individuals and organisations.

We extend our heartfelt gratitude to all concerned, particularly to Maharashtra Electricity Regulatory Commission, The Energy Department of the Government of Maharashtra, Central Electricity Authority, Grid India, Word Bank, and Forum of Load Despatchers for motivating us for this pilot on the intra-state Security Constrained Economic Despatch and their encouragement in producing this interim report.

We are also deeply thankful to the MSETCL management for extending their continuous guidance and support, which has been pivotal in ensuring the smooth progress of this interim report.

We are very grateful to Grid Integration Lab, IIT Bombay, for their guidance and continuous support in conducting this pilot, which has been instrumental in the successful completion of this interim report.

We are also deeply thankful to independent consultant experts for their continuous guidance and support, which has been pivotal in ensuring the smooth progress of this interim report.

We express our sincere thanks to all these contributors for their invaluable roles in this endeavour.

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Executive Summary

The Indian power sector is undergoing a structural transition towards optimisation-based scheduling to enhance economic efficiency, operational reliability, and transparency in grid operations. Building on the successful implementation of SCED at the national level for Inter-State Generating Stations, the MSLDC undertook a comprehensive pilot to evaluate the feasibility, benefits, and institutional readiness for implementing intra-state SCED in Maharashtra. The intra-state SCED pilot in Maharashtra was designed as a parallel, non-intrusive initiative, operating alongside the existing MOD framework without affecting real-time operations or settlements. The pilot aimed to assess techno-economic benefits, operational impacts, data and system readiness, and regulatory implications, while ensuring compliance with prevailing grid codes, contractual obligations, and security constraints.

Based on the ongoing SCED pilot implementation in Maharashtra, this interim report documents a structured comparative analysis carried out across three scheduling paradigms to evaluate the economic and operational impacts of optimisation-based generation despatch. The first scenario represents the prevailing decentralised MOD framework implemented by MSLDC which also serves as the baseline reference for comparative analysis. The second scenario applies a decentralised SCED formulation at the DISCOM level, preserving the existing institutional structure and scheduling framework. The third scenario evaluates a centralised SCED formulation, wherein state-level optimisation is undertaken at the State level with due consideration to DISCOM requestions from their respective generators (owned and contracted) and other contractual obligations and constraints. The SCED engine used in the pilot has evolved at different stages by incorporating learnings and experiences from the online pilot, thereby resulting in different versions of SCED engine over the development of the pilot over past six months. The pilot analysis presented in this interim report is based on the pilot results of the online pilot and the latest online SCED engine that has been run for six-month pilot period data (July-December 2025) to generate uniform comparative performance including comparative analysis with MOD scheduling engine.

Main Findings

Finding	*Description*
Economic Benefit	The SCED pilot demonstrates that optimisation-based scheduling delivers consistent and measurable economic benefits. Comparative analysis across multiple cases shows that SCED yields additional potential savings in the range of approximately ₹6 crore for decentralised to ₹39 Cr in centralised SCED over the pilot horizon of six months. Under centralised SCED, cost reduction of ~0.9 paise/kWh in average procurement cost has been observed.

Ease of Operation	• The SCED pilot shows that the overall ramping requirement (both up and own) under SCED remains consistently lower than MoD schedule for around **~40-90%** of the time. • The SCED framework provides greater clarity on operating reserves, including spinning reserves, ramp-constrained reserves, and cold reserves, with the potential to estimate and monitor different types of reserves, including fast-frequency and primary reserves.
Enhanced Security and Reliability	• The pilot has demonstrated that SCED is well equipped to handle the constraints with additional security cost incurring for ~32% of the time block. This ensures secure and reliable operation, which is of paramount importance in the context of the complex, evolving power system in the State. • SCED through shadow prices, penalty-driven constraints, and other sensitivity parameters helps in identifying the price labelled weak links in the system, thereby enabling the grid operator, planner, and regulators to take informed decisions to optimally and adequately enhance the security through economically effective countermeasures.
Generation Utility Benefits	• SCED ensures all ramping constraints are fully complied with; however, in MoD while ramp limits are maintained for most of the time, under certain cases ramping violation has been observed in the MoD based schedule • Overall MWhr milage of generators consistently remains better in SCED framework compared to the MoD scheduling mechanism.
DISCOM-wise Impact	SCED benefits align with DISCOM generator portfolios. MSEDCL captures the largest gains, averaging ₹3,283 per block with positive savings in 51% of blocks. AEML, BEST, and TPCL also realise measurable benefits. Block-wise variations reflect security-driven optimisation rather than uniform savings across all intervals.
Consumer Relevance	Unit energy cost duration curves demonstrate that SCED delivers lower or comparable energy costs for a majority of time blocks across all DISCOMs. Positive savings or cost neutrality are observed for roughly 70-85% of operating blocks, while higher costs attributes to the additional cost of ensuring security. These outcomes of SCED align with regulatory objectives of tariff prudence.
Computational Performance	SCED engine demonstrates improved computational performance with end-to-end schedule availability, including data processing and dashboard integration, is being achieved within 50 seconds per time block, with solver execution time of 10-20 seconds. Parallel execution of multiple SCED formulations increased total runtime to 60-70 seconds, remaining well within operational scheduling timelines.
Market Integration	SCED through SMPs (both State and DISCOM level) offer an invaluable information to the DISCOMS/Generators that can empower both the stakeholders to take informed decisions of bidding in the power exchange market by looking at SMP and MCP trends/forecast.

Energy and Cost Economy	Generator-level analysis confirms that SCED increases utilisation of lower variable cost plants while restricting over-use of higher cost or ramp-constrained units. High-cost generators that remain over-scheduled under MOD are systematically backed down under SCED, while flexible units are strategically deployed for ramping support rather than energy alone.
System Architecture and Institutional Readiness	The pilot established a robust cloud-based SCED engine and dashboard ecosystem, integrating operational data, optimisation outputs, and analytical visualisation. All SCED runs, inputs, outputs, are logged to ensure auditability and regulatory transparency. The dashboard provides real-time and historical insights into cost, despatch, reserves, ramping, and marginal prices, designed specifically for system operators and decision-makers.
Capacity Building	Capacity building and human resources remains one of the most critical dimensions in institutional development and subsequently successful implementation and sustainable operation of such new and critical initiatives. Therefore, during the pilot phase, a structured two-month capacity-building programme has been conducted for the officials of MSLDC. The programme developed in-house capability in optimisation modelling, SCED formulation, understanding of system marginals, data quality assessment and structuring data input for SCED, creating a strong institutional foundation for long-term adoption.

Major Observations of the Pilot

Economic Benefits

1. **Decentralised SCED vs MOD:**

Across generators, decentralised SCED delivers a net system cost saving of approximately ₹6.09 Cr (0.04%) compared to MOD over the period of six months. While 56% of generators benefit and 44% contributed to the system security, the overall reductions outweigh the additional cost of security, leading to a positive net system impact. This demonstrates that decentralised SCED improves system-level economic efficiency, even though benefits are not uniformly distributed across generators.

2. **DISCOM benefit:**

With overall positive net savings, the positive savings are observed in 67.7% of time blocks, indicating consistent economic benefit, while block-level excess cost of adhering system security remain limited and symmetric to gains. All DISCOMs experience savings over a substantial share of time blocks, with TPCL and BEST showing the highest consistency, demonstrating that decentralised SCED delivers stable cost benefits at the distribution level.

	TPCL	***BEST***	***AEML***	***MSEDCL***
Savings (₹Lakh)	~4.57	~6.43	~18.03	~579.92

3. Centralized SCED benefit over De-Centralised MOD:

Under centralised SCED, centralised operation achieves a lower unit cost (₹3.72/kWh) compared to decentralised MoD despatch (₹3.73/kWh), resulting in a per-unit efficiency gain of ~1 paise/kWh. The unit energy cost difference yields true savings of ₹44.74 Cr over six-month pilot period from (July-December 2025), equivalent to 0.28% of the centralised cost.

	Decentralized Unit Cost (₹/kWh)	*Centralized Unit Cost (₹/kWh)*	*Per-Unit Efficiency Gain (paise/kWh)*	*Total Savings (₹ Cr)*
MOD	3.729	3.718	1	44.74

4. Centralized SCED benefit over De-Centralised SCED:

In the SCED framework, centralised despatch continues to demonstrate cost efficiency over decentralised SCED, with a consistent unit cost advantage of ~₹0.01/kWh. In compared to the decentralised MOD, the comparison with De-Centralised SCED reveals the savings of ₹38.67 Cr over six-month pilot period (July-December 2025), or 0.20% of the centralised cost.

	Decentralized Unit Cost (₹/kWh)	*Centralized Unit Cost (₹/kWh)*	*Per-Unit Efficiency Gain (paise/kWh)*	*Total Savings (₹ Cr)*
SCED	3.727	3.718	0.9	38.67

Ease of Operation

All generators experienced both positive and negative perturbations, indicating widespread redespatch. While the average perturbations are moderate (7% in both directions) with medians around 4-5%, the relatively high standard deviations (9-10%) and extreme values (up to ±60%) highlight significant variability across units, reflecting the non-uniform impact of system-wide optimisation and congestion-driven redespatch.

Improved Generator Utilization

Out of 51 generators under optimization, 50 hit their DC at least once, with 49 generators operating at DC for more than 10% of the time blocks. On average, generators operate at their declared capacity for 62.4% of the pilot period. The maximum observed DC utilisation reaches 100%, highlighting sustained capacity saturation and limited headroom during peak operating conditions.

Future Directions

Centralised SCED Implementation: The pilot experience over past six months has demonstrated that SCED based scheduling mechanism, which is a scientific method (LP/MILP) based optimized scheduling, has a significant advantage on economic, operational and security front, thereby making a strong case for full implementation of SCED based generation scheduling mechanism. Moreover, from the pilot period outcome, adoption of centralized SCED based scheduling mechanism with due compliance of existing contractual obligations, has clearly emerged as the way forward in the intra-state scheduling framework. Centralised SCED scheduling during the pilot period has shown far additional technical,

economic and security benefits with the results demonstrating as high as six times cost savings compared to decentralized SCED.

***SCED Pilot Continuity*:** Building further from the experience of the SCED pilot which has evolved to a stabilized SCED engine over various development stages during past six months, continuation of the pilot for next four to six months is proposed in order to gain experience from the latest stable SCED engine while advancing the SCED models with new features.

***Enhancing the SCED pilot*:** During the pilot period over past six months, various potential strengthening dimensions have been identified, including hydro generation scheduling, inclusion of central (ISGS) share in the Intra-State SCED framework, strengthening of transmission line constraints, treatment of special cases such as same VC generating units/subcontracts, further streamlining of data and visualization features including IT preparedness, etc. All such aspects are planned to be developed and incorporated in the SCED pilot.

***Strengthening Institutional Capacity*:** During the pilot period, a significant institutional capacity has been developed including SCED engine and related IT development, capacity building of MSLDC staff and other technical readiness have been achieved. However, a full-scale implementation and institutionalization of SCED will require regulatory and systemic enablers. While regulatory support will be central to the successful institutionalization of intra-state SCED, an adequate IT infrastructure and data related preparedness including integration with SCADA and metering, strengthening SCED team within SLDC strongly supported through fulltime allocated/sanctioned manpower, along with defined career pathways for optimisation specialists will be required to sustain long-term operations.

1. Introduction

In recent years, the Indian power sector has undergone significant reforms aimed at improving operational efficiency, flexibility, and economic performance of generation despatch. One of the major initiatives in this direction is the implementation of Security Constrained Economic Despatch (SCED) at the national level for Inter-State Generating Stations (ISGS). This SCED based despatch mechanism seeks to optimize generation scheduling across regions while strictly adhering to technical, operational, and network security constraints. The national SCED framework has demonstrated tangible benefits, including reduction in overall generation cost, enhanced grid security, improved utilization of available reserves, and greater transparency in despatch operations. Recognizing these demonstrated benefits of the national SCED implementation, the Maharashtra State Load Despatch Centre (MSLDC) initiated a detailed deliberations with subject matter experts to examine the feasibility of implementing SCED at the intra-State level. Through a series of structured technical interactions, a comprehensive understanding of the SCED framework, optimization methodologies, and associated operational implications was developed.

Taking cognizance of the partial grid failure in the Mumbai Metropolitan Region (MMR) that occurred on 12 October 2020, the Maharashtra Electricity Regulatory Commission (MERC) initiated a Suo motu proceeding under Regulation 32 of the MERC (Conduct of Business) Regulations, 2004 read with Regulation 46.2.4 of the MERC (State Grid Code) Regulations, 2020, in Case No. 202 of 2020. Subsequently, vide its Notification dated 22 October 2020, the Commission constituted a High Level Committee (HLC) to undertake a root cause analysis of the incident, examine the shortcomings in the system restoration efforts undertaken by the licensees, verify compliance with the provisions of the MERC (State Grid Code) Regulations, 2020, and recommend remedial measures to prevent recurrence of such incidents in the future.

The HLC, recommended that the concept of Security Constrained Economic Despatch (SCED) and Security Constrained Unit Commitment (SCUC) be studied for implementation in the scheduling of embedded generation in the Mumbai area. The Committee further recommended that such a pilot be undertaken within six months from the date of the Commission's Order. Accordingly, vide Order dated 28.05.2021, the commission directed that the feasibility and applicability of SCED and SCUC be examined in the Mumbai region. Subsequently, on 23.12.2022, MSLDC submitted before the Commission that, being responsible for economic despatch, it would continuously observe and study the applicability of SCED in the Mumbai region, particularly in the context of ongoing strengthening of the Mumbai transmission network. MSLDC further submitted that there exists scope for implementation of SCUC and SCED mechanisms, subject to enhancement of transmission infrastructure and availability of appropriate algorithmic and software capabilities, and that such implementation would be pursued progressively over time.

To further assess its applicability in the state context, a dedicated working group was constituted to undertake an initial offline study using historical data from the state scheduling system, with technical support from Grid Integration Lab, IIT Bombay. The findings of this offline study that demonstrated promising benefits (economical and technical) of SCED based generation despatch in Maharashtra compared to the existing merit order despatch practice were consolidated into a comprehensive report titled "Optimising Power Despatch (An Initiative towards SCED Implementation in Maharashtra", prepared in collaboration with IIT

Bombay and domain experts. The report was formally released on 08 November 2024 in the august presence of Smt. Abha Shukla (IAS), Additional Chief Secretary (Energy), Government of Maharashtra and Dr. Sanjeev Kumar CMD, MSETCL. The event was also graced by the Director (operations) MSETCL, Director (Commercial), MSEDCL and the Director (Operations), MSPGCL prepared in collaboration with IIT Bombay and domain experts. prepared in collaboration with IIT Bombay and domain experts.

In view of the encouraging outcomes of the offline study and the significant opportunities for improving system operations, MSLDC made submission to the honourable commission proposing a pilot implementation of intra-State SCED for Maharashtra, which was subsequently approved by Maharashtra Electricity Regulatory Commission (MERC) vide Office Order No. 43. To operationalize the SCED pilot in a structured manner, MSLDC entered into a formal Memorandum of Understanding (MoU) with the IIT Bombay for initiating the pilot, pertinent to improving planning and operation of Maharashtra grid. Under this MoU, the Grid Integration Lab (GIL), IIT Bombay, is actively involved in providing technical support, SCED engine development, validation, and capacity building of MSLDC officials. As part of the pilot implementation, the development of a near real-time, cloud-based SCED dashboard was initiated. This platform was designed to fetch schedule data of MOD and optimized despatch data of SCED engine and present key system indicators such as system marginal price (SMP), generator marginal costs, reserve availability, congestion patterns, and cost savings in a transparent and user-friendly manner. optimized despatch data of SCED engine and present key system indicators such as SMP, generator marginal costs, reserve availability, congestion patterns, and cost savings in a transparent and user-friendly manner.

With the SCED optimization engine and its associated interactive dashboard now in place, the pilot implementation has transitioned from a conceptual exercise to an operational decision-support framework. This interim report has been prepared with the objective of disseminating the key learnings, operational insights, and challenges encountered during the pilot phase of intra-state SCED implementation in Maharashtra. It documents the technical, institutional, and operational experiences gained, highlights best practices adopted, and identifies areas requiring further refinement, and the way forward. The report also presents stakeholder-specific perspectives covering DISCOMs, generation utilities, system operators, consumers, grid planners, and the Regulatory Commission. The findings of this intra-State SCED pilot documented in this report aims to support informed regulatory deliberations, facilitate wider stakeholder understanding, and contribute to the development of a robust, transparent, and economically efficient despatch framework at the intra-State level.

1.1. Motivation

The present scheduling and despatch framework in Maharashtra is implemented in accordance with the directions issued by the MERC. In this regard, the Commission notified the MERC (State Grid Code) Regulations, 2020 (MEGC, 2020) on 02 September 2020, which, inter alia, laid down the principles for scheduling and despatch of generating stations. Subsequently, the Commission notified the operationalization of the Merit Order Despatch stack as specified under Regulation 33 of MEGC, 2020. In line with these regulatory provisions, MSLDC prepared the draft Scheduling and Despatch (S&D) Code after due stakeholder consultation. The draft code incorporated comments and suggestions received from stakeholders and was submitted to the Commission for approval. The Commission approved the S&D Code on 11 November 2019, thereby establishing the regulatory mandate for decentralised scheduling based on the MOD principle.

Under normal grid conditions, the SLDC is mandated to prepare schedules on a decentralised MOD basis, using power requisitions/ demand submitted by the distribution licensees. At present, renewable energy sources, including DISCOM requisitions from hydro generation, are treated as must-run resources and are excluded from the MOD optimisation process. Similarly, requisitions pertaining to central sector allocations, although submitted by distribution licensees, are also kept outside the MOD framework. Distribution licensees are responsible for optimising their power procurement portfolios by considering DISCOM owned generation, contracted capacities, ISGS allocations, and market-based procurements in the Day-Ahead Market (DAM) and Real-Time Market (RTM). The day-ahead schedule is prepared under decentralised operation. However, this schedule undergoes multiple revisions in real time, considering updated demand forecasts by discoms & Declared Capacities by generators, and cleared transactions in the RTM. As a result, a firm schedule is available only for the immediate next two-time blocks. Given this operational reality, it was decided to adopt a multi-period optimisation framework of four-time blocks to obtain meaningful and reliable optimisation results. Extending the optimisation horizon to all 96 blocks of the day could potentially lead to issues due to the non-firm nature of schedules in subsequent blocks. Moreover, DISCOMs also retain the discretion to back down generating units during surplus conditions, in consultation with the MSLDC. However, the framework provides for centralised despatch intervention by MLSDLC under specific conditions, particularly when:

- Inter-State deviations exceed the permissible band (currently ±250 MW), or
- Transmission/grid security constraints arise within the intra-State network

In such scenarios, the SLDC assumes centralised MOD control and undertakes rescheduling of generation to relieve congestion and maintain grid security to financially settle the transition between decentralised and centralised modes of operation, a Virtual State Entity (VSE) has been introduced. The VSE captures the deviations in generator schedules arising due to the switch between the two operational modes (centralised and decentralised) and facilitates transparent financial settlement of these differences. While the VSE mechanism has enabled smoother operational transitions and settlement accounting, it introduces additional layers of complexity in scheduling, settlement reconciliation and operational coordination. To operationalise this framework, SLDC has implemented an advanced scheduling application that integrates multiple data streams through Application Programming Interfaces (APIs). These include Demand forecasts submitted by distribution licensees, Declared Capability (DC) of generating stations, Generator technical constraints (minimum and maximum generation limits, ramp rates), Variable cost data, market results from power exchanges, REMC data and Bilateral contract details.

While the standard APIs for data streaming and the existing MOD engine are already in place, the geographical dispersion of intra-state thermal generating stations, as shown in Figure 1, and the fragmentation of individual physical generating units into multiple virtual units (due to multiple subcontracts) further add to the operational complexity. Managing such a system through decentralised decision-making and manual interventions becomes increasingly challenging, particularly under dynamic real-time conditions. These operational realities, and potential of optimising the operational cost, formed the core motivation for undertaking the intra-State SCED pilot. The pilot was conceived as a controlled, learning-oriented exercise to evaluate the feasibility, challenges and benefits of a centralised, optimisation-based despatch framework under real system conditions. Through this pilot, MSLDC sought to assess potential efficiency gains, identify implementation challenges, and build institutional readiness before any large-scale rollout.

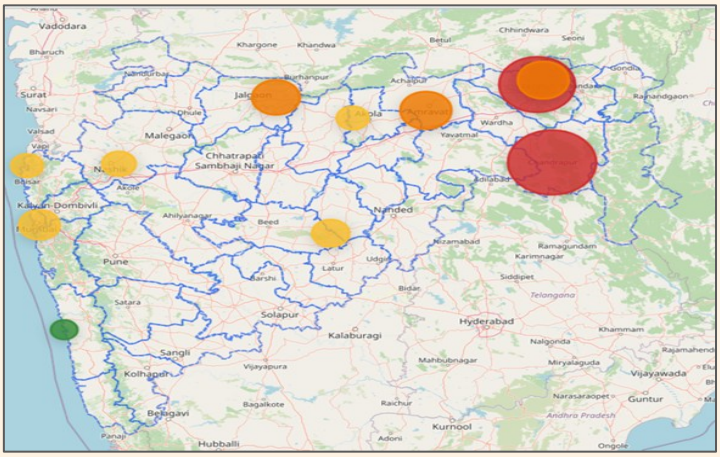


Figure 1 Geographic dispersion of Intra-State Thermal Generators

1.2. Need for Intra-State SCED Implementation

In recent years, the Government of India and the Central Electricity Regulatory Commission (CERC) have undertaken a series of progressive reforms to promote flexibility, efficiency, and optimisation in power system operations. A key milestone in this direction was the Scheme on Flexibility in Generation and Scheduling of Thermal Power Stations, notified by the Ministry of Power on 30 August 2018, which enabled generating companies to utilise their coal linkages in a more flexible manner by delinking rigid plant-specific coal allocations. This reform laid the foundation for system-wide cost optimisation and efficiency-driven despatch. The implementation of SCED at the national level was initiated under CERC regulatory directions for Inter-State Generating Stations (ISGS), aimed at enabling system-wide optimisation of generation despatch while honouring all technical and network constraints. This landmark reform marked a shift from fragmented scheduling practices to a centralised, optimisation-driven framework for inter-state operations.

The national SCED mechanism has delivered tangible economic benefits to DISCOMs by enabling optimised cost power procurement and improved utilisation of generation resources. More importantly, it has enhanced grid security through coordinated reserve management, adequate accounting of generator limits, and congestion handling. These demonstrated benefits have reinforced confidence in optimisation-based despatch as a reliable and efficient operational framework. Building upon the successful national implementation, the importance of SCED was further institutionalised through its formal inclusion in the Indian Electricity Grid Code (IEGC), 2023. By embedding SCED within the national regulatory framework, CERC provided statutory recognition to optimisation-based despatch, establishing it as a core principle of secure and economic grid operation. This regulatory provision also created a harmonised pathway for extending SCED practices from the inter-state level to intra-state systems.

However, it is pertinent to examine the existing scheduling framework. In the current scheduling framework in Maharashtra, the MOD mechanism is implemented in a decentralised manner, where along with system operator, each distribution licensee independently optimises its portfolio. Whenever operational issues such as congestion or deviation breaches arise, a separate centralised run is triggered to account for these constraints. This frequent switching between multiple scheduling mechanisms introduces operational discontinuity and complexity. Managing ramping constraints across multiple generating units under a decentralised

framework has emerged as a binding challenge. Since ramping decisions are taken independently by different entities, system-wide coordination becomes difficult, particularly during sharp demand variations and real-time market corrections. This often necessitates repeated operator interventions, which may adversely impact cost efficiency and operational consistency. Further, the existing mechanism provides limited system-level visibility in terms of marginal costs, price signals, reserve adequacy, and congestion impacts. The absence of a unified optimisation framework restricts the ability to derive holistic insights that are essential for informed operational and regulatory decision-making.

With the increasing penetration of renewable energy, the system is witnessing new and complex operational challenges such as higher net-load variability, steeper ramping requirements, frequent intra-day forecast revisions, must-run obligations for renewable generators, reduced system inertia, growing need for flexible resources, and the emergence of localized network congestion due to spatial mismatch between generation and demand. Incorporating these evolving constraints within the existing decentralised MOD framework has become operationally challenging, as the current mechanism does not support integrated multi-period and security-constrained optimisation. Going forward, the operational paradigm is expected to evolve towards shorter despatch intervals, requiring faster and more responsive scheduling decisions. In such an environment, the existing decentralised MOD framework faces inherent limitations in handling emerging constraints such as localized congestion, reduced system inertia, enhanced reserve requirements, and inter-temporal operational coupling.

In this context, a linear programming-based SCED framework offers a future-ready solution by enabling coordinated, multi-period, and security-constrained optimisation within a single model. The proven computational efficiency of linear programming based SCED frameworks, combined with its scalable modelling structure, positions SCED as a critical enabler for managing upcoming grid challenges. Accordingly, transitioning towards an LP-based SCED framework is not only a technical necessity but also a strategic preparedness measure aligned with evolving power system, regulatory directions and national market reforms. The SCED enables the derivation of transparent financial indicators such as system marginal price, generator marginal values, congestion signals, and reserve pricing, thereby strengthening economic despatch decisions and supporting informed regulatory oversight.

1.3. Objectives and Scope of the Pilot

The Intra-State SCED pilot has been undertaken to evaluate the technical feasibility, operational practicality, and institutional readiness of implementing an LP-based SCED framework in Maharashtra. The pilot has been structured to operate in a parallel online mode, wherein the SCED engine independently generates despatch schedules concurrently with the existing scheduling framework. This approach enables a controlled evaluation of SCED outcomes against prevailing practices, facilitating the identification of benefits, implementation challenges, and institutional readiness, without disrupting ongoing real-time operations. The scope of the intra-state SCED pilot encompasses both technical development and institutional engagement activities. Specifically, the pilot includes:

1. Custom development and continuous refinement of the SCED optimization engine in line with existing operational constraints, regulatory provisions, contractual obligations and system operating practices.
2. Design and deployment of a custom visualization pipeline for both online and offline monitoring of SCED outcomes.

3. Development of an interactive dashboard to track various performance indicators.
4. Detailed analysis of optimization results to quantify economic benefits, operational improvements, and system impacts.
5. Development of framework for transitioning to SCED based scheduling implementation.
6. Human resources and Capacity building for inhouse operation of SCED based scheduling.
7. Dissemination of key learnings through webinars, workshops, technical conferences/journal publications.
8. Documentation of challenges, lessons learnt, and best practices for regulatory review.

1.4. Stakeholders and Their Roles

With this structured pilot framework in place, the effective participation and coordination of all stakeholders become critical. Accordingly, the roles and responsibilities of key stakeholders involved in the intra-state SCED pilot are as follows: The MSLDC acts as the nodal agency for the execution and governance of the pilot. MSLDC is responsible for overall project coordination, integration of the SCED engine, developed by Grid Integration Lab, IIT-Bombay, with existing scheduling systems, and ensuring the daily execution of SCED runs in parallel mode. MSLDC also contributes to the iterative development and refinement of the SCED engine through continuous operational feedback, validation against real system conditions, and recommendations for practical modifications to model formulation, constraints, and workflows, ensuring operational relevance and deployability. It undertakes validation of optimisation outputs against real system conditions, documents implementation challenges. MSLDC also bears responsibility for periodic reporting and submission of the national pilot outcome report to the Regulatory Commission. The MERC provides regulatory oversight and strategic direction to the pilot initiative. The Commission has granted formal approval for pilot implementation, ensured compliance with prevailing regulatory frameworks, and laid down the conditions under which the pilot is to be executed. MERC will review the pilot outcomes, stakeholder feedback, and cost-benefit analysis, and provides guidance on the regulatory roadmap for potential scale-up and institutionalisation of intra-state SCED.

- The Grid Integration Lab, IIT Bombay serves as the technical knowledge partner for the pilot. GIL provides domain expertise in optimisation modelling, supports model development SCED engine and validation, assists in troubleshooting and refinement of formulation, automation workflows, insight for dashboard development, performance evaluation. The institution also contributes to documentation, analysis, and dissemination of technical learnings.
- Independent consultants provide industry expertise and objective oversight to the intra-state SCED pilot. Their role includes continuous monitoring of pilot execution, validation of results, and identification of operational and implementation gaps and provide critical inputs for dashboard design and visualization development.
- The IT partner supports the pilot primarily in dashboard data workflows and IT integration. This includes facilitating automated data fetching from the SCED engine and the existing MOD engine to enable online monitoring and developing visualization outputs in line with operational insights provided by MSLDC, with technical inputs from IIT Bombay and independent consultants.

1.5. Structure of the Report

The report is structured so as to progressively build the technical, operational, and institutional case for optimisation-based scheduling and its adoption at the intra-state level. Chapter 1 (Introduction) sets out the context, motivation, and objectives of the intra-state SCED pilot. Chapter 2 describes the existing MOD-based scheduling practices in Maharashtra and highlights their key limitations. The SCED Modelling Framework is presented in Chapter 3, covering both decentralised and centralised SCED formulations developed under the pilot. Chapter 4 details the Integration with the SCED Engine and Dashboard Framework, describing the system architecture, data pipelines, and operator-centric visualisation design. Chapter 5 provides an overview of the Maharashtra power system, including demand characteristics, generation mix, and DISCOM-wise generation portfolios. Chapters 6 and 7 present system marginal and operational insights derived from SCED runs. The cost-benefit analysis in Chapter 8 quantifies economic outcomes across different scheduling scenarios, followed by stakeholder-specific insights in Chapter 9. Chapter 10 discusses governance considerations and regulatory directions for scaling SCED. Chapter 11 documents the capacity-building and training initiatives undertaken during the pilot, while Chapter 12 summarises key learnings. The report concludes with the Way Forward, consolidating pilot insights and outlining recommendations for full-scale implementation.

2. Overview of Existing MOD-Based Scheduling Practices

The Maharashtra State Power Grid is operated as an integrated power pool, with the MSLDC vested with overall responsibility for scheduling, despatch, monitoring of drawls, and real-time system operation. These functions are carried out in accordance with the MERC DSM Regulations, 2019, MERC Forecasting & Scheduling Regulations, 2018, the State Grid Code, the Indian Electricity Grid Code (IEGC), and the Merit Order Despatch (MOD) principles notified by the Commission. MSLDC is mandated to prepare time-block-wise day-ahead schedules, revise schedules under emergency or congestion conditions, and coordinate inter-state drawls in consultation with Western Regional Load Despatch Centre (WRLDC). In line with the State Grid Code, MSLDC has developed a comprehensive Scheduling and Despatch (S&D) Code defining roles, responsibilities, and information exchange protocols among all state entities.

The Scheduling and Despatch (S&D) Code facilitates preparation of day-ahead generation schedules for sellers, drawl schedules for buyers, and maintenance of the state load generation balance. Its scope includes scheduling of intra-state generators, coordination with WRLDC for inter-state generation, structured information exchange among stakeholders, and real-time rescheduling instructions. The Code applies to all generating stations above 25 MW, DISCOMs, open access consumers, and renewable generators (with wind and solar governed separately). Within this regulatory and institutional framework, the existing scheduling and despatch process in Maharashtra operates predominantly through a de-centralized MOD mechanism. The following section describes the current scheduling and despatch workflow, detailing the end-to-end process from data submission and day-ahead scheduling to real-time revisions and operational interventions.

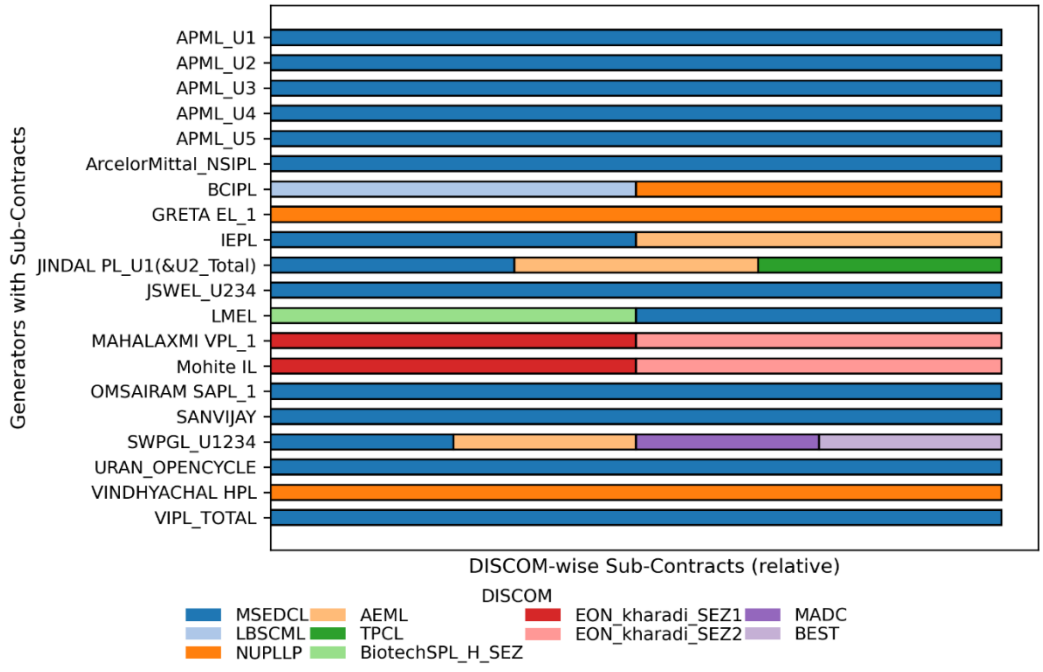


Figure 2 Contractual allocation of the Intra-State generators on a sample day

Presently, the Maharashtra system comprises 266 intra-state generators with a total installed capacity of 31,637.44 MW (ex-bus 29,523.25 MW), characterized by varying schedulable and complex contractual arrangements. Of these, only forty-eight generators are classified as schedulable, while the remaining 218 generators are non-schedulable for SLDC or must-run in nature, including renewable resources. In addition, twenty generators participate in multiple contractual sub-entitlements, resulting in forty-nine sub-contracts mapped across 10 DISCOMs. Figure 2 illustrates the contractual allocation of these intra-state generators, where each generator (y-axis) is mapped to multiple DISCOMs through fragmented capacity shares (x-axis). Among these, only twenty sub-contracts are schedulable, while the remaining twenty-nine sub-contracts are non-schedulable. Within this regulatory and institutional framework, the existing scheduling and despatch process in Maharashtra operates predominantly through a de-centralized MOD mechanism.

2.1. Current Scheduling and Despatch Framework at Intra-State Level

The DSM Scheduling Module, as shown in Figure 3, represents the end-to-end workflow followed by MSLDC for preparation of schedules under the existing MOD-based framework. The process begins with the collection of multiple input data streams through dedicated system interfaces. State generating stations submit their Declared Capability (DC) through the declaration module, indicating their available generation capacity considering technical limits, fuel availability, and outages. These declarations are reviewed and approved by MSLDC operations. In parallel, data related to bilateral contracts is captured, including intra-state contracts (LTA/MTOA/STOA) and inter-state allocations from ISGS. These inputs are validated through the open access and operations modules to determine actual contractual availability. Renewable energy data, including wind and solar generation, is processed through the REMC module and treated as must-run in accordance with regulatory provisions, and hence excluded from MOD optimisation. Market transactions cleared through power exchanges such as IEX and PXIL are also captured, as these directly impact the net demand to be met through state generators. Additionally, DISCOMs upload their forecasted demand through the demand upload module, which is subsequently validated and approved by MSLDC during current day operations.

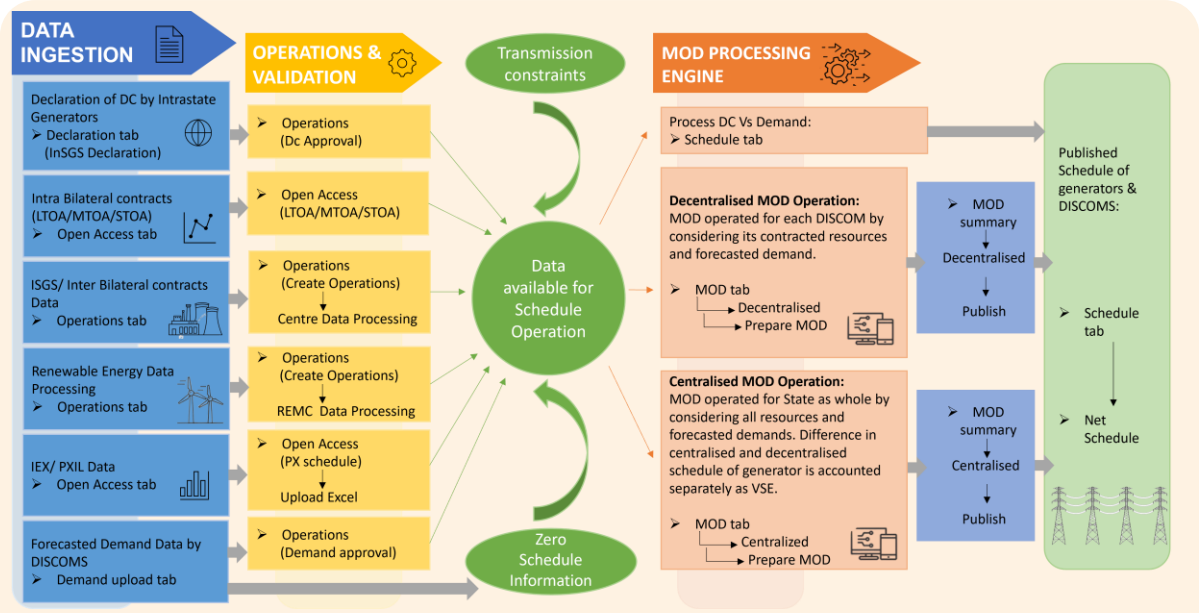


Figure 3 MSLDC generator scheduling framework

Once all inputs are validated, the data flows into the scheduling engine, where transmission constraints and system limitations are considered. The approved demand is processed against the available generation resources to prepare schedules. Under the decentralised MOD operation, scheduling is carried out separately for each DISCOM by considering its contracted resources and forecasted demand. In this mode, each DISCOM's portfolio is optimised independently, resulting in separate schedules. In case of system constraints or deviations in the day of operation, a centralised MOD run is triggered, wherein optimisation is performed at the state level by considering all resources collectively. The difference between decentralised and centralised schedules for generators is accounted separately through the VSE mechanism to enable transparent settlement.

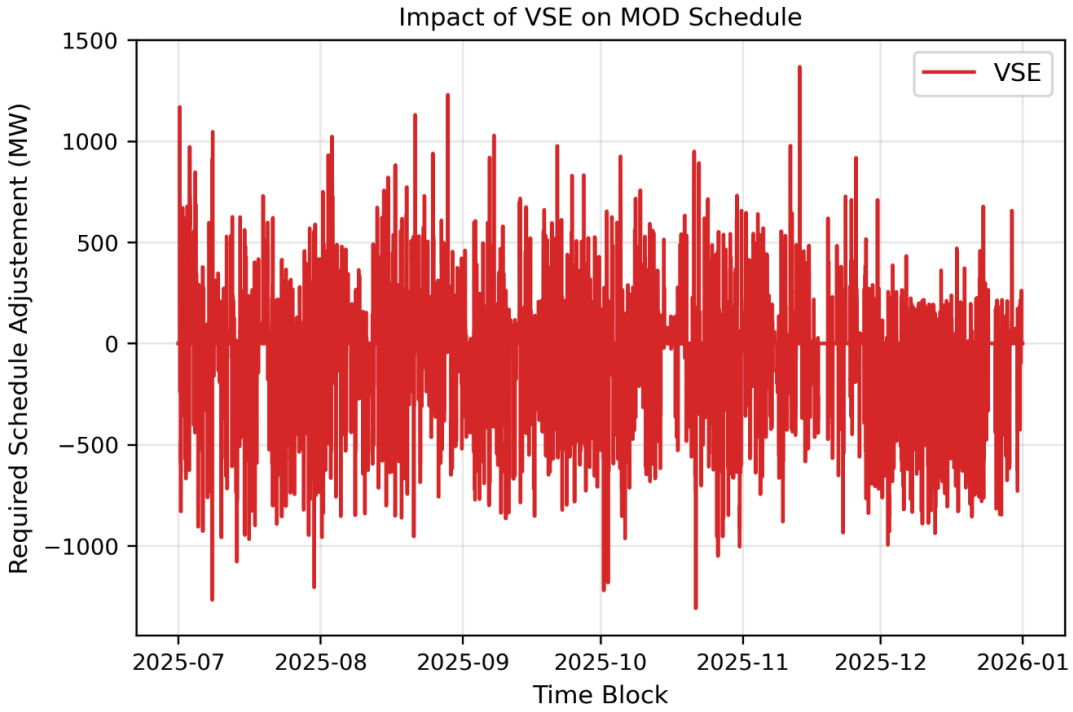


Figure 4 Schedule adjustment due to transmission constraints and/or state over/under drawl

Following the optimisation process, schedule summaries are generated and published. In decentralised operation, a MOD summary is prepared and published for each DISCOM, while in centralised operation, a consolidated summary is issued. Finally, the approved schedules for generators and DISCOMs are published, along with net schedules and summary reports. This structured workflow ensures regulatory compliance, contractual adherence, and system security, while also highlighting the operational complexity arising from multiple data streams, approval layers, and switching between decentralised and centralised scheduling modes.

2.2. Limitations of MOD-Based Scheduling

While the existing MOD-based scheduling framework has ensured regulatory compliance, contractual discipline, and grid security, several structural and operational limitations have become increasingly evident with growing system complexity. The framework follows a decentralized optimization approach, wherein each DISCOM independently optimizes its portfolio. This fragmented decision-making restricts system-wide economic efficiency, as lower-cost generation resources are not always fully utilized when higher-cost units are scheduled simultaneously across different DISCOMs, as shown in Figure 5.

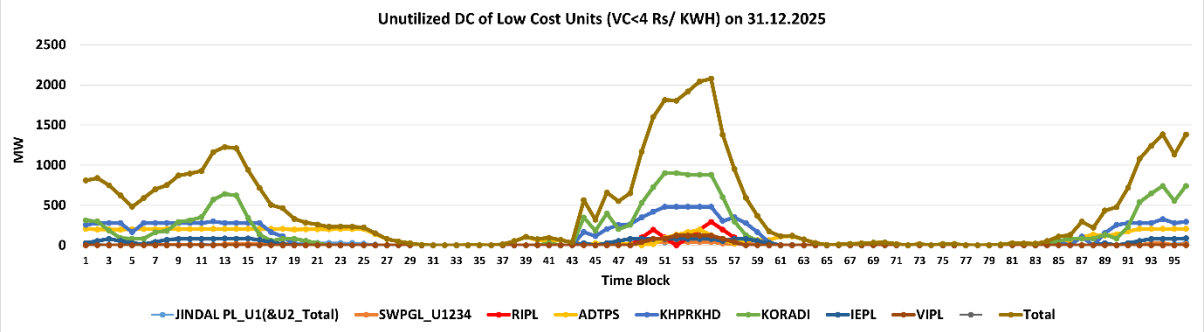


Figure 5 Illustration of the unutilized DC of cheaper plants

The operational process also requires frequent switching between decentralized and centralized modes whenever congestion or system constraints emerge. This dual-mode operation increases procedural complexity, necessitates repeated manual operator interventions. Ramping coordination across multiple generating units is managed in a decentralized manner, often resulting in binding ramp constraints, particularly during sharp load variations or renewable energy fluctuations, as shown in Figure 6. This limits operational flexibility and may lead to higher overall system costs.

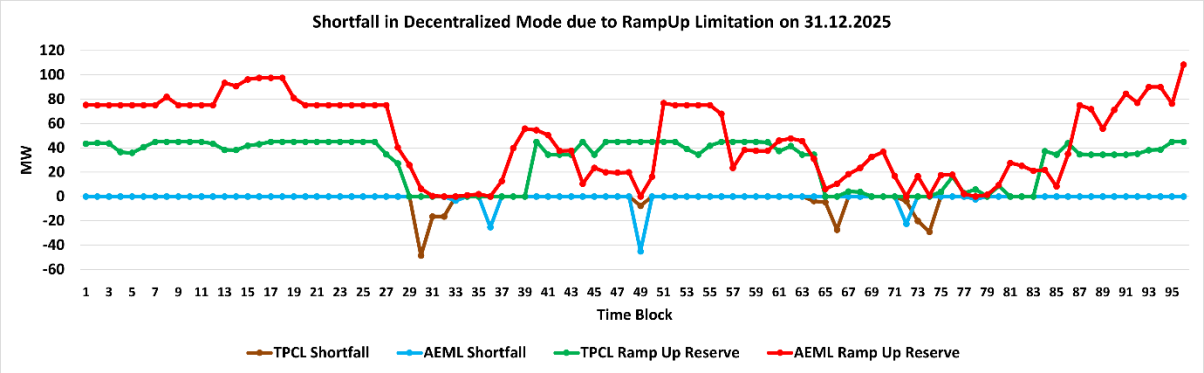


Figure 6 Ramp limitation driven DISCOM shortfall during morning & evening ramping

Further, the current framework provides limited real-time economic visibility. Key market and operational indicators such as system marginal price, shadow prices of binding constraints, and reserve valuation are not explicitly available, reducing transparency and constraining analytical depth for both regulators and stakeholders. The rising penetration of renewable energy has introduced greater variability and forecast uncertainty, which is difficult to address effectively within the existing MOD framework due to the absence of integrated multi-period capabilities. In addition, the reliance on frequent operator interventions and experience-driven decisions introduces a degree of subjectivity into system operations, potentially impacting cost efficiency, auditability, and governance robustness. Collectively, these limitations underscore the need for a, improved framework capable of addressing system-wide constraints in a coordinated, transparent, and analytically robust manner.

2.3. Operational and Economic Challenges Observed

The insights into the operational and economic challenges of the existing scheduling framework were derived from the historical operational data, which provided a controlled environment to compare decentralized MOD outcomes with optimization-based despatch results and served as the first evidence base for identifying systemic inefficiencies. The

analysis revealed suboptimal utilization of low-cost generation resources, as shown in Figure 7, wherein higher-cost units continued to be scheduled in parallel with cheaper generators across different DISCOM portfolios.

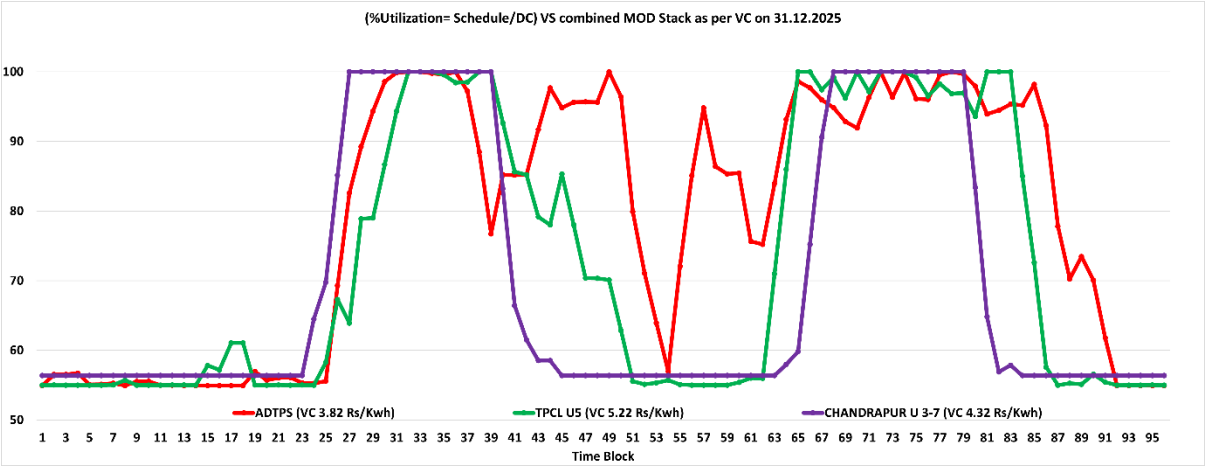


Figure 7 Comparison of Merit order stack and actual generation despatch of a sample day

The analysis further observed frequent binding network and operational constraints, which necessitated switching from decentralized to centralized scheduling modes. This reactive mode of operation increased dependency on manual interventions and reduced predictability in despatch decisions. The frequency of change in scheduling mechanism is highlighted in Figure 8. Additionally, Ramping constraints emerged as a major operational challenge during periods of sharp demand variation and renewable energy fluctuations. The analysis, as shown in Figure 9, revealed that decentralized ramp management often resulted in binding ramp limits, restricting system flexibility and increasing reliance on costlier fast-ramping units.

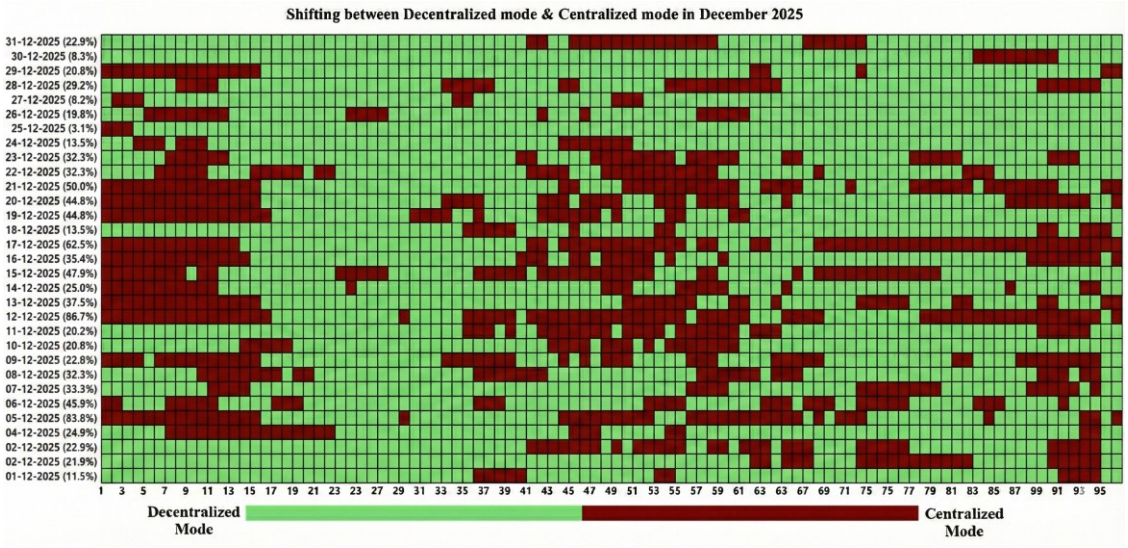


Figure 8 Shifting between Decentralized mode & Centralized mode in December 2025

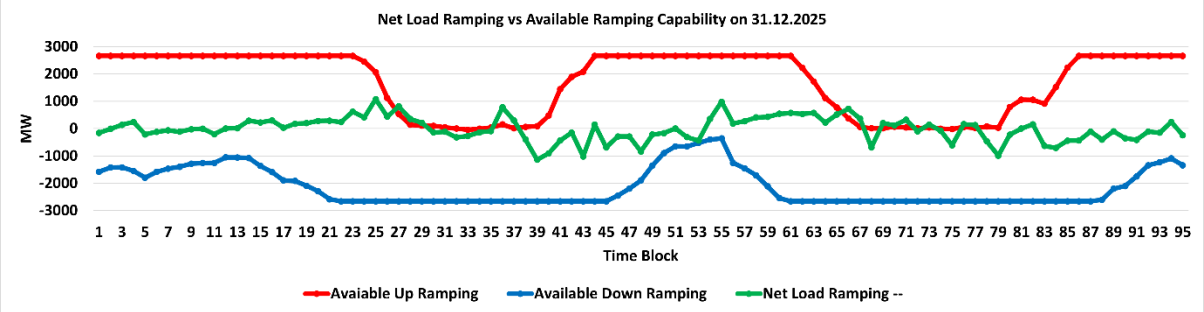


Figure 9 Net-load ramp vs available thermal ramp capability

Operational complexity was further amplified by multiple data validation steps and manual interventions, affecting response time and consistency.

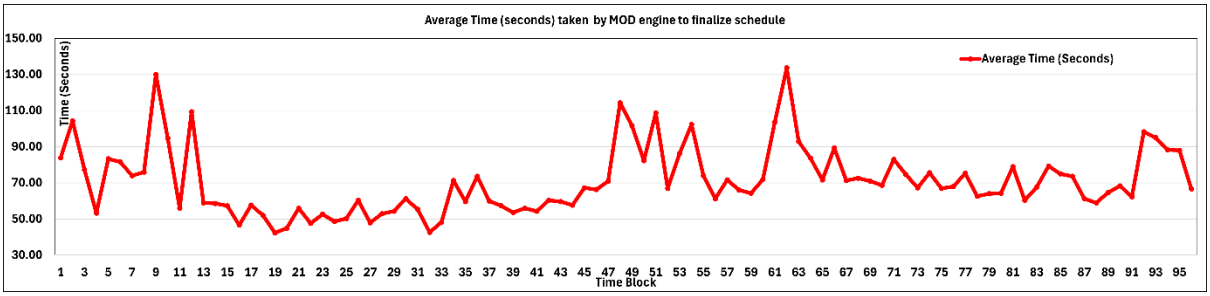


Figure 10 Average time taken to schedule finalization

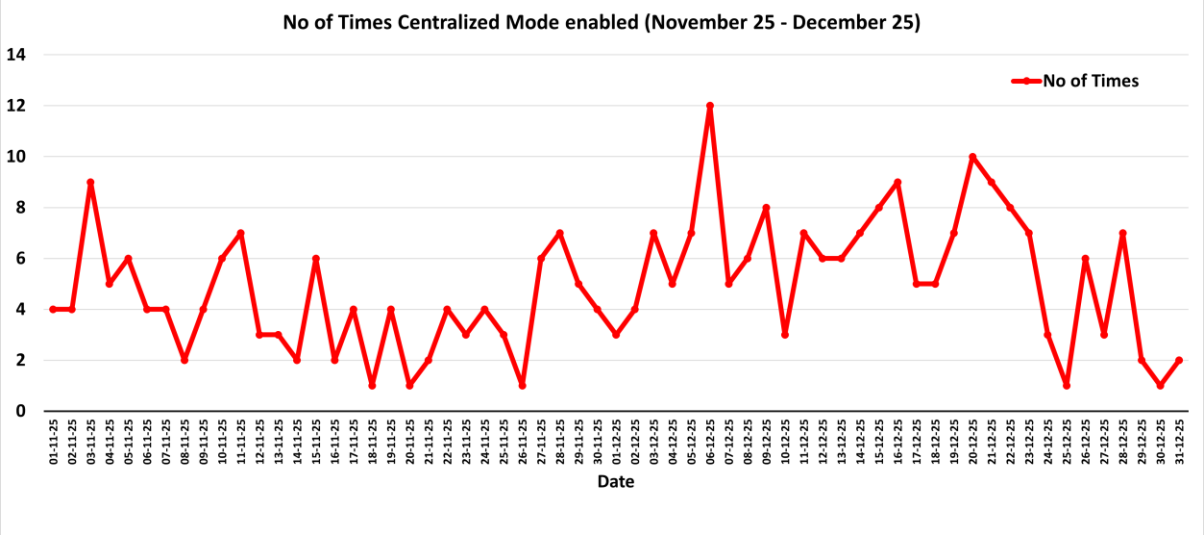


Figure 11 Number of operator interventions across the scheduling days

These demonstrations clearly highlight the persistent operational and economic challenges inherent in the existing MOD-based scheduling mechanism. The observed deviations from merit order, frequent manual interventions, limited system-wide visibility, and constrained flexibility collectively underline the structural limitations of decentralised despatch practices. In this context, the need for a scientific, transparent, and scalable optimisation framework becomes evident. As system complexity increases with higher RE penetration and dynamic market participation, conventional rule-based scheduling is no longer sufficient to ensure cost efficiency and operational robustness. This naturally leads to the requirement for a LP-based optimisation approach, which can systematically co-optimise all generation resources while respecting technical, contractual, and network constraints.

2.4. Need for Optimization-Based Scheduling

The evolving operational landscape of the power system, characterised by increasing renewable penetration, tighter operational margins, and dynamic market participation, necessitates a transition from rule-based and decentralised scheduling towards a scientific, optimisation-driven framework. Optimisation-based scheduling, implemented through linear programming (LP), enables system-wide co-optimisation of generation resources while explicitly accounting for technical constraints, ramping limits, reserve requirements, and network security.

At the national level, the implementation of SCED for inter-state generating stations has already demonstrated tangible economic and operational benefits. The centralised optimisation framework has resulted in significant reduction in total generation cost, improved utilisation of low-cost generation resources, and enhanced reserve management. These outcomes have provided strong empirical evidence that coordinated despatch outperforms decentralised scheduling in both efficiency and reliability. International experience further reinforces these advantages. Power markets in regions such as PJM (USA), ERCOT (USA), and the European electricity markets operate on optimisation-based despatch mechanisms, where centralised unit commitment and economic despatch have led to Improved system reliability, transparent price formation, efficient congestion management. From an operational perspective, optimisation-based scheduling facilitates coordinated management of ramping and flexibility requirements, allowing system operators to respond more effectively to rapid demand changes and renewable variability. The framework also supports proactive handling of network constraints by embedding transmission limits directly within the optimisation process, thereby reducing the need for reactive interventions. Further, it allows explicit modelling of reserve requirements, ensuring adequate contingency preparedness while maintaining economic efficiency. Collectively, this reduces the dependence on manual operator interventions, enhances consistency in decision-making, and improves overall operational robustness. From an economic standpoint, optimisation-based despatch enables transparent price signals for generators and DISCOMs, improving market visibility and investment confidence. The structured optimisation framework enhances auditability and regulatory oversight by providing traceable and data-driven despatch decisions. It also establishes an objective basis for market settlement and policy evaluation, strengthening governance and accountability. With increasing RE volatility, future system operations are expected to transition towards shorter despatch intervals, requiring faster and more frequent despatch decisions. LP-based optimization engines, capable of generating optimal solutions within seconds, are technically well-suited to meet such real-time operational needs, unlike conventional manual or rule-based approaches. Therefore, the transition towards optimization-based despatch is not merely a technological upgrade, but a structural reform aligned with national policy objectives, international best practices, and future grid requirements.

2.5. Overview of Intra-State SCED Pilot

The intra-state SCED pilot was conceived as a practical learning exercise rather than a theoretical implementation. The primary intent was to understand how an optimization-based despatch framework would behave under real system conditions, while operating in parallel with the existing scheduling mechanism. Instead of replacing current processes, the pilot was designed to observe, compare, and learn from SCED outcomes without impacting live operations. The pilot aims to evaluate not only the technical feasibility of LP-based SCED but

also its operational practicality and institutional readiness. It seeks to answer key questions such as:

1. Can SCED generate reliable despatches on a daily basis?
2. How do SCED outcomes differ from existing MOD-based schedules?
3. What operational challenges emerge during live execution?
4. How prepared are system operators to adopt LP-based optimization tools?
5. What regulatory and process changes would be required for scale-up?

Beyond cost optimization, the pilot also focuses on building confidence, capability, and governance frameworks necessary for long-term adoption. The learnings from this exercise are intended to support evidence-based regulatory decision-making for future implementation.

2.6. Pilot Philosophy and Design Principles

The pilot has been guided by a set of practical design principles to ensure realism, credibility, and operational relevance. The SCED engine was deployed in a parallel online mode, as shown in Figure 12, generating despatches independently while the existing system continued to govern actual despatch. This ensured grid security while allowing for objective comparison between conventional and optimized schedules.

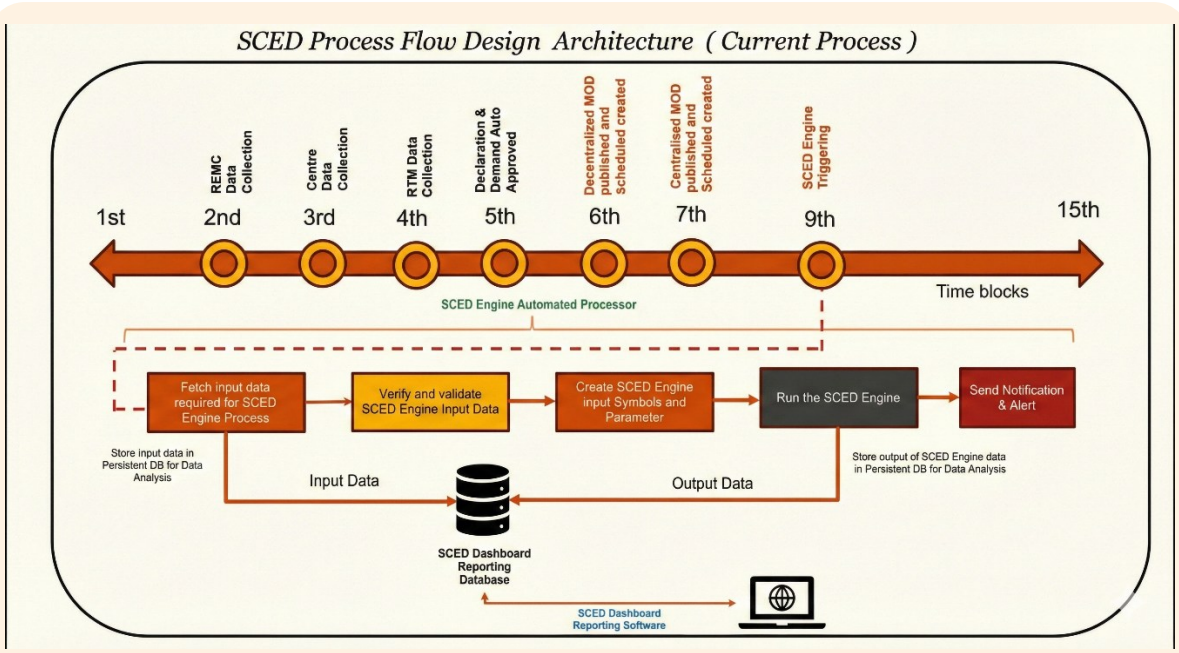


Figure 12 Architecture of the parallel online mode

The pilot was not treated as a performance benchmark exercise, but as a structured learning platform to identify gaps, challenges, and readiness levels. Errors, infeasibilities, and deviations were treated as learning opportunities rather than failures. The pilot is rooted in the idea of continuous learning and adaptive development. Instead of treating the SCED engine as a fixed solution, the approach is to continuously refine and evolve the model based on operational experiences, system behaviour, and stakeholder feedback. The objective is to ensure that the optimisation framework remains practically relevant and aligned with real-world conditions.

Equally important is the emphasis on operator usability. The pilot design consciously prioritises the needs of system operators by focusing on clarity, interpretability, and practical relevance of outputs. The intention is to present insights in a manner that supports day-to-day operational understanding. Visualization and analytics are therefore conceptualised as decision-support tools, enabling operators to interpret results easily and gradually build confidence in optimisation-based scheduling.

- To evaluate the technical and economic benefits of implementing SCED at the intra-state level in Maharashtra.
- To strengthen the despatch process by incorporating system-wide operational constraints and resource-level limitations in a structured and transparent manner.
- To demonstrate the real-time integration of an optimisation engine with existing scheduling applications and validate its suitability for live operational environments.
- To conduct sensitivity and scenario analysis to assess strengths, weaknesses, opportunities, and threats (SWOT) under varying system conditions.
- To develop intuitive dashboards and visualisation tools that improve situational awareness, decision-making, and transparency.
- To generate operational insights and practical learnings, and to enable systematic deliberation of pilot activities and results for developing a stable and sustainable regulatory framework for long-term SCED implementation in Maharashtra.

The following section outlines a phased approach to SCED implementation, designed to balance innovation with system reliability and stakeholder readiness.

2.7. Phased Approach to Implementation

The power system scheduling directly impacts grid security and market operations, any change to the existing framework needs to be introduced carefully and in a controlled manner. Therefore, during a phased approach has been adopted to test, learn, and adapt progressively, while safeguarding existing scheduling operation. The phased approach has been conceptualized as a structured roadmap to guide the transition towards optimization-based scheduling in a controlled and systematic manner. While several of these stages have already been undertaken as part of the pilot, they are presented here as a strategic framework to illustrate the logical progression envisaged for full-scale implementation.

2.7.1. Baseline Model Validation and Data Readiness

This stage focuses on using the SCED model developed during the offline study as a reference framework for conducting initial data validation and integration checks. The intent is to establish confidence in data accuracy, consistency, and completeness as a pre-requisite for dashboard development to monitor online SCED engine performance. The expected outcome of this stage is the establishment of a reliable and consistent data foundation for optimization-based scheduling. Through systematic validation, discrepancies across demand forecasts, declared capacities, technical parameters, and contractual inputs are identified and addressed.

2.7.2. Parallel Operation of MOD and SCED Engine

This stage envisages the parallelization of the SCED engine, wherein optimization outputs are generated alongside existing schedules. Conceptually, this allows continuous benchmarking, learning, and confidence-building without impacting live system operations. It is expected to

generate regular benchmark comparisons between conventional MOD schedules and optimization-based outcomes. The primary outcome is enhanced operator familiarity with SCED results, along with an improved understanding of potential cost savings and operational improvements, without any impact on real-time despatch decisions.

2.7.3. Diagnostic and Visualization Framework

In this phase, emphasis is placed on developing visualisation and diagnostic tools to systematically identify data inconsistencies, infeasible solutions, and deviations between conventional schedules and SCED engine outcomes. The key outcome of this stage is the availability of structured diagnostic tools and dashboards that highlight inconsistencies, infeasibilities, and deviations in a transparent manner.

2.7.4. Progressive SCED Engine Enhancement

This phase proposes gradual refinement of the SCED model, moving from decentralized formulations to more advanced configurations incorporating transmission and system-level constraints. The objective is to increase modelling complexity in alignment with institutional readiness and operational requirements. This stage is expected to deliver a more realistic and robust SCED model, capable of representing decentralized and centralized operations with transmission and system-level constraints. The outcome is improved model fidelity, allowing simulation of complex operational constraints.

2.7.5. System Integration and Validation

This stage envisages integration of SCED outputs with SCADA and energy metering systems to enable validation against actual system behaviour and support performance monitoring and analytics. The expected outcome is the establishment of a closed-loop validation mechanism, wherein SCED outputs are continuously compared with actual system behaviour using SCADA and metering data.

2.7.6. Institutional Deliberation and Knowledge Sharing

This stage focuses on structured dissemination of interim learnings through internal workshops and stakeholder discussions. The intent is to facilitate institutional alignment, capture feedback, and promote collective learning.

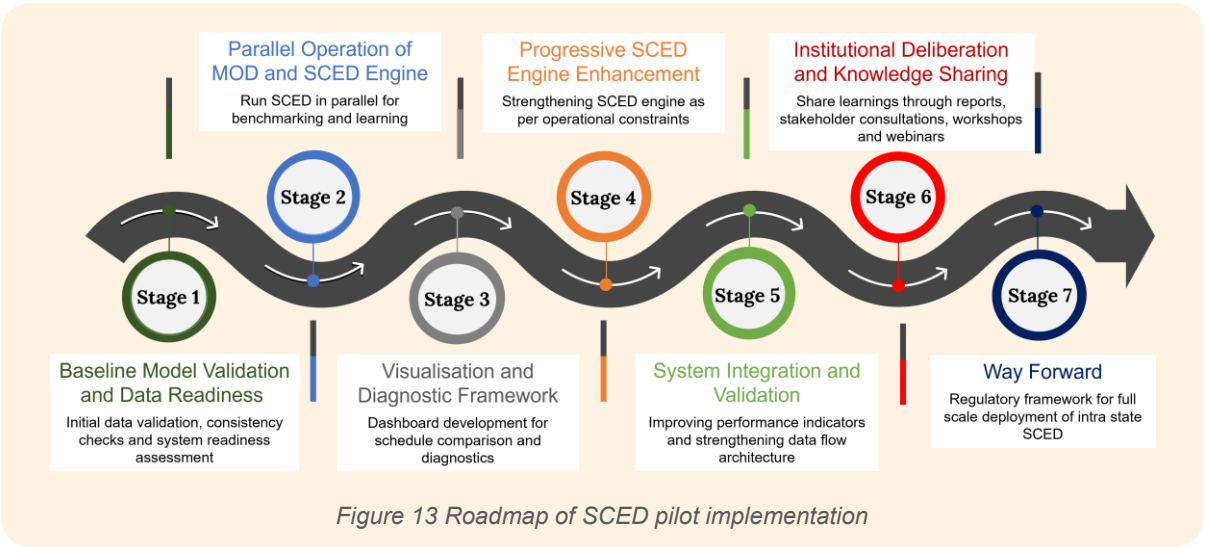


Figure 13 Roadmap of SCED pilot implementation

2.8. Institutional Collaboration

The intra-state SCED initiative in Maharashtra evolved through a phased and consultative process. It began with an offline pilot by MSLDC to assess the feasibility of optimisation-based despatch using historical data, which helped establish the technical foundation and highlight potential benefits and challenges. Based on these initial learnings and regulatory deliberations, guidance from MERC provided strategic direction to formalise the initiative. MSLDC subsequently entered into a formal MoU with the Grid Integration Lab, IIT Bombay, to strengthen technical capability and transition the exercise into a structured pilot programme, with Grid Integration Lab serving as the technical knowledge partner.

2.8.1. Governance Structure for Intra-State SCED Pilot

As the pilot moved into online parallel operation, independent consultants were engaged to provide industry perspective and objective oversight, supporting validation of results and identification of operational gaps. In parallel, PwC was engaged as the IT partner to establish data workflows, automate data integration between the SCED and MOD engines, and enable online dashboard visualization. PwC's role is confined to IT integration and data orchestration, while core optimization activities remain with IIT Bombay and MSLDC.

The institutional arrangement follows a hub-and-spoke governance model, with MSLDC at the centre as the executing agency. Technical expertise flows from GIL, IIT Bombay, regulatory oversight from MERC, industry validation from independent consultants, and IT support from IT partner. This structure ensures clear accountability, segregation of roles, and transparent decision-making. A schematic organogram illustrating reporting lines, collaboration interfaces, and governance hierarchy is presented in Figure 14.

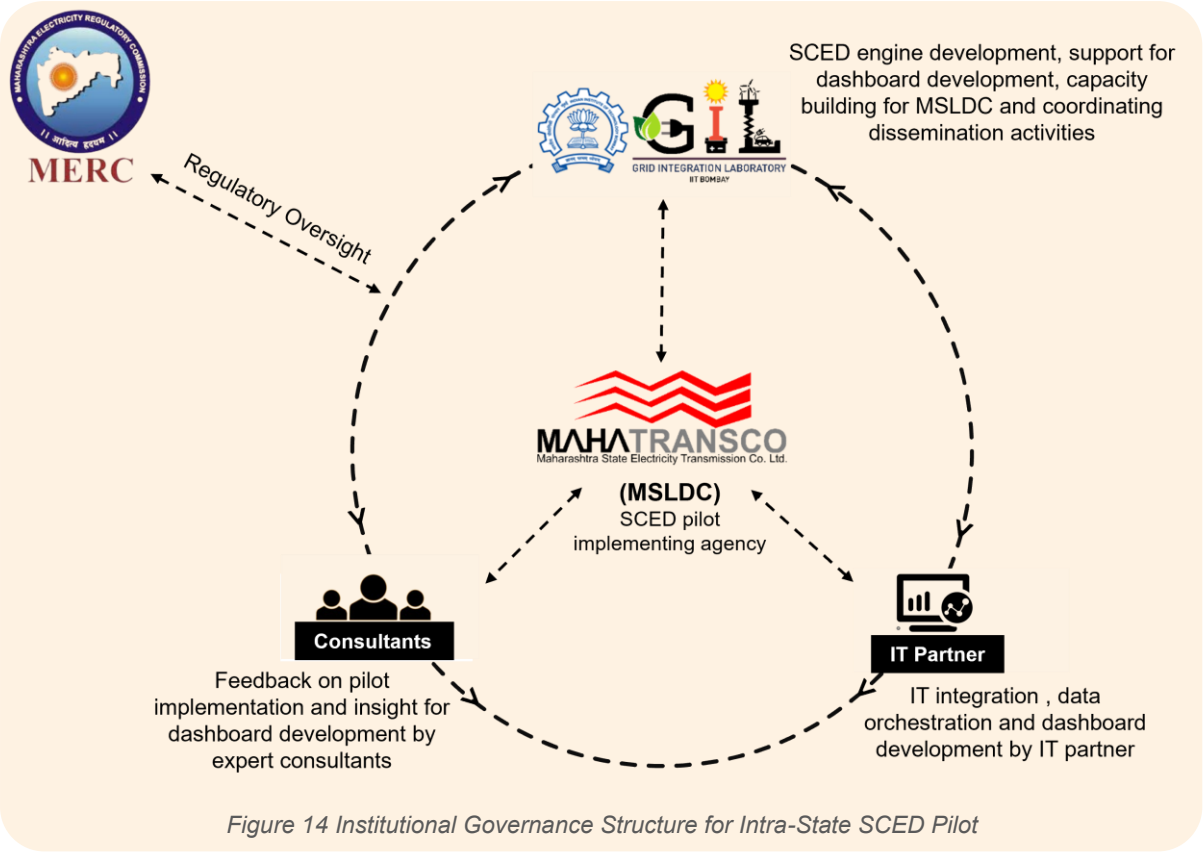


Figure 14 Institutional Governance Structure for Intra-State SCED Pilot

2.8.2. Operational Workflow of the Online SCED Pilot

To translate the collaborative framework and pilot objectives into day-to-day operations, a well-defined end-to-end process has been established. This workflow ensures seamless coordination between data sources, optimization systems, IT platforms, and operational teams. It also provides clarity on how information flows across different institutional layers, from data acquisition to regulatory reporting. The end-to-end workflow, as shown in Figure 15, illustrates how data flows across systems and institutions to support the daily execution of the intra-state online SCED pilot. The process begins with data acquisition from multiple operational sources, including generator declared capacity, technical parameters, contractual allocations, DISCOM demand forecasts, renewable generation data, and market transactions. These inputs are sourced from existing scheduling applications, databases, and field systems.

Once collected, the data passes through a validation and preprocessing layer managed by MSLDC. At this stage, data completeness, consistency, and logical checks are performed to ensure that only reliable inputs are used for optimization. Any anomalies or gaps identified through automated checks, and visual diagnostics are flagged for corrective action.

Validated data is then fed into the SCED optimization engine, developed by GIL, IIT Bombay, where a linear programming model computes the cost-optimal despatch while respecting all system-level and unit-level constraints such as ramp rates, minimum and maximum generation limits, reserve requirements, contractual obligation and network constraints. The optimization outputs are subsequently routed to the IT integration layer, where automated scripts fetch results and structure them for downstream s. This enables seamless integration with existing scheduling systems and analytical platforms without manual intervention.

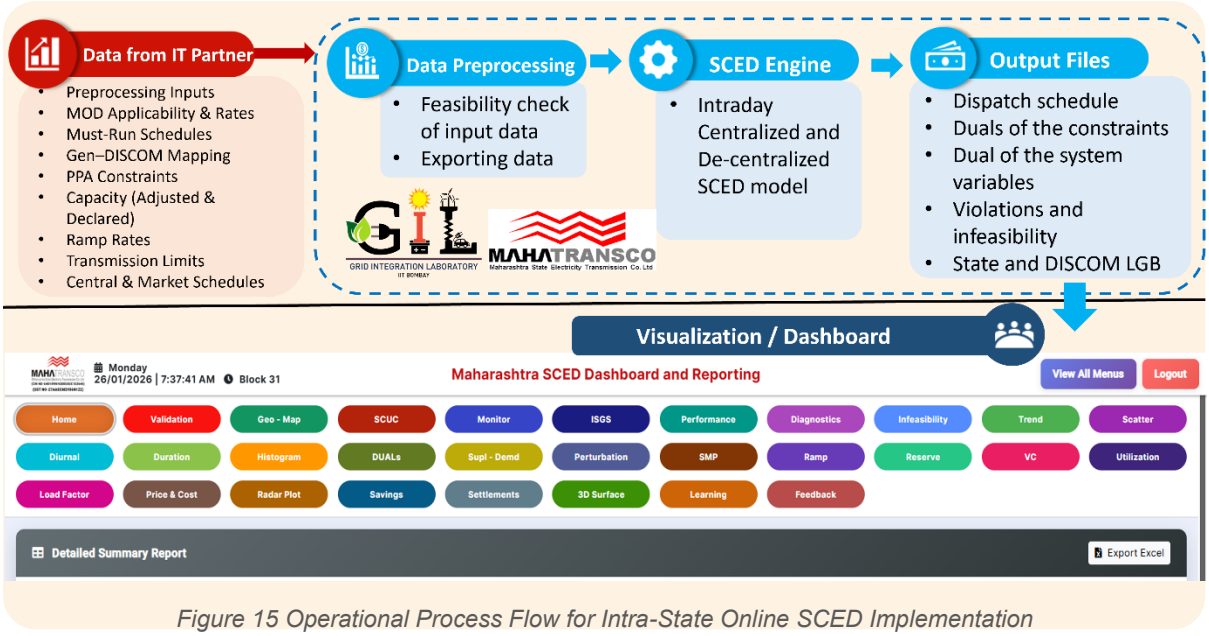


Figure 15 Operational Process Flow for Intra-State Online SCED Implementation

The processed outputs are displayed through the interactive SCED dashboard, allowing system operators to visualize despatch schedules, marginal prices, reserve status, constraint binding, and cost comparisons with the existing MOD-based schedules. This visual layer acts as the primary interface for operational interpretation and learning. Feedback from operators, consultants, and technical partners is then fed back into model refinement, enabling continuous improvement of formulations, constraints, and handling procedures.

2.9. Scope of Pilot

The scope of the intra-state SCED pilot is focused on evaluating different optimization frameworks and their operational implications under realistic system conditions. The pilot encompasses the development and testing of multiple SCED models, including decentralized SCED and centralized SCED formulations, both with and without transmission constraints. As summarized in Table 1, the pilot primarily covers online parallel execution of these models, enabling continuous comparison with existing scheduling practices without affecting live operations. This approach supports real-time learning and operational benchmarking.

Table 1 Summary of SCED Model Variants Evaluated during the online SCED pilot

Model Variant	Optimisation Approach	Transmission Constraints	Execution Mode	Regulatory Relevance
Decentralised SCED	DISCOM-wise optimisation respecting existing contracts	Not considered	Online (Parallel)	Assesses efficiency gains within current decentralised framework
Decentralised SCED with Network Constraints	DISCOM-wise optimisation	Considered	Online (Parallel)	Evaluates impact of congestion-aware despatch and VSE
Centralised SCED	State-level system optimisation	Not considered	Online (Parallel)	Demonstrates benefits of full system coordination
Centralised SCED with Network Constraints	State-level system optimisation	Considered	Online (Parallel)	Tests security-constrained economic despatch
Decentralised SCED including ISGS (Exploratory)	DISCOM-wise optimisation + central sector entitlements	Considered	Offline	Work in Progress
Centralised SCED including ISGS (Exploratory)	State + central sector entitlements	Considered	Offline	Work in Progress

In addition, the scope includes an exploratory offline study to assess the feasibility of incorporating central sector (ISGS) entitlements into the optimization framework. This component aims to understand the potential system-level benefits and complexities of extending centralized optimization beyond intra-state resources. With the evaluation of different optimization models, the scope of the intra-state SCED pilot goes beyond model development and extends to broader institutional and governance objectives. Specifically, the pilot includes:

1. Design and deployment of a custom visualization pipeline for both online and offline monitoring of SCED outcomes, enabling transparent and structured performance assessment.

2. Development of an interactive dashboard to track key performance indicators and support informed operational and regulatory decision-making.
3. Detailed analysis of optimization results to quantify economic benefits, operational improvements, and overall system impacts under various model configurations.
4. Dissemination of key learnings through webinars, workshops, technical conferences, and journal publications to facilitate knowledge sharing and institutional capacity building.
5. Systematic documentation of challenges, lessons learnt, and best practices to support regulatory review and inform the formulation of a long-term SCED implementation framework.

2.10. Data Sources and Information Flow Architecture

The intra-state SCED pilot is supported by robust data and system architecture designed to ensure reliability, traceability, and real-time operational relevance. The overall framework integrates multiple operational data streams through a structured information flow, as illustrated in the data flow diagram Figure 16. At the source level, data inputs are drawn from existing operational systems of MSLDC. These include generator declared capacities, technical parameters, contract allocations, DISCOM demand forecasts, renewable generation schedules, and market transactions from the scheduling application. In addition, real-time measurements from SCADA systems and energy meter data from the State Energy Accounting system are utilized for post-run validation and performance assessment.

All raw inputs are first routed to a centralized data storage layer, where data used to run SCED engine and the existing MOD engine are archived in a structured manner. This ensures traceability, version control, and auditability of scheduling outcomes. Both engines write their outputs to this common storage layer, enabling seamless comparison and analytical processing. A dedicated pre-processing and data sanity layer operates on this stored data. Automated scripts perform format standardization, logical consistency checks, missing data handling, and boundary validation. This stage also involves input file conversion to align operational data with optimization model requirements, ensuring compatibility with the SCED engine's mathematical formulation. Validated inputs are then fed into the SCED optimization engine, which generates optimal despatch schedules, marginal values, reserve metrics, and constraint indicators. In parallel, outputs from the existing MOD engine are also captured, enabling direct benchmarking between conventional MOD and SCED optimized schedules.

The processed outputs are subsequently passed to the visualization and analytics layer, where structured datasets are transformed into interactive charts, performance indicators, and trend analyses. The interactive dashboard serves as the primary interface for operators, analysts, and management to interpret system behavior. Further it is proposed to close the loop by validating the SCED outputs against actual system behavior using SCADA and energy meter data. Deviations between optimized schedules and realized despatch will be analyzed to improve operational understanding.

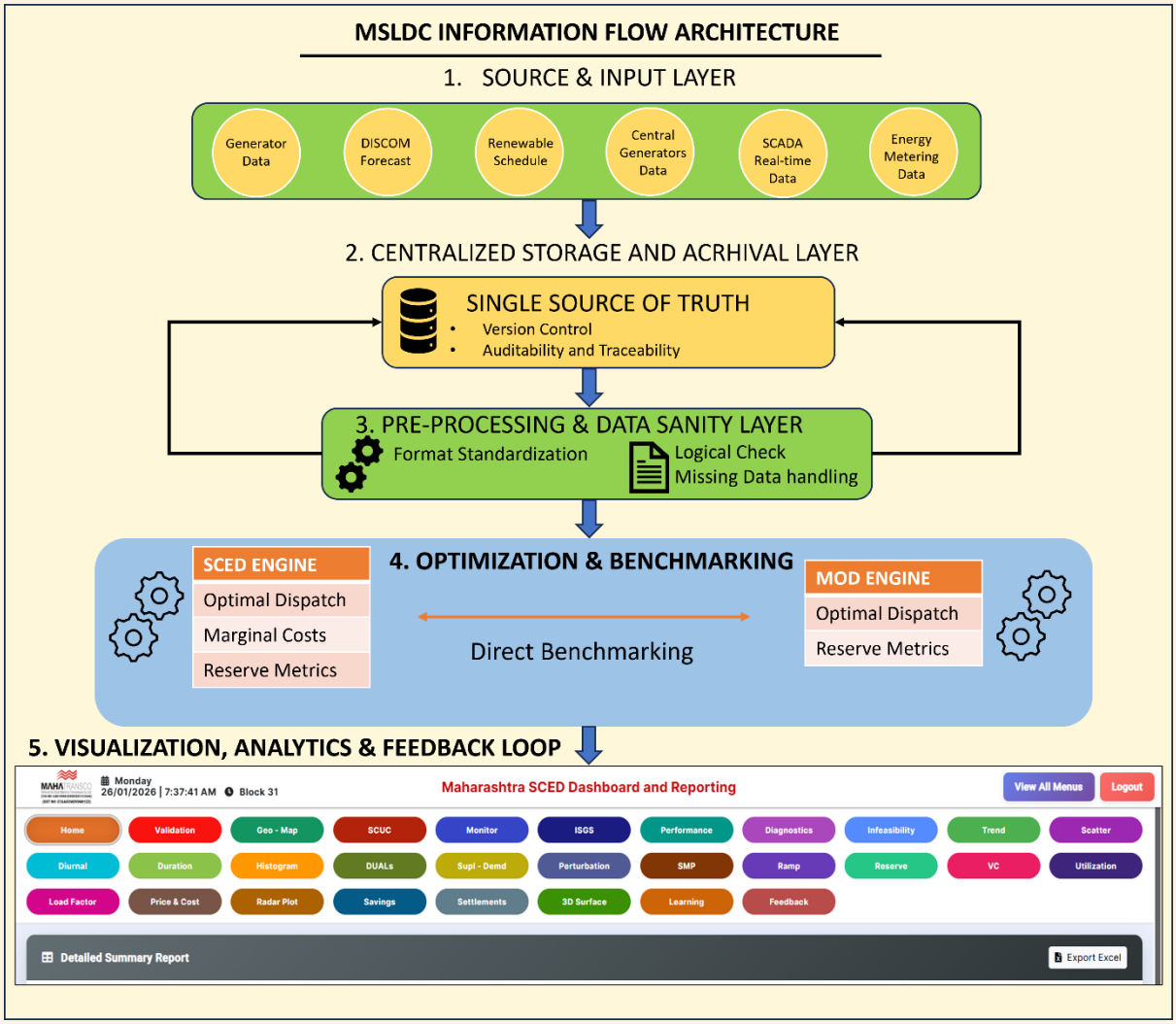


Figure 16 Data Sources and Information Flow Architecture for Intra-State SCED Pilot

3. SCED Modelling Framework

SCED is a well-established optimization framework used globally to achieve cost-efficient and secure system operation. The concept of centralized economic despatch dates back several decades and has evolved with advances in computing, optimization techniques, and power system operations. Over time, SCED has become a standard practice in many mature power markets, where system operators rely on optimization algorithms to schedule generation while explicitly respecting network and operational constraints.

In the Indian context, the formal adoption of SCED at the national level for inter-state generating stations marked a significant shift from rule-based scheduling to optimization-based despatch. The experience gained from national implementation has demonstrated tangible benefits which reinforced the value of SCED as a reliable and scalable operational tool.

3.1. Conceptual Overview of Security Constrained Economic Despatch

At a broader level, SCED is designed to achieve system-wide cost minimization by optimally scheduling available generation resources while respecting all operational and security constraints. Unlike conventional rule-based scheduling, SCED relies on mathematical optimization to deliver transparent and objective despatch decisions, ensuring that the least-cost resources are utilized first in a coordinated manner. The conceptual overview of the SCED optimization engine is depicted in the Figure 17, where the entire engine is centered around four main building blocks that are input, output, objective and constraints.

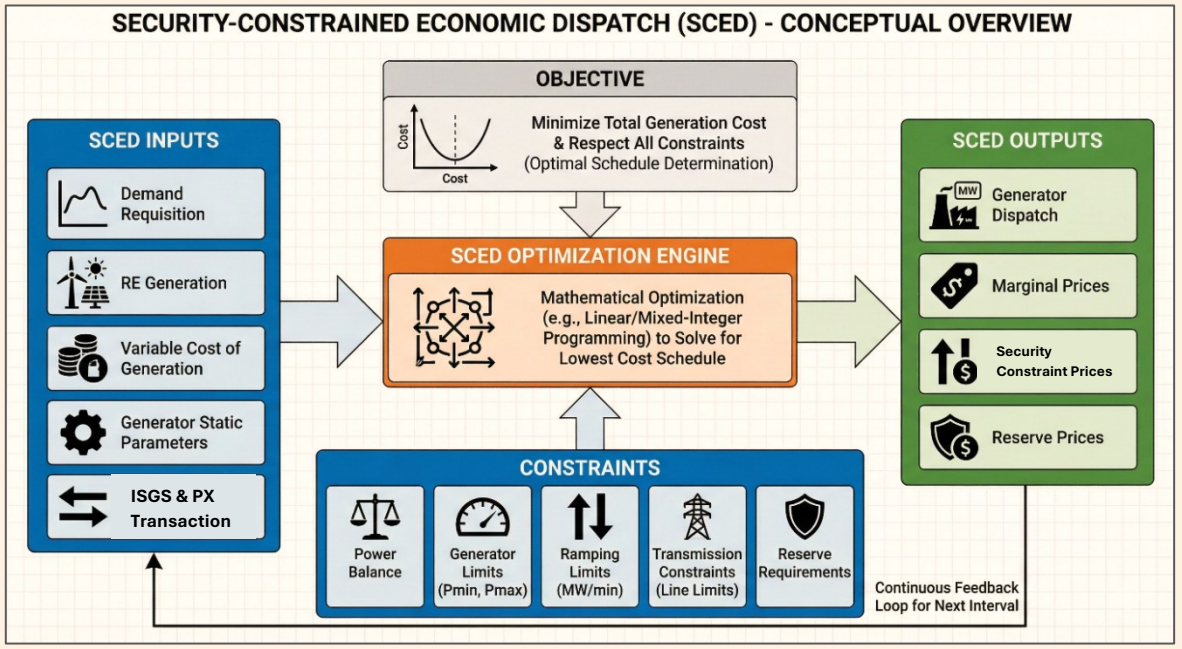


Figure 17 Conceptual overview of the SCED

To execute this SCED optimization, the engine processes a diverse set of critical inputs, including real-time demand requisitions, renewable energy generation schedules, and inter-

state interchange schedules. It also incorporates specific generator parameters such as variable costs and static technical limits. These inputs are rigorously evaluated against a set of hard constraints, including power balance equations, generator capacity limits, ramp rate restrictions, and transmission security boundaries, ensuring that the resulting solution is physically feasible and secure. The final output of the SCED process provides operators with actionable despatch instructions, specifying the precise MW setpoint for every generator for the upcoming time blocks. Beyond physical schedules, the model generates key economic indicators such as system marginal prices, ramp prices, and reserve prices. These metrics provide deep visibility into the system's economic status and resource scarcity, enabling informed decision-making for real-time grid management.

Inspired from this SCED conceptual overview, Grid Integration Lab, IIT Bombay indigenously developed the SCED engine as per the operational constraints of the decentralized and centralized scheduling mechanism.

3.2. Decentralized SCED Formulation

Set and Indices:

T	Set of despatch time blocks [15 minutes]
$Gsub$	Set of schedulable intrastate generators with multiple sub-contracts
D	Set of DISCOMs
C	Set of contractual sub-entitlements for generators in $Gsub$
G	Set of schedulable intrastate generators without sub-contracts

Variables:

$P_{j,d,t}$	Power scheduled from generator $j \in G$ to DISCOM d in time t (MW)
$P_{j,d,c,t}$	Power scheduled from generator $j \in Gsub$ contract c to DISCOM d in time t (MW)
$P_{j,t}$	Total scheduled output of generator j at time t (MW)
$RU^{infe}_{j,d,t}/RD^{infe}_{j,d,t}$	Ramp-up/ramp-down infeasibility slack variables for generators in $\boldsymbol{G}$ (MW)
$RU^{infe}_{j,d,c,t}/RD^{infe}_{j,d,c,t}$	Ramp-up/ramp-down infeasibility slack variables for generators in $\boldsymbol{G_{sub}}$ (MW)
P^{LS}_{d}/P^{EG}_{d}	Load shedding/ Excess generation for DISCOM d (MW)

Parameters:

γ_j	Variable cost of j^{th} generator in (₹/kWh)
$\gamma_{j,d,c}$	Variable cost of c^{th} sub-contract with d^{th} of j^{th} generator in (₹/kWh)
P^{d}_{RTM}	Scheduled shared of d^{th} DISCOM in RTM (MW)
P^{d}_{center}	Entitlement of d^{th} DISCOM in Inter-State generators (MW)
P^{d}_{PX}	Scheduled shared of d^{th} DISCOM in day ahead market (MW)
P^{d}_{RE}	Schedule of must run RE generators for d^{th} DISCOM (MW)
P^{d}_{IDT}	Inter- DISCOM transactions (MW)
$P^{d}_{stand-by}$	Scheduled stand-by generation for d^{th} DISCOM transactions (MW)
$\underline{P}_{j,d,t}/\overline{P}_{j,d,t}$	Lower bound/Upper bound of j^{th} generator for d^{th} $DISCOM$ (MW)
$\underline{P}_{j,d,c,t}/\overline{P}_{j,d,c,t}$	Lower bound/Upper bound c^{th} sub-contract with d^{th} $DISCOM$ of j^{th} generator (MW)

This section presents the SCED model developed for coordinated scheduling of schedulable intrastate generators, including generators with and without contractual sub-entitlements. The

formulation minimizes total generation cost while ensuring power balance, generator operational feasibility, contractual compliance, and transmission security. Central sector allocations, renewable generation, and market transactions are treated as exogenous inputs. The objective minimizes the total system cost across all time blocks, comprising generation costs from schedulable intrastate generators (with and without sub-contracts) and penalties associated with infeasibilities, as given in equation (1). C_{infe} is the penalty cost for overriding the ramping violation, shortfall and excess generation. The graded penalty has been used to trace the violation and its effect on the system marginals.

$$min\ \text{Cost} = \sum_{t\in T}\left(\sum_{j\in G}\sum_{d\in D} P_{j,d,t}\times\gamma_j + \sum_{j\in G_{sub}}\sum_{d\in D}\sum_{c\in C} P^{sub}_{j,d,c,t}\times\gamma_{j,d,c} + C_{infe}\right) \quad (1)$$

3.2.1. DISCOM-wise Optimization Framework

The power balance constraint, as defined in (2), ensures that for every DISCOM and each despatch time block, the total available supply exactly matches the net demand after accounting for excess generation and load shedding. System demand is met through a coordinated combination of schedulable and must-run Intra-State generation (P^d_{RE}), central sector allocations (P^d_{center}), renewable and hydro generation (P^d_{Hydro}), inter-DISCOM transfers (P^d_{IDT}), standby resources ($P^d_{stand-by}$), and market-based procurements (P^d_{PX}), including the Real-Time Market P^d_{RTM}.

$$\sum_{j\in G} P_{j,d,t} + \sum_{j\in G_{sub}}\sum_{c\in C} P_{j,d,c,t} + P^d_{center} + P^d_{PX} + P^d_{RE} + P^d_{IDT} + P^d_{stand-by} + P^d_{RTM} + P^d_{Hydro} - P^{EG}_d = P_d - P^{LS}_d \quad \forall d\in D, t\in T \quad (2)$$

3.2.2. Representation of Generator Sharing and Virtual Units

In the proposed formulation for decentralised SCED, generators are fragmented at a DISCOM-wise level to reflect contractual entitlements, effectively resulting in the creation of virtual generator units corresponding to each generator-DISCOM pair as shown in Figure 18.

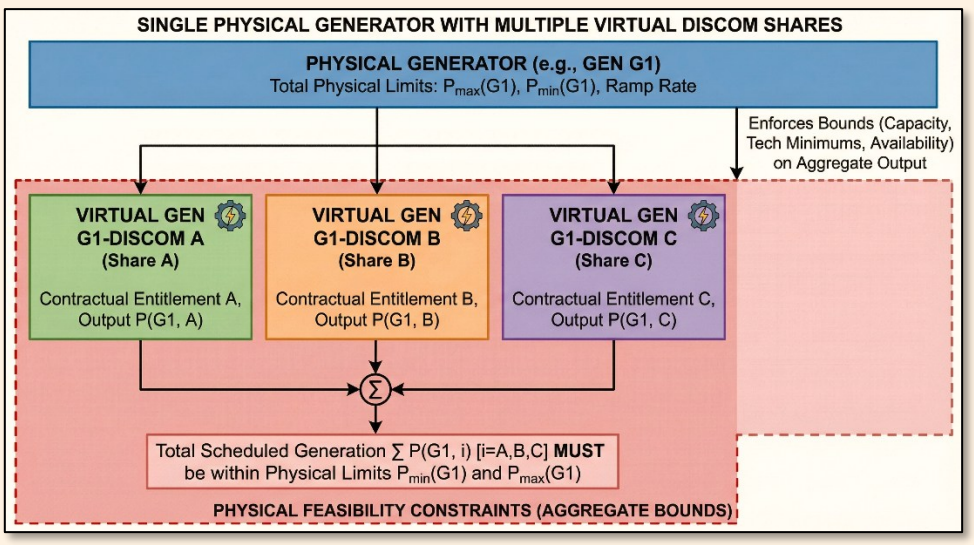


Figure 18 Representative fragmentation of the generator

3.2.3. Constraints and Operational Limits

To ensure that the resulting despatch remains physically feasible and consistent with generator capabilities, the proposed formulation further enforces bounds on individual virtual generators, as defined in (3) through (6). These constraints reflect declared capacity limits, technical minimums, and operational availability, and ensure that scheduled generation remains within permissible operating ranges under all system conditions.

$$\underline{P}_{j,d,t} \leq P_{j,d,t} \leq \overline{P}_{j,d,t} \qquad \forall d \in D, j \in G, t \in T \tag{3}$$

$$P_{j,t} = \sum_{d \in D} P_{j,d,t} \qquad \forall j \in G, t \in T \tag{4}$$

$$\underline{P}_{j,d,c,t} \leq P_{j,d,c,t} \leq \overline{P}_{j,d,c,t} \qquad \forall c \in C, d \in D, \forall j \in G_{sub}, t \in T \tag{5}$$

$$P_{j,t} = \sum_{d \in D} \sum_{c \in C} P_{j,d,c,t} \qquad \forall j \in G_{sub}, t \in T \tag{6}$$

For generators without sub-contracts, each virtual unit represents the share of a physical generator allocated to a specific DISCOM. The upper bound of the scheduled output for each virtual unit is determined based on the DISCOM's percentage share of the generator's block-wise declared capacity, ensuring that despatch respects contractual allocations. Similarly, the lower bound reflects the minimum allowable generation corresponding to the entitled share. By enforcing bounds at the virtual unit level, the SCED formulation ensures that the aggregate despatch across all DISCOMs remains consistent with the physical capabilities of each generator, while explicitly accounting for entitlement-based fragmentation. Like the operational lower and upper bound of the generators, the ramp-up/down constraint for virtual unit has been enforced using equation (7) to (10).

$$P_{j,d,t} - P_{j,d,t-1} \leq RU_{j,d,t} + RU^{infe}_{j,d,t} \qquad \forall d \in D, j \in G, t \in T \tag{7}$$

$$P_{j,d,t-1} - P_{j,d,t} \leq RD_{j,d,t} + RD^{infe}_{j,d,t} \qquad \forall d \in D, j \in G, t \in T \tag{8}$$

$$P_{j,d,c,t} - P_{j,d,c,t-1} \leq RU_{j,d,c,t} + RU^{infe}_{j,d,c,t} \qquad \forall c \in C, d \in D, j \in G_{sub}, t \in T \tag{9}$$

$$P_{j,d,c,t-1} - P_{j,d,c,t} \leq RD_{j,d,c,t} + RD^{infe}_{j,d,c,t} \qquad \forall c \in C, d \in D, j \in G_{sub}, t \in T \tag{10}$$

3.2.4. System Security Constraints

To account for network security considerations within the state grid, the SCED formulation incorporates transmission-related constraints using a proxy-based approach. Instead of explicitly modelling full network power flows, limits are imposed on the output of identified generators whose injections have a significant impact on power flows in specific network corridors or sections that are prone to congestion. The set of generators subject to these proxy transmission limits is time-block dependent, reflecting the dynamic nature of network loading and congestion patterns across the day. For each despatch interval, limits are applied only to those identified generators whose injections are expected to influence power flows in congestion-sensitive network sections under prevailing system conditions, as defined in equation (11).

$$P_{j,t} \leq P^{Trans-Limit}_{j,t} \qquad \forall j \in G_{Trans}, t \in T \tag{11}$$

Overall, the proposed SCED formulation is developed using continuous decision variables to represent generator despatch, contractual sub-entitlements, and infeasibility overrides, resulting in a linear optimization model suitable for real-time and intraday applications. The model explicitly captures key operational characteristics of state-level system operation, including entitlement-based scheduling, ramping behaviour, and proxy transmission constraints, while remaining computationally tractable. The following section presents performance of the proposed SCED framework is evaluated against the existing merit order despatch approach using one year of operational data, with a focus on despatch outcomes, operational flexibility, and the additional insights enabled through price-based signals.

3.3. Centralized SCED Formulation

The contractual obligations and the representation of a single physical generator through multiple virtual units are explicitly retained in the centralized SCED formulation. This modelling approach preserves the commercial structure of existing sub-contracts while enabling system-wide optimization. By treating each sub-contract as a distinct virtual unit with its own variable cost, the framework captures cost heterogeneity across DISCOM agreements, thereby providing greater operational flexibility and enhanced potential for system cost reduction.

$$min\ \text{Cost} = \sum_{t\in T}\left(\sum_{j\in G} \mathrm{P_{j,t}} \times \gamma_j + \sum_{j\in G_{sub}}\sum_{d\in D}\sum_{c\in C} P^{sub}_{j,d,c,t} \times \gamma_{j,d,c} + C_{infe}\right) \tag{12}$$

In contrast to the decentralized SCED formulation, the centralized SCED minimizes the total system generation cost, as expressed in equation (12). Although optimization is performed at the system level, each virtual unit continues to represent a fraction of the same physical generator, ensuring that despatch outcomes remain technically feasible while honoring contractual arrangements.

3.3.1. Load Generation Balance

The power balance constraint, as defined in (13), ensures that all DISCOM demand including the state under drawl and over drawl are aggregated at the state level and for each despatch time block, the total available supply exactly matches the net demand after accounting for excess generation and load shedding. System demand is met through a coordinated combination of schedulable and must-run Intra-State generation (P^d_{RE}), central sector allocations (P^d_{center}), renewable and hydro generation (P^d_{Hydro}), inter-DISCOM transfers (P^d_{IDT}), standby resources ($P^d_{stand-by}$), and market-based procurements (P^d_{PX}), including the Real-Time Market P^d_{RTM}.

$$\begin{aligned}\sum_{j\in G} P_{j,t} + \sum_{j\in G_{sub}}\sum_{d\in D}\sum_{c\in C} P_{j,d,c,t} \\ + \sum_{d\in D}\left(P^d_{center} + P^d_{PX} + P^d_{RE} + P^d_{IDT} + P^d_{stand-by} + P^d_{RTM} + P^d_{Hydro}\right) \\ - P_{EG,t} = \sum_{d\in D}\left(P_{d,t}\right) - P_{LS,t} \quad \forall t \in T\end{aligned} \tag{13}$$

3.3.2. Network-Aware Constraints and Security Considerations

Transmission constraints modelling remains similar to decentralized SCED formulation, equation 11, where the generation is constrained to respect the network congestion.

3.3.3. Treatment of Generator Constraints and Flexibility

Generator operating characteristics such as technical limits, ramp rate constraints, and flexibility variations are explicitly represented at the unit level, including generators owned by subcontractors, which are subject to unit-level ramping limits, unlike decentralized SCED where resources are fragmented and modelled at a virtual unit level.

3.4. SCED Framework Strengthening During the Pilot

The SCED framework implemented during the pilot phase has evolved progressively from the initial offline model to ensure close alignment with existing operational practices. While the offline study provided a strong analytical foundation, several refinements were introduced during the pilot to enhance practical applicability and consistency.

3.4.1. Representation of Technical Minimum and Declared Capacity

One important improvement was in how Technical Minimum and Declared Capacity were represented. In the initial offline model, these limits were applied at the physical unit level. However, in real operations, the output of a single generator is often split across multiple DISCOM contracts, each treated separately in the scheduling process. In line with this, the pilot model was modified to apply technical minimum and DC at the virtual unit level. This means each virtual unit now carries its own operational limits, proportional to its contractual share. In the case of the virtual unit representing subcontract, the limits are as per the contracts. This change made the optimisation outcomes honouring contractual arrangements and brought the model consistent with the actual scheduling practice.

3.4.2. Ramping Constraints and Overriding Mechanisms

Similar to the operational lower and upper bound of the virtual units, a similar refinement was carried out for the ramp-up and ramp-down constraints. In the initial offline formulation, ramp limits were applied at the physical unit level, assuming that the entire generating capacity responded uniformly to changes in schedule. However, in actual operations, the generation of a single unit is distributed across multiple DISCOM contracts, and each contractual share is treated independently in the scheduling process. The SCED engine was enhanced to apply ramping constraints at the virtual unit (sub-contract) level. Each virtual unit is now assigned ramp-up and ramp-down limits proportional to its contractual share, while ensuring consistency with the physical ramp capability of the generator. For sub-contract-based virtual units, the ramp limits are aligned with contractual provisions wherever applicable. In addition, infeasibility override mechanisms have also been implemented at the virtual unit level.

3.4.3. Ride-through infeasibilities

During real-time operation, certain system conditions may lead to infeasible optimisation problems where all constraints cannot be simultaneously satisfied. To address this in a structured manner, gradual refinement through a graded penalty-based relaxation mechanism has been incorporated directly into the SCED objective function. The ramp-down relaxation is penalised at ₹11.5/kWh, ramp-up at ₹12/kWh, excess generation at ₹12.5/kWh, and load shedding at ₹13/kWh. The graded nature of these penalties ensures that the optimisation engine prioritises less disruptive corrective actions and treats load shedding strictly as a last-resort measure. Additionally, the activation of specific penalty terms provides direct insight into the root causes of unusual marginal prices, supporting transparent analysis.

3.4.4. Switching Decentralized and Centralized SCED

A further strengthening of the SCED framework during the pilot has been the introduction of a continuous centralised SCED run operating in parallel with the decentralised SCED model. Both models are executed independently using the same input datasets, ensuring a like-to-like comparison of outcomes under decentralised and centralised despatch paradigms. This parallel operation enables systematic assessment of cost impacts, despatch patterns, marginal prices, and constraint behaviour across the two approaches without disturbing live system operations. During the pilot, a dynamic switching logic between the two models is being progressively developed and tested.

3.4.5. Look Ahead Planning Horizon

During the offline study phase, the SCED model was executed with a full-day planning horizon covering all 96-time blocks. While this approach was useful for theoretical analysis, it did not reflect the operational reality where firm schedules are available only for near-term blocks. Accordingly, for the online pilot, the planning horizon has been revised to a rolling forward-looking window, with optimisation initiated at least one block ahead. With the implementation of a time-based trigger, the feasibility of optimising schedules for the next block (T+1) is considered, and the horizon may be adjusted based on operational readiness. This approach aligns with implementation feasibility and regulatory expectations.

3.4.6. Inter-Temporal Continuity

To ensure inter-temporal consistency and avoid artificial ramping violations between successive runs or day changeover, a structured initialisation mechanism has been introduced. After each SCED run, an initial condition file is generated capturing the final despatch of the current block. This file is then automatically passed as an input to the subsequent time block run. By doing so, the optimisation engine respects the actual operating point of generators from the previous block, ensuring smooth transitions and realistic ramping behaviour across time blocks. This rolling initialisation framework ensures smooth transitions, realistic ramping behaviour, and improved model stability, aligning optimisation outcomes with physical system dynamics and real-time despatch practices.

4. Integration with SCED Engine and Dashboard Framework

While the modelling framework includes the key consideration of the operational constraints in LP-based SCED, the integration architecture will ensure the how the developed SCED engine is executed, monitored, and interpreted in real time. The focus of this chapter is to explain how the SCED engine has been embedded within the existing operational ecosystem of MSLDC and how its outputs are transformed into actionable insights through a dedicated dashboard. The primary objective of this integration layer is to ensure that optimization outputs are:

- Generated automatically without manual intervention
- Consistently validated against operational data
- Easily accessible to MSLDC
- Visually interpretable for decision support
- Auditable for regulatory and governance purposes

4.1. Architecture of the Cloud-Based Data Flow

The integration architecture has been designed to ensure that SCED outputs are automatically generated, validated, securely stored, and presented in an interpretable manner for operational and regulatory use. The end-to-end flow can be understood in the following logical layers shown in Figure 19.

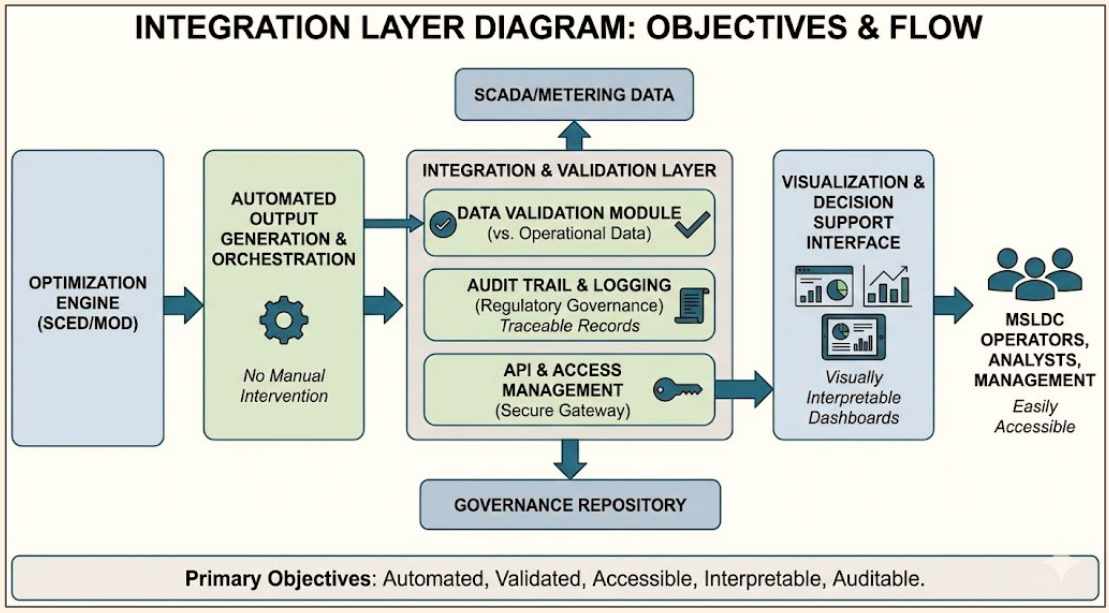


Figure 19 Architecture of the cloud-based data flow to integrate SCED engine and dashboard

4.1.1. Optimization Engine Layer

At the core of the architecture lies the optimization engine, which includes both the SCED engine and the existing MOD engine. These engines generate despatch schedules, cost outputs, marginal values, and system indicators based on input data received from operational systems. The engines function independently but follow a common output structure to enable comparison and benchmarking.

4.1.2. Automated Population of Output

Once the optimization runs are triggered, an automation layer orchestrates the entire process. This ensures scheduled execution of models, automated SCED file generation, no manual intervention in daily operations, standardized output formats.

4.1.3. Integration and Validation

The outputs generated by the SCED engine will be systematically validated against operational datasets from the existing MOD engine, with provisions for progressive integration of SCADA and energy meter data. This enables a structured comparison between optimized SCED schedules and actual operational despatch, supporting objective performance assessment. All model runs, input datasets, output files, and subsequent modifications are automatically logged and archived within the cloud-based storage environment, ensuring complete traceability of every despatch outcome. This comprehensive audit trail strengthens regulatory governance, facilitates post-event analysis, and supports transparent decision-making. Data exchange across systems is governed through secure API gateways and access control mechanisms. These measures ensure role-based access, adherence to data standard among authorized users, thereby ensuring confidentiality.

4.1.4. Visualization, Diagnostic and Decision Support Interfaces

The processed datasets are subsequently routed to the dashboard and visualization layer, where optimization outputs are transformed into intuitive visual charts and performance indicators. Key performance metrics are continuously tracked, temporal trends are highlighted, and direct comparisons between SCED and MOD outcomes are enabled. The interface has been deliberately designed for ease of interpretation, ensuring that system operators and management can readily understand system behaviour and performance without requiring specialized knowledge of optimization techniques.

4.1.5. Data Acquisition from Operational Systems

The SCED pilot relies on a time-synchronized data acquisition framework that fetches inputs from multiple operational systems within each 15-minute time block. For decentralized scheduling, generator declared capacity and demand revisions received up to the 5th minute of time block $T-3$ are considered for optimization of time block T. Any revisions received after the 5th minute are automatically deferred and processed in the subsequent cycle for time block $T-2$. Based on this structured cutoff mechanism, final schedules for time block T are frozen during the $T-2$ block, ensuring operational certainty. Under centralized operation, the schedule for time block T is finalized during the $T-1$ block, allowing sufficient lead time for secure system operation. The data is collected in a structured sequence from various sources, including Renewable Energy Management Centre (REMC), Web-Based Energy Scheduling (WBES), power exchange portals, scheduling databases, and DISCOM submissions, as illustrated in Figure 20. This entire process is fully automated and driven by time-based triggers, ensuring that no manual intervention is required during live operation.

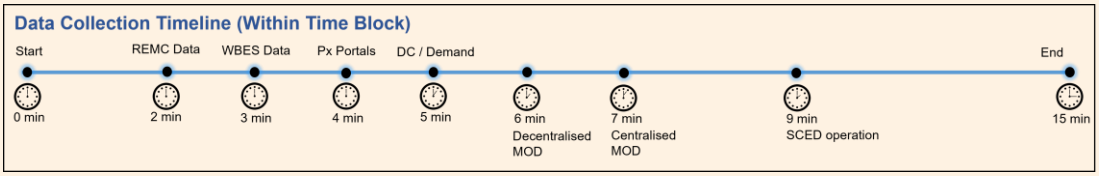


Figure 20 Data acquisition timeline from the operational system

At the start of the block, the data collection cycle is initiated automatically. Around the 2nd minute, data from the REMC is fetched, capturing updated wind and solar schedules and forecasts to account for renewable variability. This is followed by extraction of WBES data around the 3rd minute, which includes inter-state schedules and central sector allocations approved by WRLDC. Around the 4th minute, cleared transactions from power exchange portals such as IEX and PXIL are fetched to reflect market positions in the load generation balance. Declared Capacity submissions from generators and demand forecasts from DISCOMs are accepted up to the 5th minute of time block T-3, after which the system automatically freezes inputs for optimisation. Any revisions received beyond this cut-off are deferred and processed in the subsequent scheduling cycle. Based on the consolidated dataset, decentralised MOD optimisation is triggered around the 6th minute, followed by automated checks for system conditions such as congestion or periphery limit violations. The SCED run triggered around the 9th minute.

4.2. Linkage Between SCED Engine and Visualization Layer

Once the SCED engine completes its run, all output files, such as despatch schedules, cost metrics, marginal values, reserve indicators, and constraint shadow prices, are automatically transferred to the central data repository through secure APIs. A dedicated data processing layer converts the raw optimization outputs into structured datasets suitable for visualization. During this stage, the data is standardized, time-aligned, and tagged with relevant identifiers such as generator, DISCOM, and time block. Basic validation checks are performed to ensure data completeness and consistency before the information is exposed to the dashboard. All post-optimization data processing, performance indicator generation, and analytical computations are carried out within the optimization routine by GIL, IIT Bombay to ensure technical integrity. This includes structuring raw SCED outputs, deriving key metrics, and preparing standardized datasets required for dashboard display.

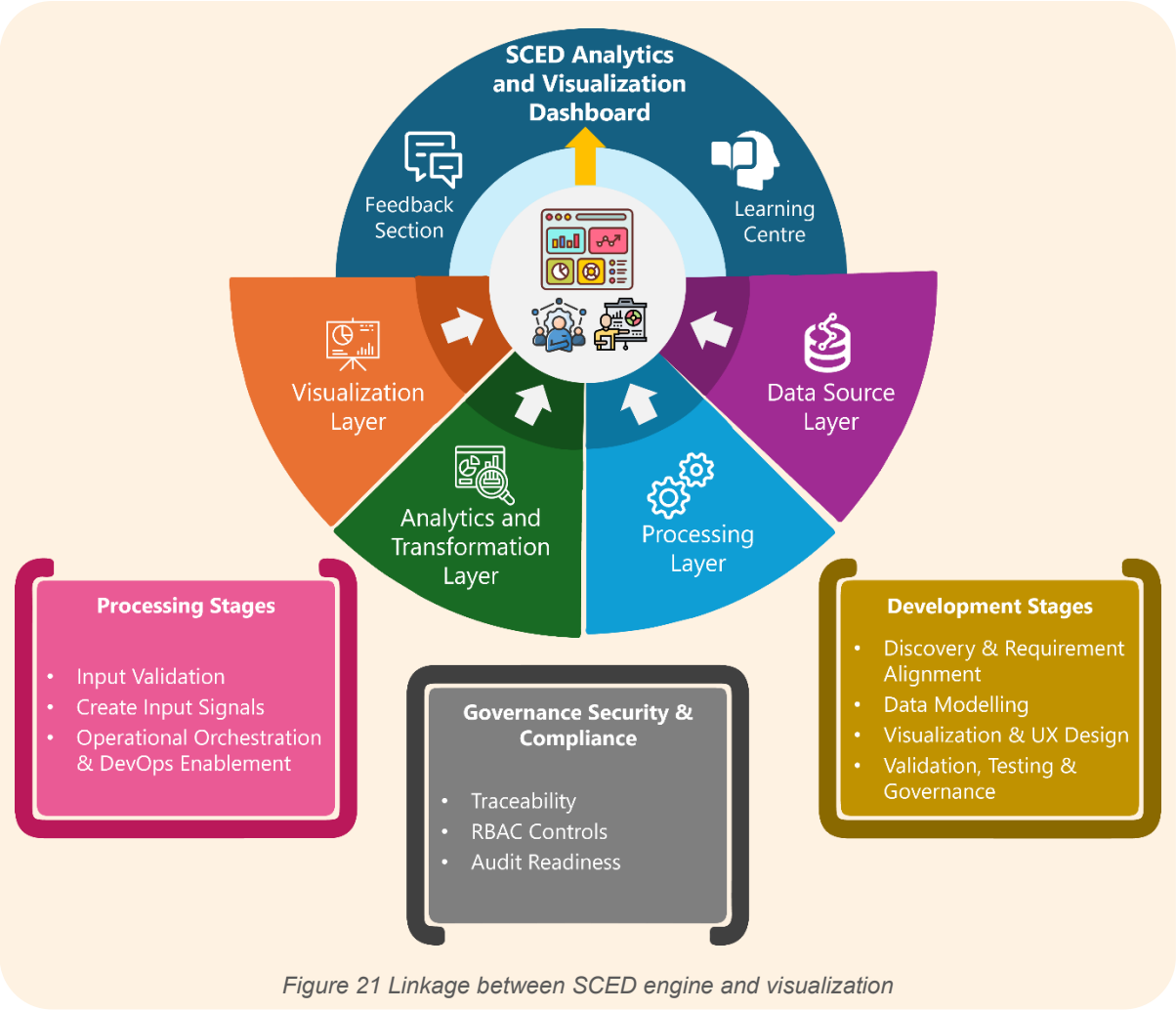


Figure 21 Linkage between SCED engine and visualization

The visualization platform directly reads from this processed data layer. This ensures that the dashboard always reflects the latest SCED results in near real-time. Operators can view block-wise schedules, cost comparisons, reserve margins, congestion indicators, and differences between SCED and MOD outcomes through intuitive charts and tables The dashboard framework has been designed to provide both real-time operational visibility and access to historical performance data, ensuring that stakeholders can monitor current system behaviour while also analyzing past trends for informed decision-making. In real-time mode, the dashboard automatically refreshes after every SCED execution cycle. This allows system operators to view the latest despatch outcome and other performance indicators. Parallelly, the system maintains a comprehensive historical data repository, where all past SCED runs, MOD schedules, and derived performance indicators are securely archived. Users can access block-wise, daily, and period-wise data to analyze performance indicators, track generator and DISCOM performance, and assess the consistency of optimization outcomes. A flexible filter and query interface has been built into the dashboard, enabling users to select specific dates or time ranges, compare multiple days, check performance across multiple generators and DISCOMs, and export data for further analysis. The SCED dashboard has been designed as a decision-support tool, not merely a monitoring interface. The design philosophy is prepared in operational relevance, ensuring that every visual element serves a clear purpose in supporting system operations and performance assessment. The proposed high-level functional architecture of the dashboard is depicted in Figure 21.

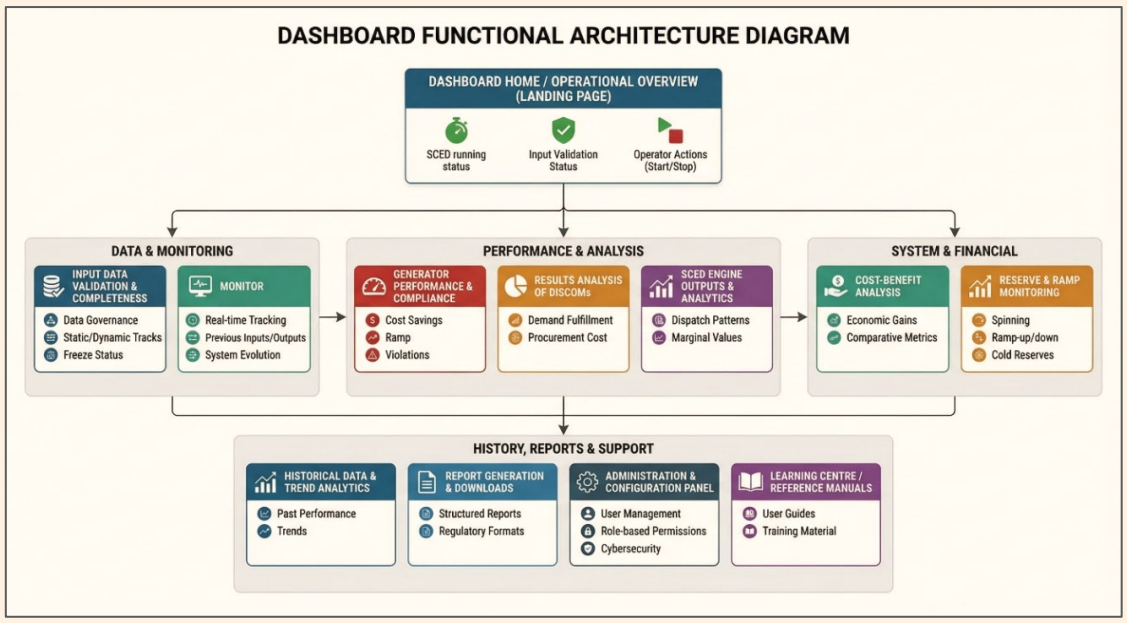


Figure 22 Dashboard functional architecture diagram

Figure 22 shows an operator centric approach has been adopted, where the layout, navigation, and visual elements are aligned with the day-to-day working style of MSLDC control room operators. The dashboard focuses on interpretable indicators such as schedules, cost comparisons, reserve margins, congestion alerts, and deviations between MOD and SCED outcomes. The dashboard follows a layered information structure as summarized in Table 2.

Table 2 Functional Components of the SCED Dashboard Platform

Component	Description
Dashboard Home / Operational Overview	Displays the running status of the SCED module, input data validation status, operator interventions, and Start/Stop controls for model execution.
Input Data Validation & Completeness	Monitoring of static and dynamic input data, validation status, DISCOM revision logs, and time-block-wise data freezing. Detailed view provided as a separate dashboard section.
Monitor	Real-time monitoring of previous block inputs and outputs to track system behaviour.
Generator Performance and Compliance	Assessment of cost savings, ramp compliance, perturbations, and operational violations at generator level.
Results Analysis of DISCOMs	DISCOM-wise analysis of optimisation outputs, including schedule adjustments and performance indicators.
SCED Engine Outputs and Analytics	System-level analysis of optimisation results, solver performance, and key technical indicators.
Cost-Benefit Analysis	Evaluation of economic benefits achieved through optimisation-based despatch.

Reserve and Ramp Monitoring	Monitoring of various reserve categories and ramp availability for system security.
Historical Data and Trend Analytics	Analysis of long-term data trends and performance patterns.
Report Generation & Downloads	Automated generation of standard reports as per MSLDC requirements.
Administration and Configuration Panel	Dashboard administration, user management, and configuration controls.
Learning Centre / Reference Manuals	Repository of reference documents, user manuals, and training material.

The backend architecture of the dashboard is designed to automatically pull data from multiple sources, including SCED solvers, real-time telemetry systems, and historical databases such as SQL and Big Query repositories. Output refresh is event-driven, primarily triggered upon completion of each SCED run. This ensures that the dashboard always reflects the most recent optimization results without manual intervention. The execution frequency of the system is aligned with market timelines, operating at a 15-minute resolution to match real-time despatch cycles

4.3. User Access and Role-Based Views

Secure web-based access is provided to a defined set of stakeholders, including planning teams within SLDC and collaborator for SCED pilot. A robust authentication framework with role-based access control is planned to be included to ensure that each user can access only the information relevant to their role, thereby maintaining data confidentiality and governance. To support proactive system management, it is proposed to include a comprehensive alert and notification framework. Real-time alerts are triggered for critical events such as optimization infeasibilities, missing or incomplete input data (DC, variable cost, ramp declarations), excessive schedule deviations, and reserve shortfalls. In addition, email and SMS notifications are proposed to include for automatically sent to designated users based on their roles, enabling timely corrective action. Overall, from a design perspective, the platform is proposed to be scalable and future ready. Planned enhancements include integration of Security-Constrained Unit Commitment (SCUC) functionality, and development of mobile-friendly access for on-the-go monitoring. This will ensure that the dashboard evolves in line with anticipated regulatory directions and increasing system complexity. The dashboard will also support advanced analytical integration, allowing connectivity with tools such as Python and R for post-processing. A wide range of visualization formats are supported, including heat maps, 3D charts, tables, line plots, duration curves, scatter plots, box plots, bar charts, pie charts, radar charts, and histograms.

5. Overview of Maharashtra Power System

Maharashtra operates one of the largest and most diverse intra-state power systems in the country, characterized by a wide geographical spread, a heterogeneous generation mix, and significant variation in demand across time and regions. The system serves a mix of industrial, commercial, and residential consumers, resulting in pronounced daily and seasonal load fluctuations. Managing this complexity requires a scheduling and despatch framework that balances economic efficiency with operational security, while accommodating evolving demand patterns and increasing renewable penetration. An understanding of the underlying demand-generation mix is essential to contextualize system operations. Accordingly, this section presents an overview of demand variation in the Maharashtra power system, highlighting intra-day, inter-day, and seasonal trends that shape operational requirements.

5.1. System Demand

The intra-day and seasonal variation of electricity demand in Maharashtra for the year 2025 is shown in Figure 23. The heatmap represent that the peak demand observed during the summer months (March-May), particularly in daytime and evening hours, reflecting higher cooling loads. The lower demand levels occur during the monsoon period (July-September), while moderate demand is seen in winter months.

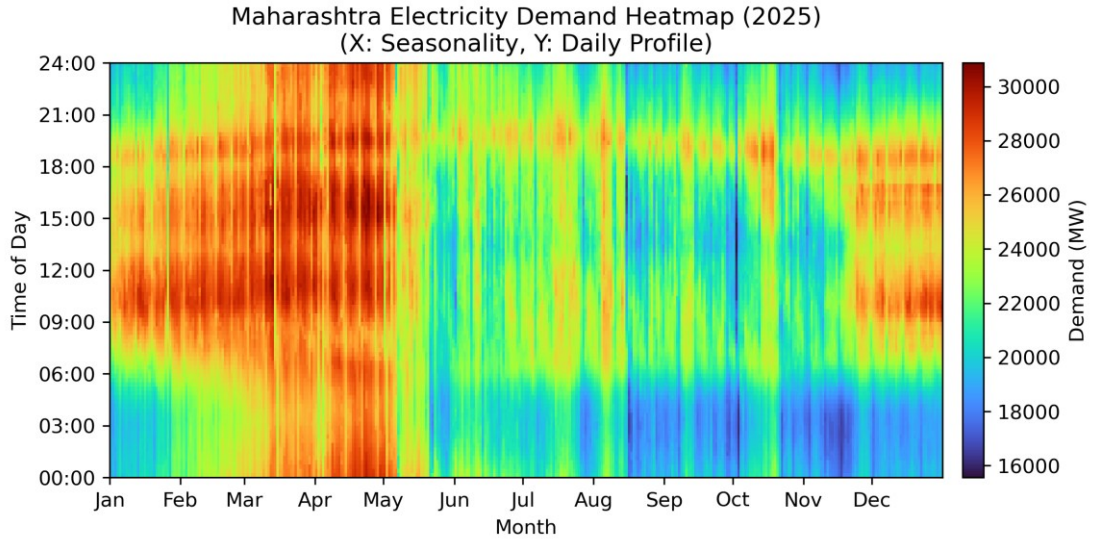


Figure 23 Variation of Maharashtra Electricity demand in 2025

A three-dimensional surface plot of Maharashtra's electricity demand, showing simultaneous variation across months and intra-day time blocks is shown in . On a daily basis, demand remains low during night and early morning hours, rises steadily through the day, and consistently peaks during evening hours. Notably the timing of the daily peak remains largely unchanged across seasons, whereas the magnitude of the peak varies, indicating that seasonal stress on the system is driven more by intensity rather than by a shift in consumption behaviour.

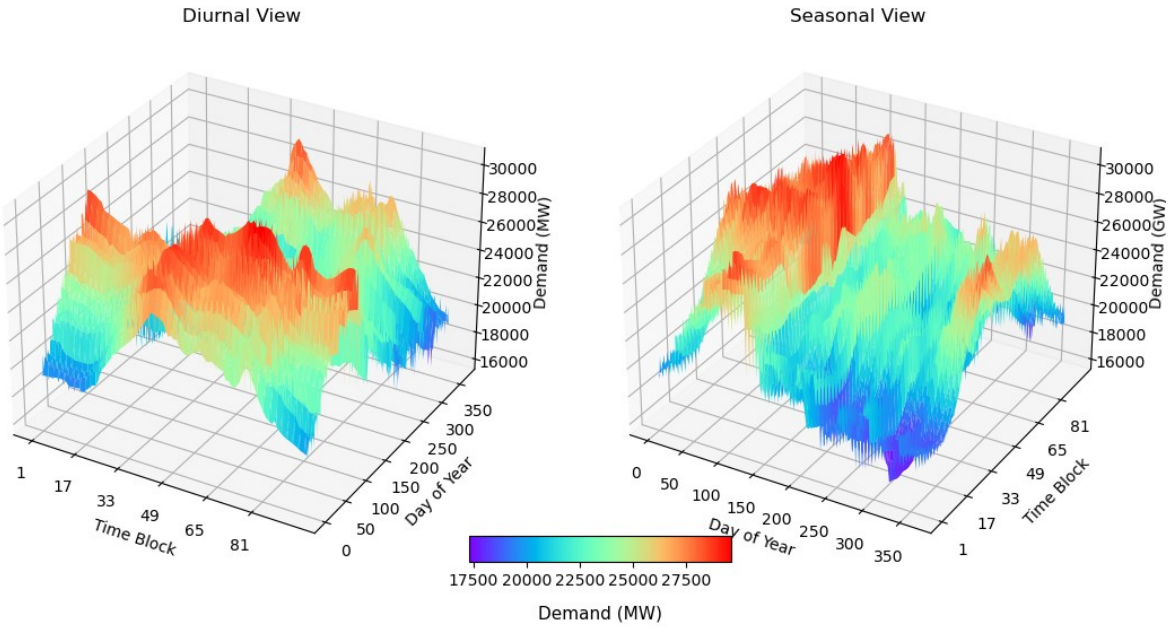


Figure 24 Diurnal and Seasonal variation of the Maharashtra's demand

With the diurnal and seasonal variation of demand, the average demand of Maharashtra over the year period (2025) remains around 22-23 GW. Lean demand is observed during early morning hours (blocks 12-18) at around 20-21 GW, while a pronounced evening peak occurs during blocks 75-82, reaching 25-26 GW. The resulting 4-5 GW peak-lean gap highlights significant daily variability.

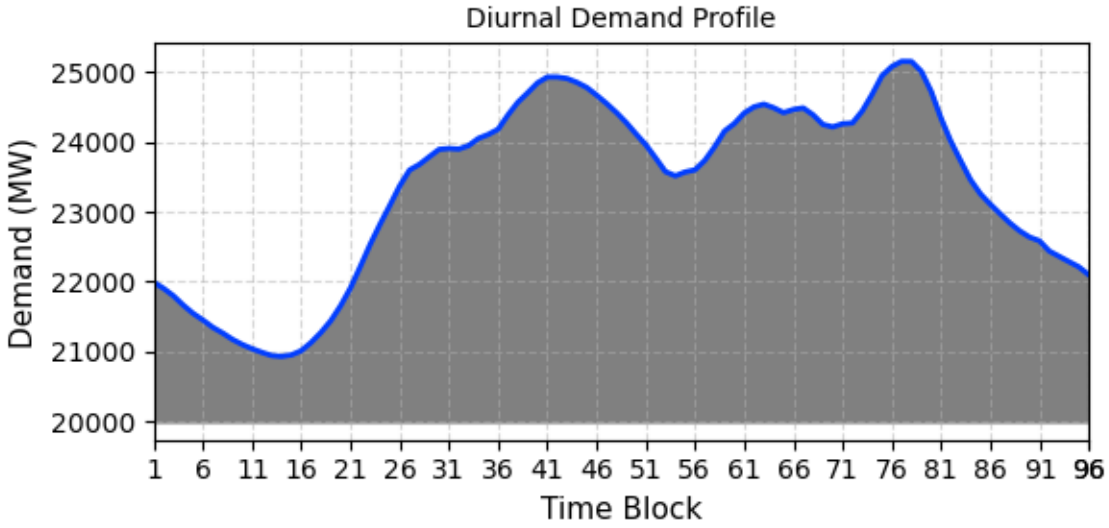


Figure 25 Daily average diurnal demand profile of Maharashtra

With the peak demand around ~30 GW, percentage contribution of different DISCOMs to Maharashtra's total state demand over a sample week is shown in Figure 26. MSEDCL consistently accounts for the dominant share (around 85-90%), reflecting its large consumer base and statewide coverage. Urban utilities, AEML, BEST, and TPCL, contribute smaller but stable shares, together forming roughly 8-12% of the total demand. The Other category represents DISCOMs operating within the state that is met through supplementary arrangements and has an important peripheral implication on state.

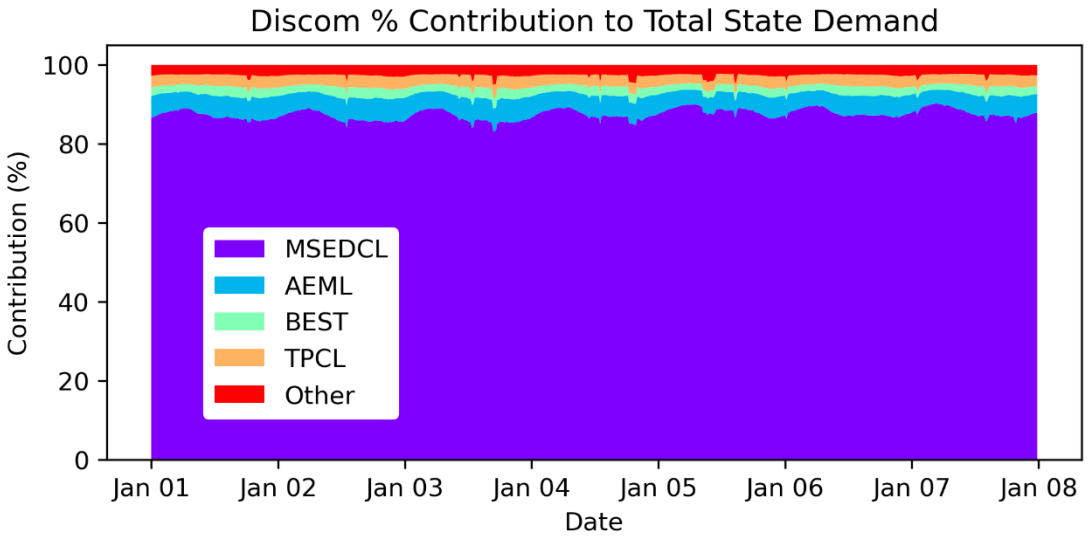


Figure 26 Discom % contribution to the state demand

5.2. Ramping Requirement

With increasing demand variation, the associated ramping stress highlights the system's flexibility requirement to reliably follow load changes. The 3D plot in Figure 27 shows demand ramp rates ranging from about -2,000 MW/block to +1,500 MW/block across time blocks and days of the year. The largest positive ramps occur during morning load pick-up and evening peak build-up, while steep negative ramps are observed after the evening peak and during late-night hours.

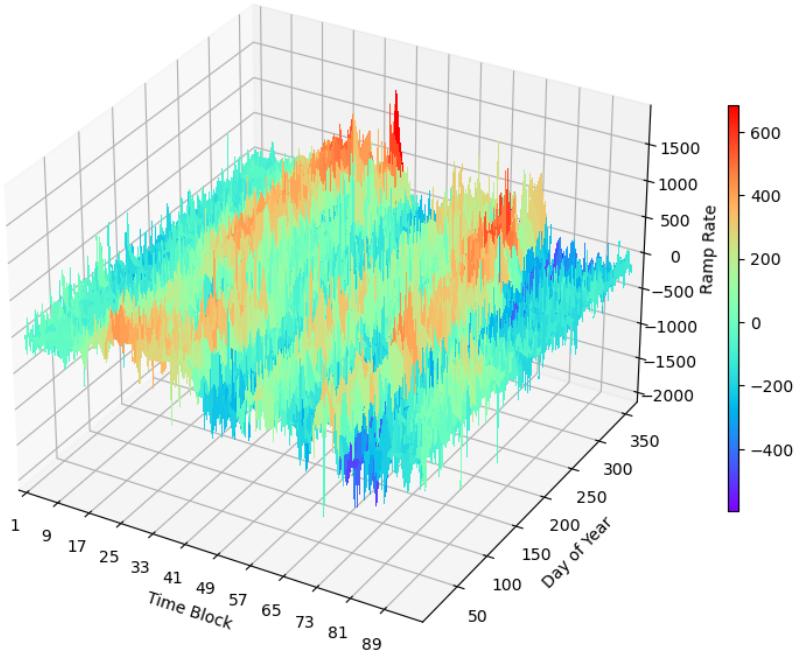


Figure 27 State demand ramp rate (~±600 MW/block) across the days and time blocks

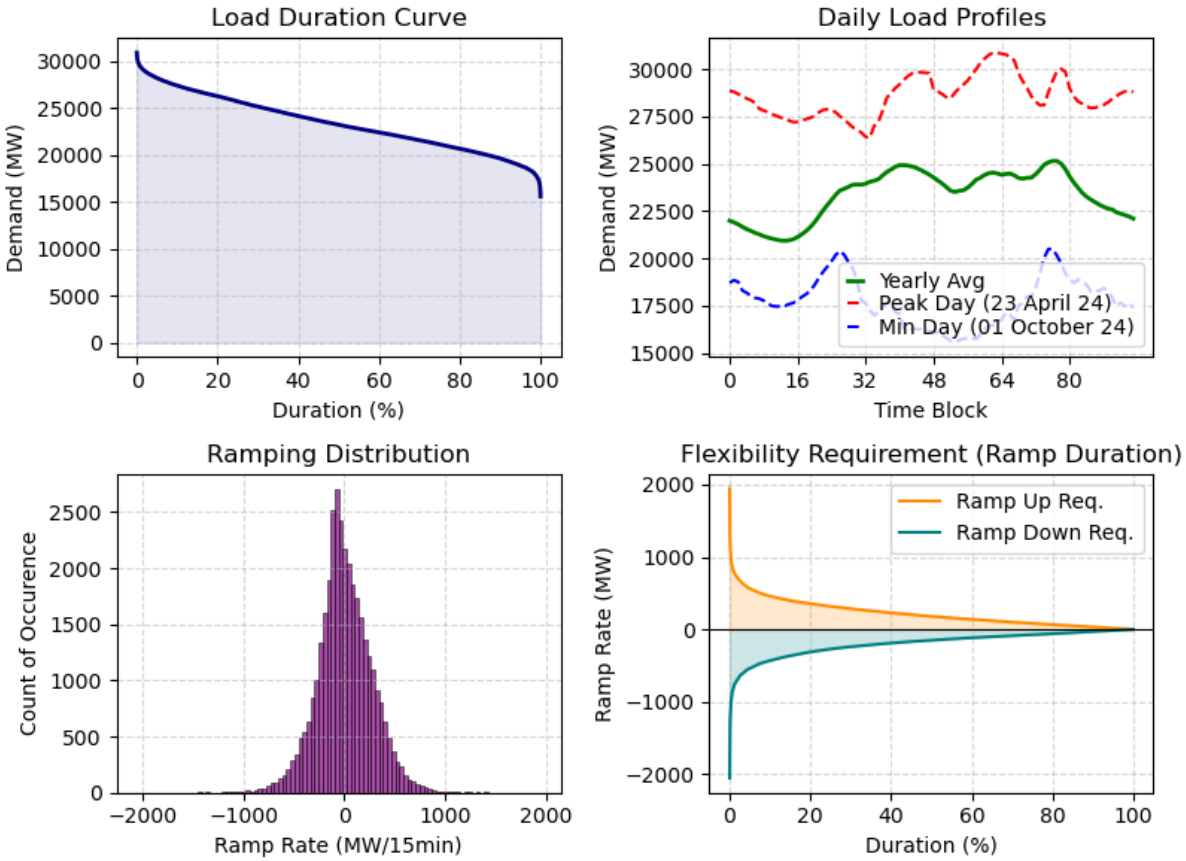


Figure 28 Characteristics of Maharashtra demand along with flexibility requirement

With the annual demand ranging from a minimum of ~15.56 GW to a peak of ~30.88 GW, with an average system load of approximately ~23.38 GW the ramping stress and flexibility requirement is highlighted in Figure 28. The load duration curve in Figure 28 indicates that high-demand conditions occur over a limited share of the year, while a substantial portion of time is spent at moderate load levels, highlighting scope for flexible and economically efficient despatch. Daily load profile shows that the system peak is driven by a distinct high-demand day, whereas minimum demand days exhibit significantly flatter profiles, underlining strong intra-day and inter-day variability. Ramping analysis reveals that the system experiences both upward and downward ramps on a regular basis. The maximum observed ramp-up requirement is ~1.95 GW per 15 minutes, while the maximum ramp-down requirement is 2.056 GW per 15 minutes. Flexibility duration curves indicate that extreme ramping requirements are infrequent. 95% of ramp-up events remain below 563 MW per 15 minutes, and 95% of ramp-down events remain within 538 MW per 15 minutes. Overall, the demand profile exhibits pronounced variability across time scales.

5.3. Arrangement of Generation Resources for Demand Supply

The system comprises a total of ~265 generators comprising total installed capacity is ~31.64 GW (till December 2025), with an effective ex-bus capacity of ~29.5 GW after accounting for auxiliary consumption and losses. The generation mix includes renewable, thermal, hydro, and gas resources. In capacity terms, thermal generation contributes ~21.15 GW, followed by renewables at ~5.82 GW, hydro at ~3.10 GW, and gas at ~1.56 GW, collectively defining the supply-side structure used for meeting system demand. The state covers 19 DISCOMs, of

which 5 (including one virtual entity) have at least one generator mapped, while the remaining 14 DISCOMs have no directly mapped generation. For DISCOMs with mapped resources, the number of generators ranges widely from 1 to 161, with an average of 9.9 generators per DISCOM, indicating significant concentration of generation access, as highlighted in Figure 29 . DISCOMs without mapped generators are therefore reliant on market-based procurement or external contracting arrangements to meet their demand.

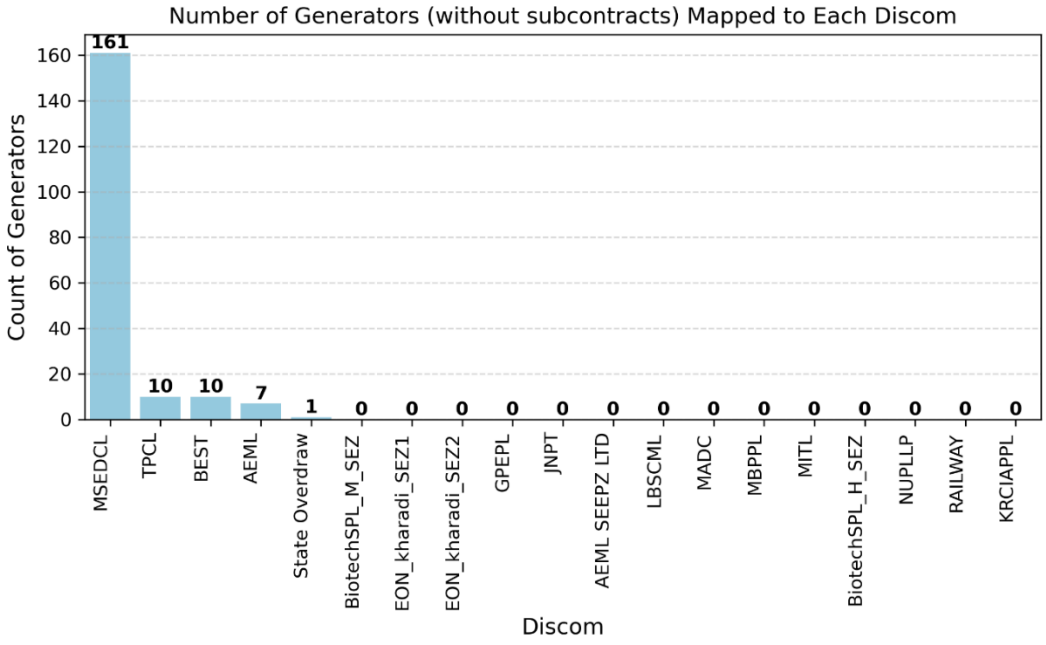


Figure 29 Number of generators mapped to the DISCOMs

Accordingly, DISCOMs with directly mapped generation are represented in Figure 30, where each DISCOM is shown alongside its corresponding mapped generators, including the fictitious generator. DISCOMs without mapped generation are not associated with specific units in the figure, reflecting their reliance on system-level and market-based procurement rather than dedicated generation resources.

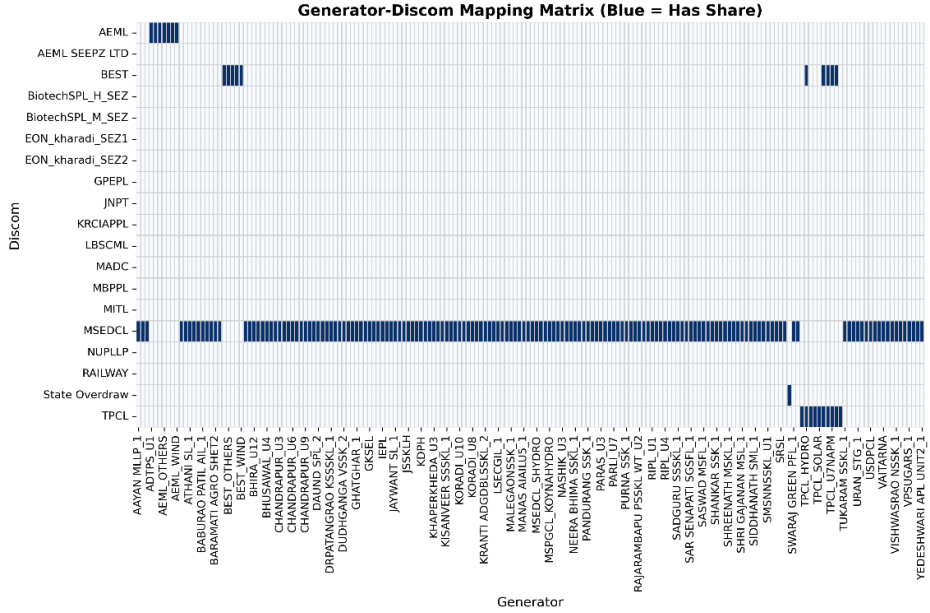


Figure 30 Generators (without subcontracts)-DISCOM mapping matrix

In addition to the mapped generators, there are other generators operating under open access and subcontracting arrangements that also contribute to meeting DISCOM demand.

5.4. Generator Availability and Price Formation

The stacked area plot in Figure 31 through Figure 35 illustrates the evolution of generation availability for the selected DISCOM/state, disaggregated by variable cost bands over the pilot period. Each coloured layer represents the declared capacity available from generators operating within a specific variable cost range, with lower-cost resources shown at the bottom of the stack and higher-cost resources layered above. The total height of the stacked area at any point in time indicates the aggregate declared capacity available to the DISCOM/state on that day to supply net-demand. Variations in the thickness of individual layers reflect changes in generator availability, contract applicability, and cost structure over time. An expansion of the lower-cost bands signifies greater access to economical generation, while a widening of higher-cost bands indicates increased reliance on relatively expensive resources. Seasonal and temporal shifts in the composition of the stack highlight how the cost profile of available generation evolves.

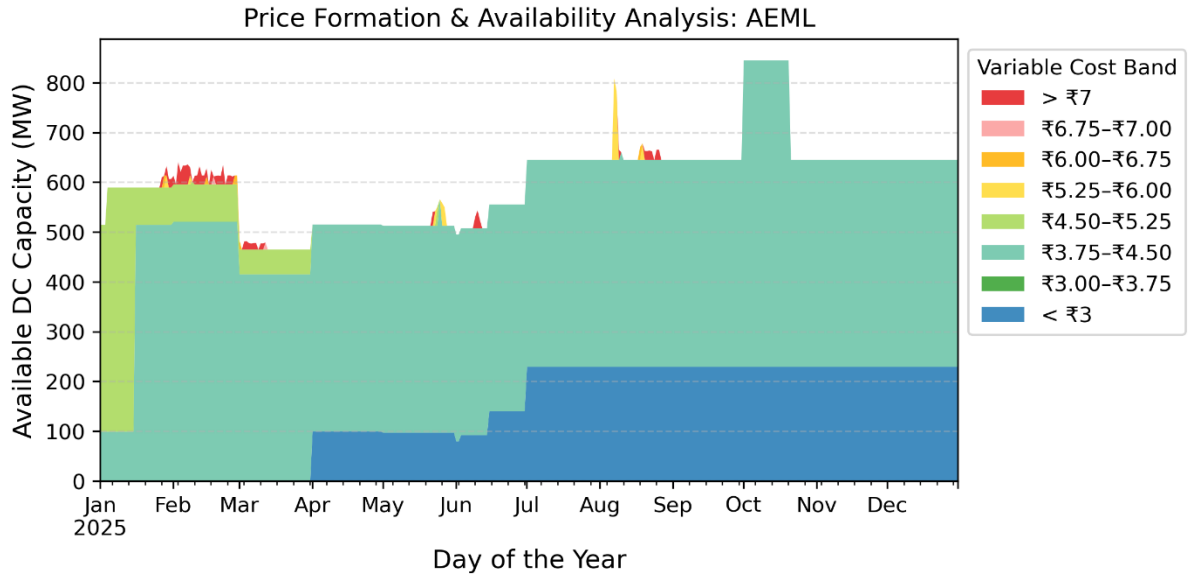


Figure 31 AEML generation availability and price formation

In the early months, AEML's available capacity is largely driven by mid-cost generation (₹3.75-₹5.25), with limited access to sub-₹3 resources, indicating constrained availability of very low-cost generation in the first quarter. From April onwards, low-cost capacity (< ₹3 and ₹3.00-₹3.75) increases steadily, improving the overall cost profile and reducing dependence on higher-cost resources under normal conditions. During the monsoon and post-monsoon period (July-October), total declared capacity rises significantly, led by the ₹3.75-₹4.50 band, while occasional contributions from ₹6.75-₹7.00 and > ₹7 bands indicate reliance on expensive generation during peak system conditions. Similar trends are observed across

other DISCOMs, with price formation dominated by low- and mid-cost generation and high-cost resources contributing primarily during short-duration peak or stressed conditions.

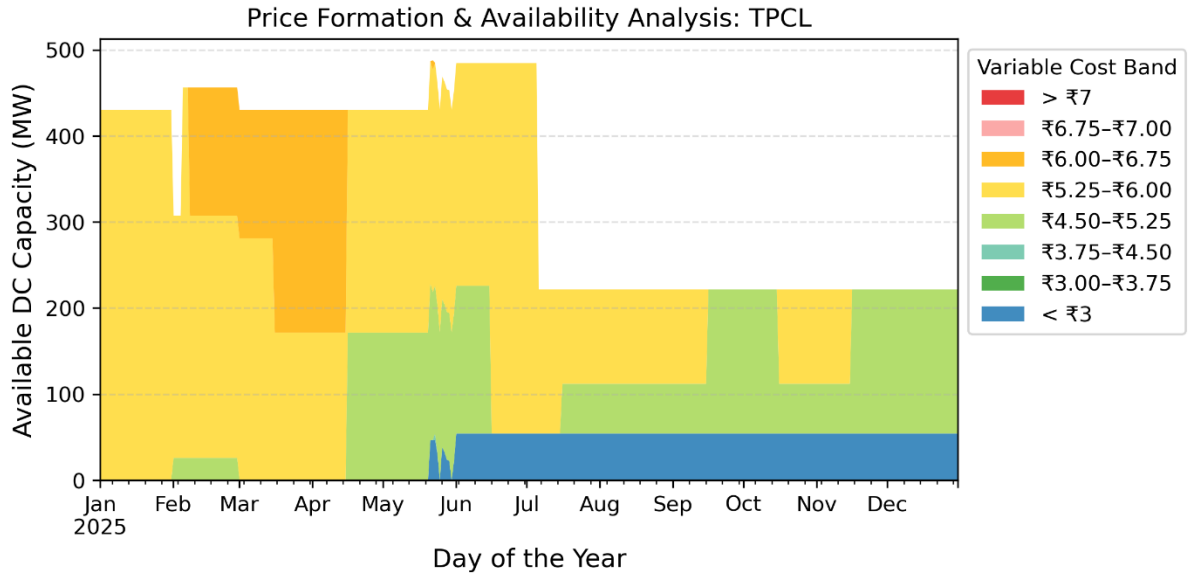


Figure 32 TPCL generation availability and price formation

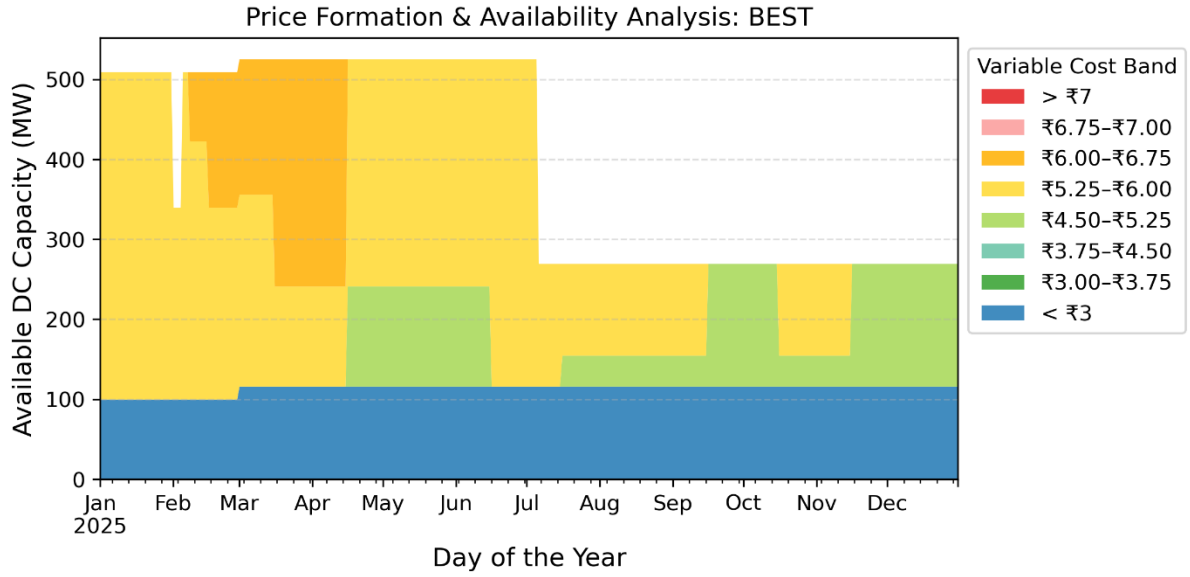


Figure 33 BEST generation availability and price formation

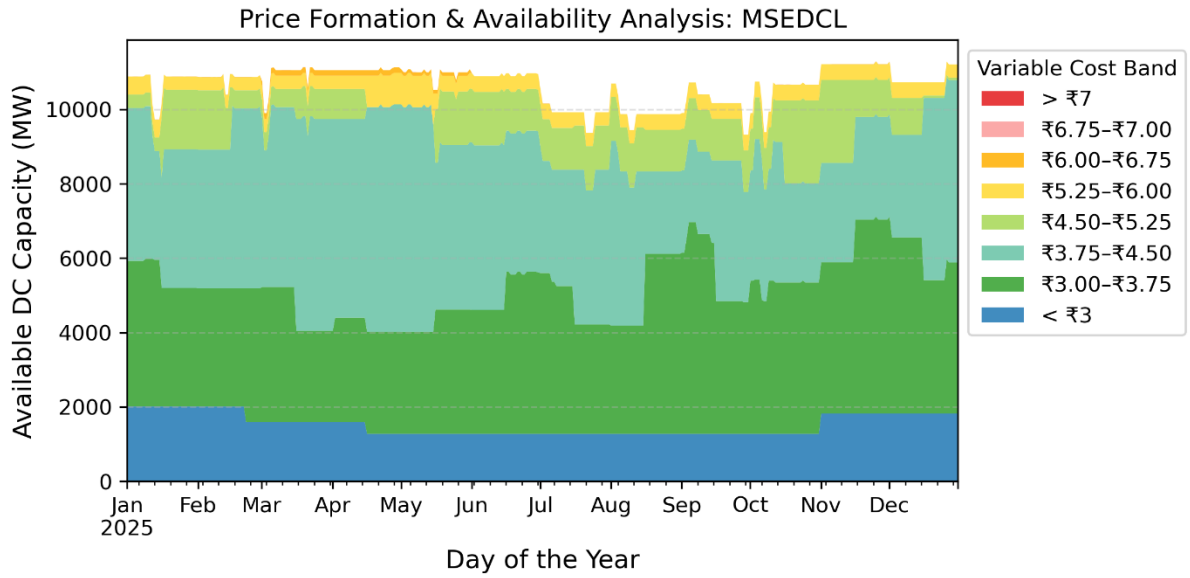


Figure 34 MSEDCL generation availability and price formation

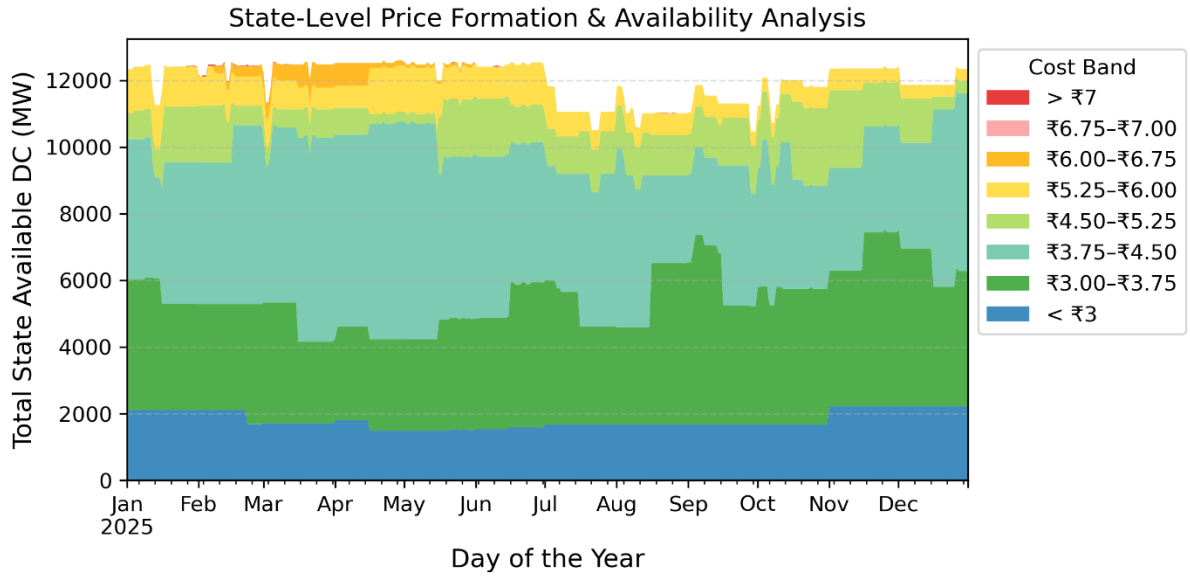


Figure 35 Centralized generation availability and price formation

Compared to DISCOM-level variability, the state-level view in Figure 35 highlights smoother price formation and greater flexibility enabled.

5.5. Resource Mix and Load Generation Balance

To supply a system demand ranging up to ~30 GW, the state relies not only on intra-state generation but also on a diversified portfolio of external and market-based resources. While state-owned coal and renewable generators form the backbone of supply, a substantial portion of demand is met through central sector generation, supplemented by real-time market (RTM) purchases, power exchanges, inter-DISCOM trading, and standby generators to manage variability. For the representative day a despatch and %resource mix is given Figure 36 and Figure 37. The intra-state coal contributes around 45-50%, central sector generation accounts

for approximately 30-35%, renewables supply about 15-20%, while RTM, inter-DISCOM trades, standby sources together contribute 3-5% and hydro supply about 2-10%.

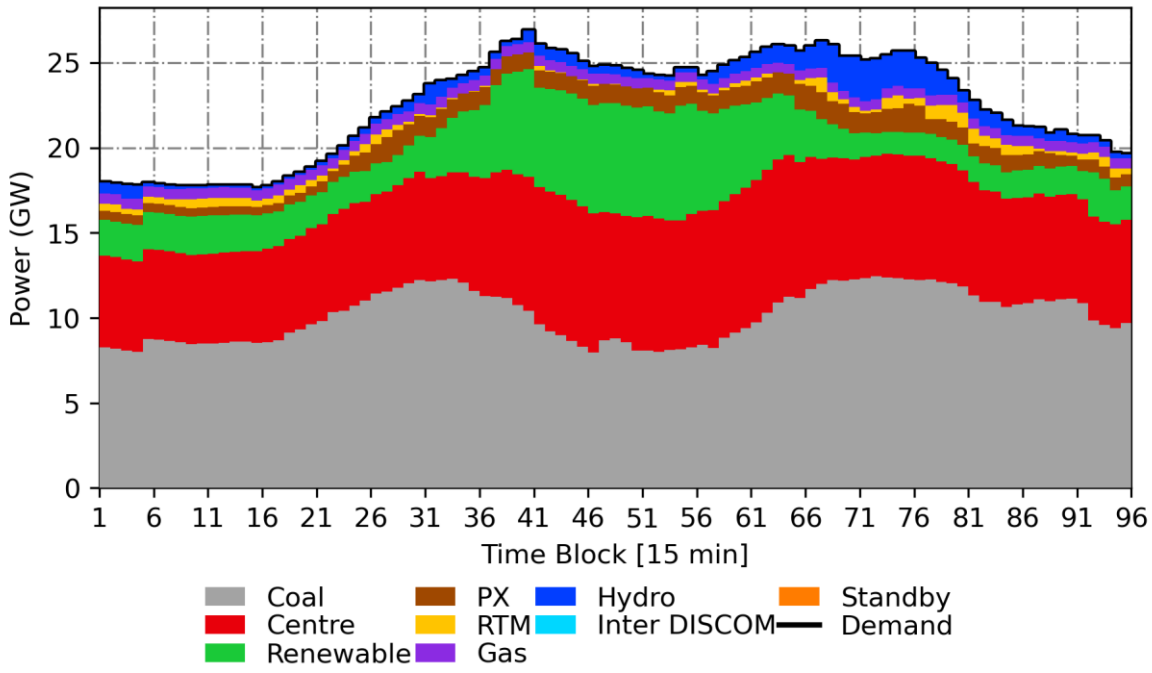


Figure 36 Block wise generation mix of the sample day

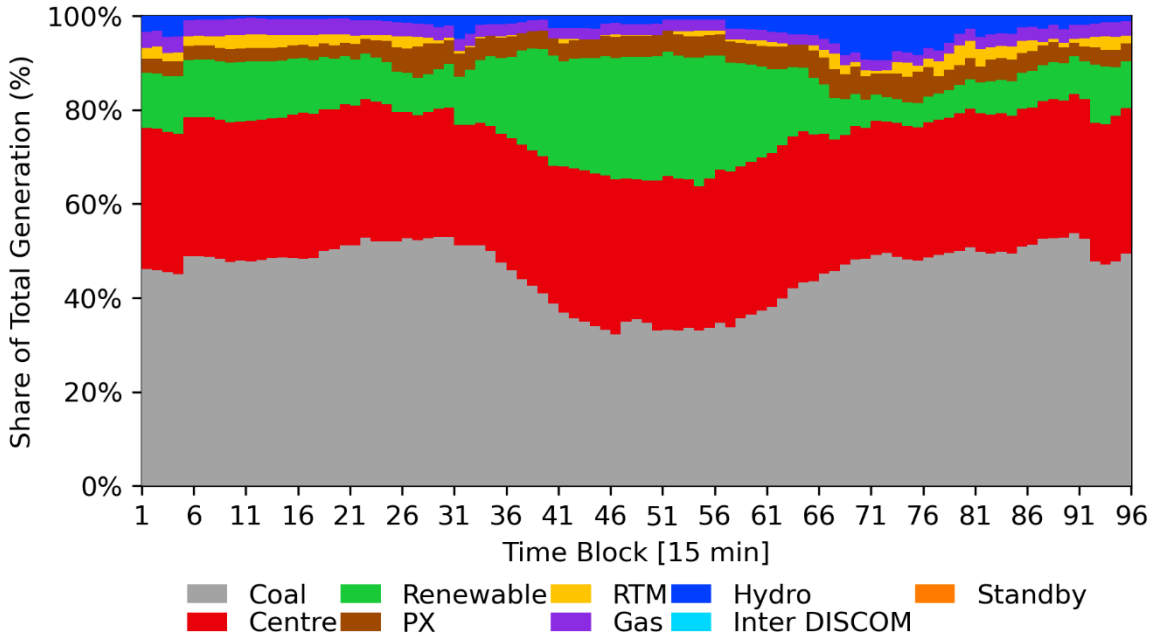


Figure 37 Block wise percentage generation mix of the sample day

6. System Marginals /Shadow Price

This chapter summarises the key insights emerging from the SCED-based scheduling analysis. While cost reduction remains an important outcome, the pilot demonstrates that the larger value of SCED lies in the availability of marginal prices and shadow values, which enable informed operational decisions and support transparent market participation. The six-month analysis shows that optimisation-based despatch produces meaningful economic signals. Following section includes the details of the outcomes derived under the decentralised/centralised SCED formulation for all DISCOMs, presented in the following section. This is followed by a discussion on the marginals of binding constraints, including generation limits, ramping, reserves, and network constraints, to illustrate how SCED translates physical system limitations into actionable economic indicators.

6.1. SMP Under Decentralized SCED

The block wise average System Marginal/Shadow/Dual prices for MSEDCL is shown in Figure 38 through Figure 41, where the higher SMPs are concentrated during morning and evening ramping intervals. These periods often coincide with binding ramp-rate constraints or marginal units with higher variable costs setting the price. In contrast, midday blocks exhibit relatively stable and lower SMPs over the pilot period (July-Dec 2025).

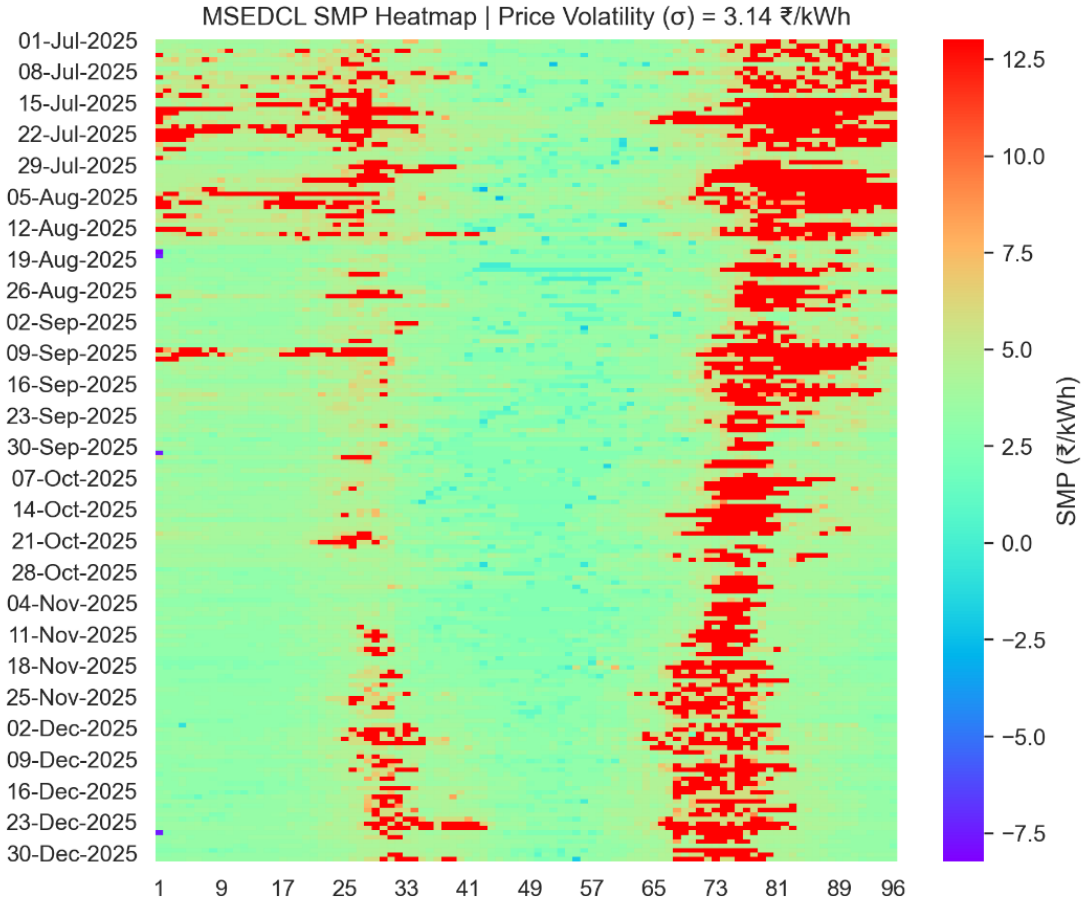


Figure 38 SMP of MSEDCL under De-Centralised SCED

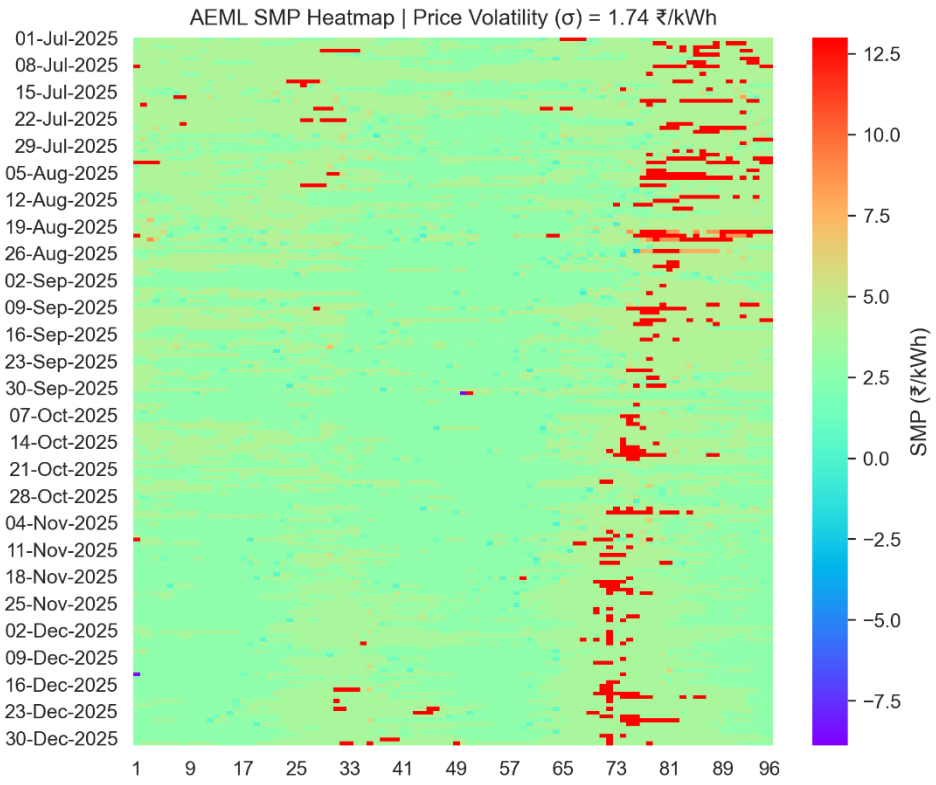


Figure 39 SMP of MSEDCL under De-Centralised AEML

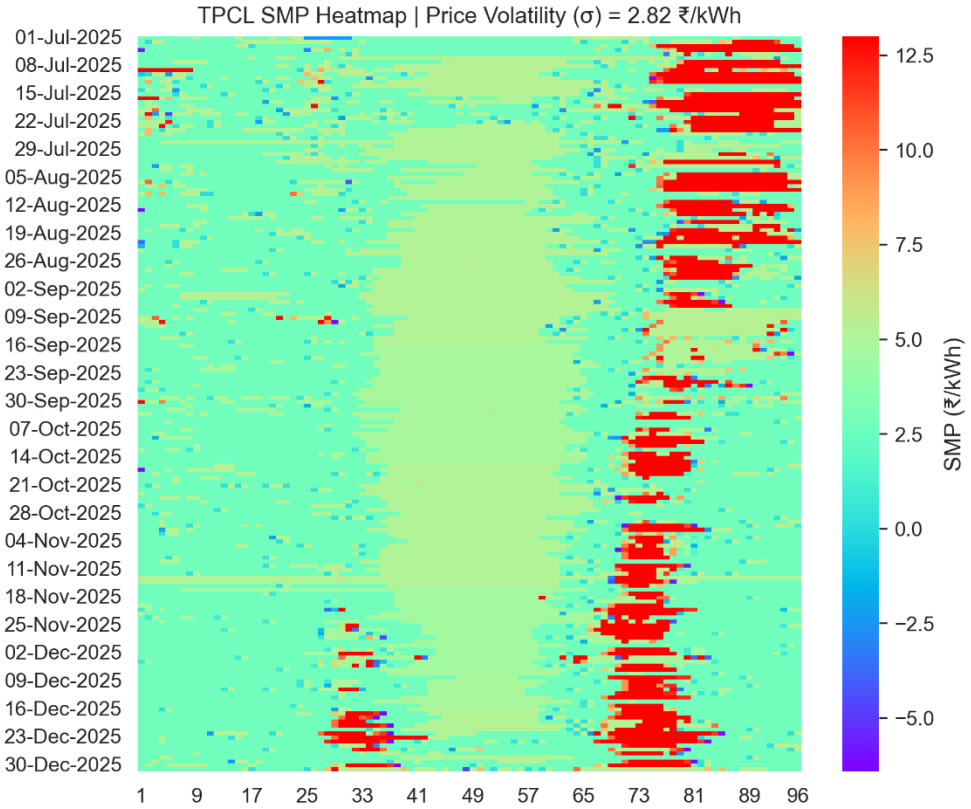


Figure 40 SMP of TPCL under De-Centralised SCED

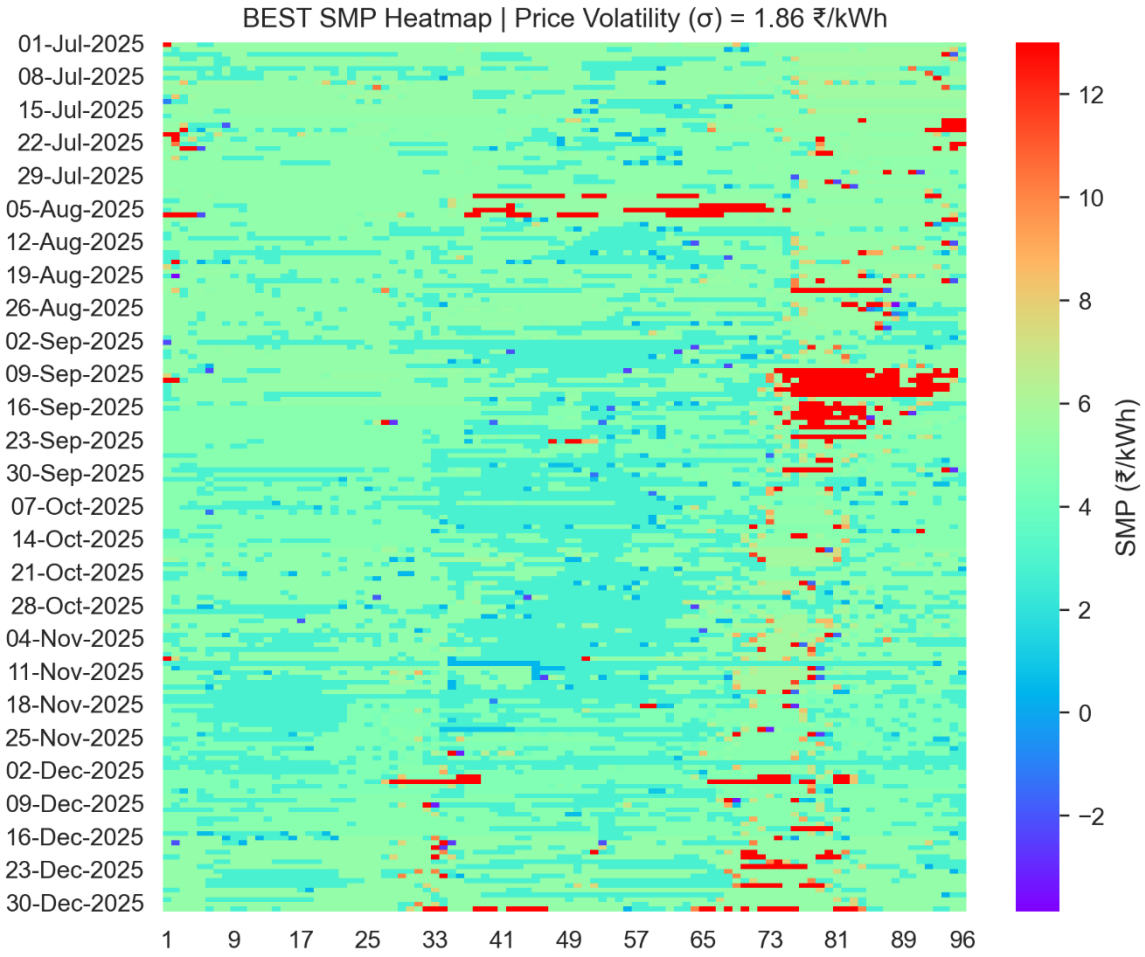


Figure 41 SMP of BEST under De-Centralised SCED

6.2. Decentralized and Centralized SMP

In comparison to the de-centralized SCED the average SMP during centralized SCED, as shown in range of ~04 ₹/kWh to 5.5 ₹/kWh, which is comparably lower than the other discom under de-centralized SCED.

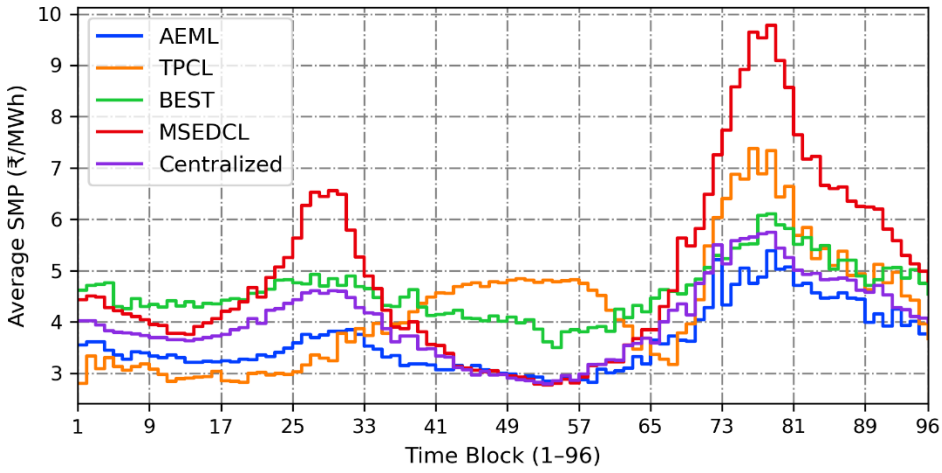


Figure 42 Block wise average SMP under De-Centralised and Centralised SCED

6.3. Energy Arbitrage Potential

The SMP through de-centralized SCED provides comparable measures to account for the market participation. In the percentage duration plot in Figure 43, it is shown that for ~10% to 25% of duration, the market prices are higher and provides the arbitrage potential.

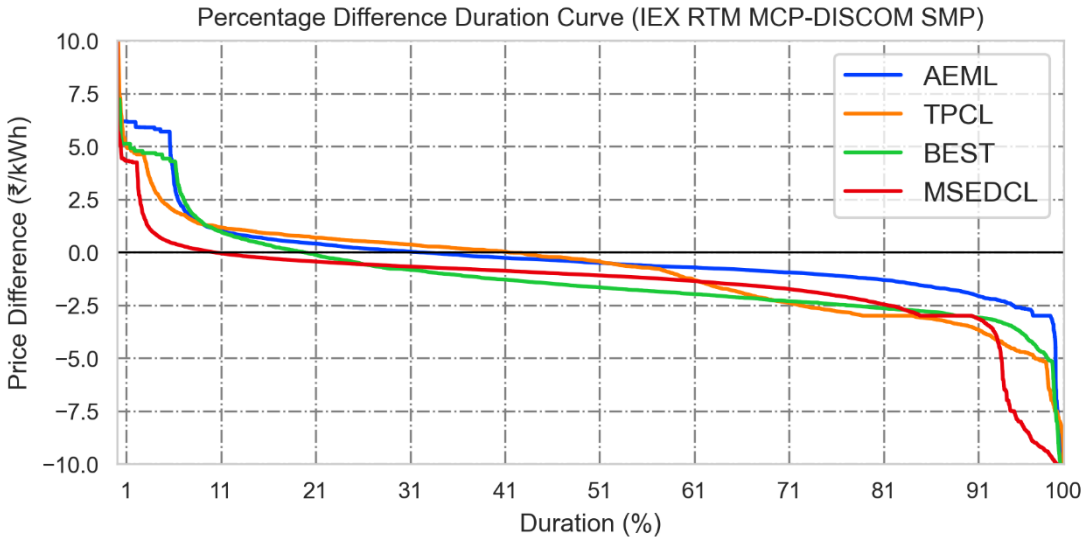


Figure 43 Price signalling for the energy arbitrage potential

6.4. Generator Marginal Costs and Despatch Signals

The average marginal value of capacity and ramping constraints is shown in the Figure 44. It is shown in the figure that during the daytime the average marginal price the technical minimum constraint is more, whereas the declared capacity constraint increased during the ramping period.

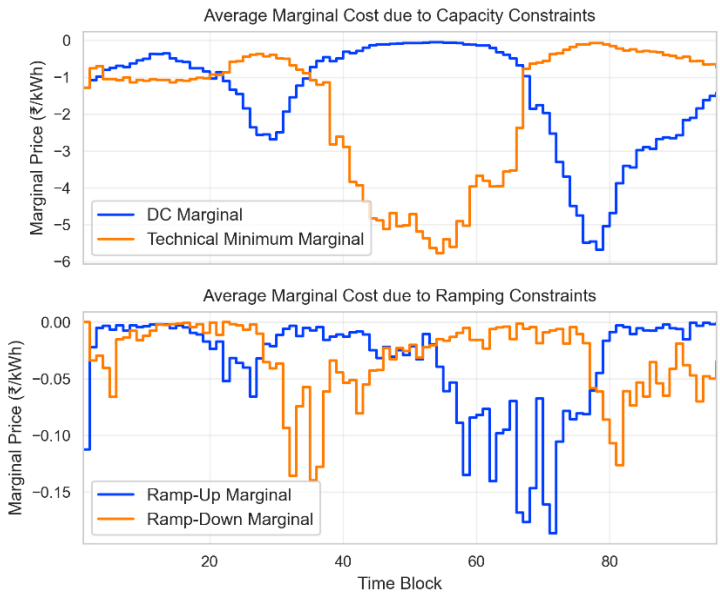


Figure 44 Block wise average shadow price of the binding constraints

Comparably, average shadow price of the ramp up/down constraint is also shown. During the morning ramping ramp-down marginals are binding and has its cost revealed through SCED.

The opposite trend is observed during the evening ramping period. The generator wise details of the binding constraints are shown in the Figure 45 to Figure 49.

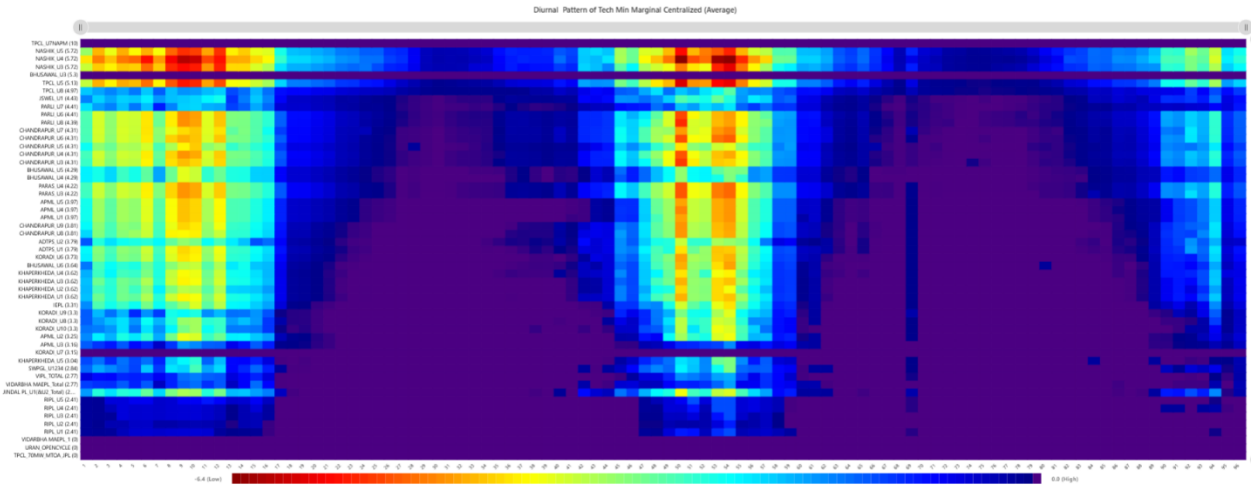


Figure 45 Shadow price of technical minimum constraints under Decentralized SCED

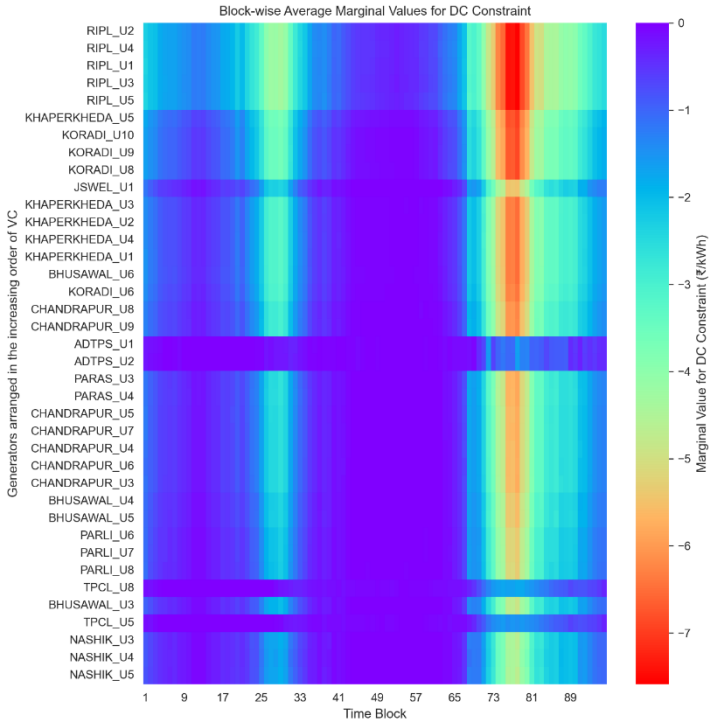


Figure 46 Shadow price of Declared Capacity constraints under Decentralized SCED

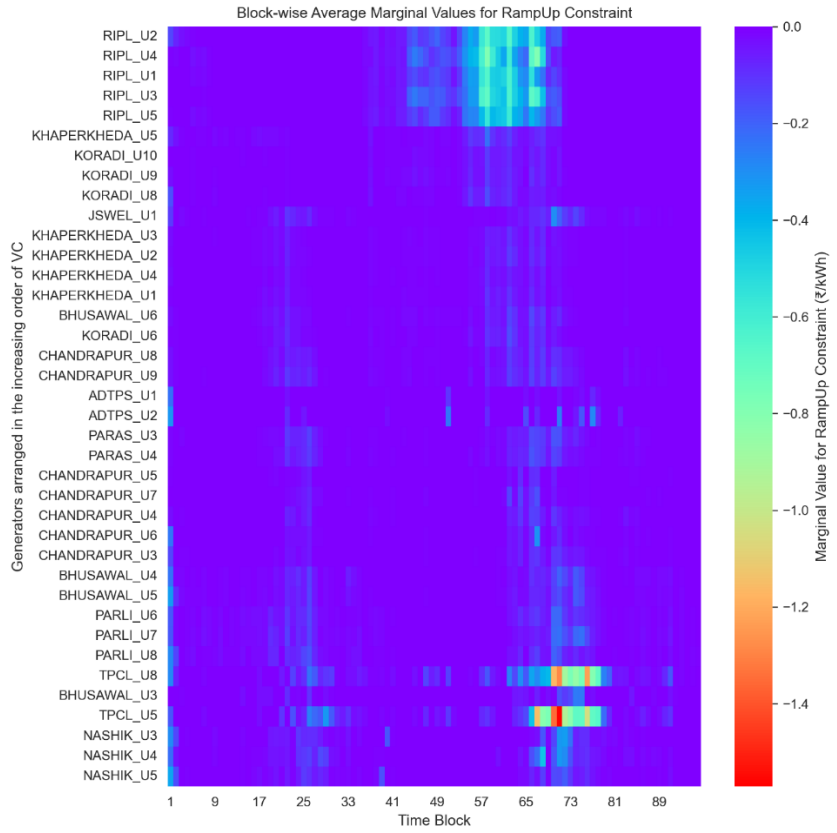


Figure 47 Shadow price of the ramp-up constraint under Decentralized SCED

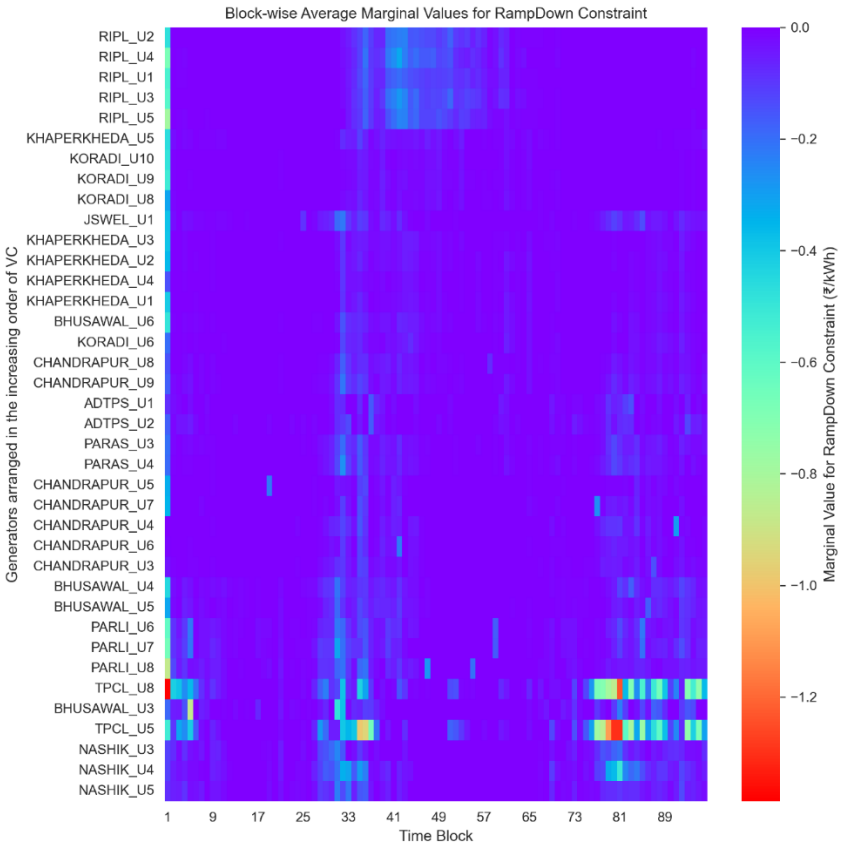


Figure 48 Shadow price of the ramp-down constraint under Decentralized SCED

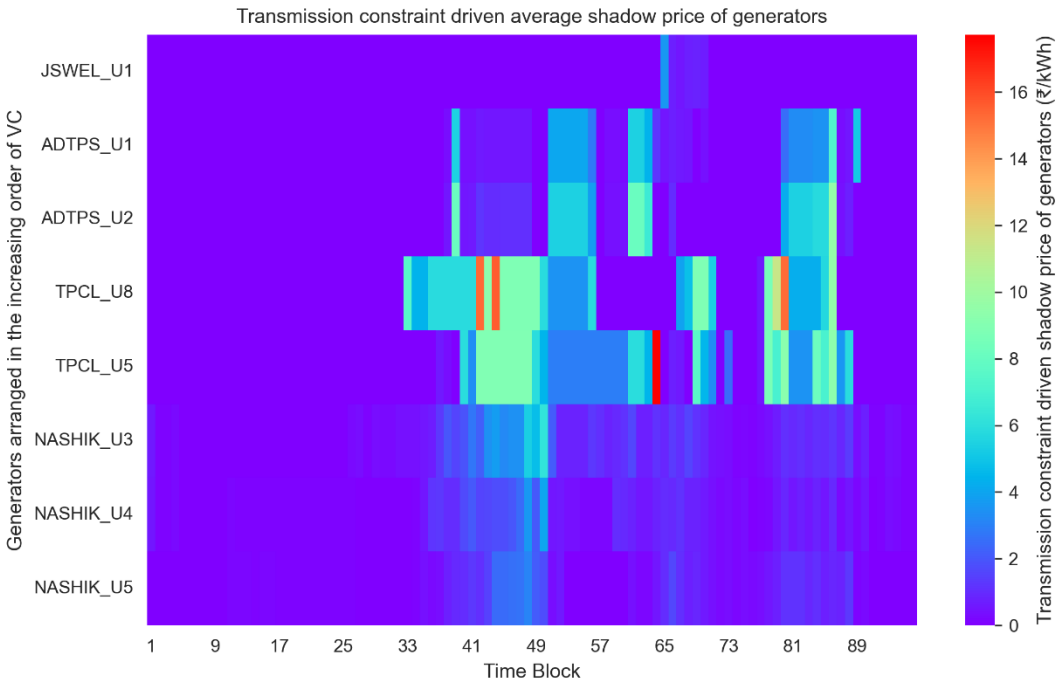


Figure 49 Transmission constraint driven shadow price of generators under Decentralized SCED

7. Operational Insights from the Online SCED Pilot

This chapter presents the key operational insights observed during the pilot implementation, which emerged as critical monitoring metrics for the system operator. These insights are systematically extracted from the SCED engine and reflect practical operational behaviour, decision signals, and system-level implications identified over the pilot period.

7.1. Price Formation with Demand Variability

While system marginal prices and constraint shadow prices have been discussed in the previous chapter, it is important to examine the price formation behaviour under varying demand conditions. Figure 50 presents the declared capacity stack for a representative time block, illustrating the intersection of net demand with the declared capacity curve. For an average net demand of approximately 7,455 MW, the discovered price is 4.35 ₹/kWh. Overall, the price varies within a range of 3.71 ₹/kWh to 5.06 ₹/kWh across the observed demand conditions.

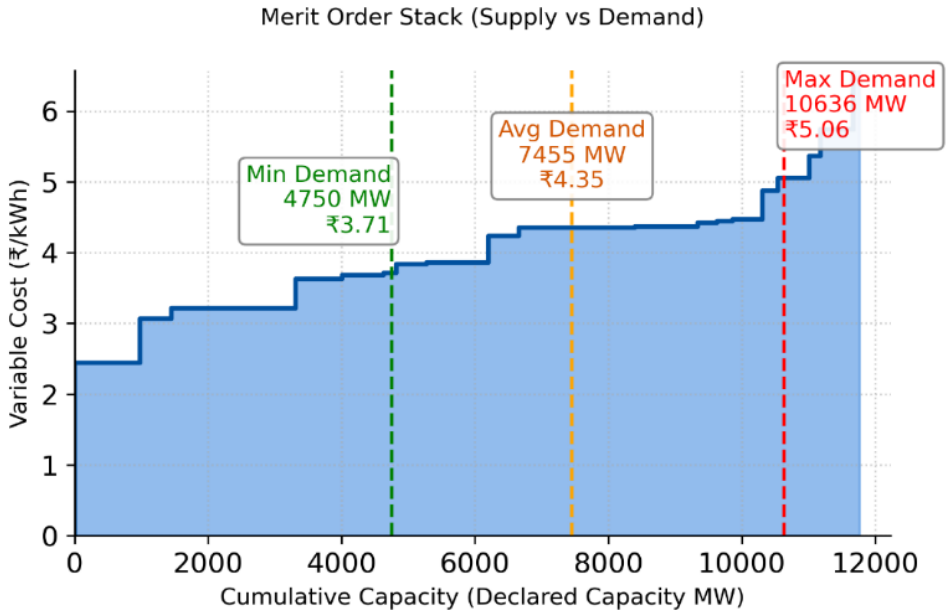


Figure 50 Merit order stack along with variation of the discoverable price with demand variation

7.2. Reserve Availability and Monitoring

In addition to insights on price variation with demand, information on operating reserves has been extracted and configured into a dashboard for daily reserve monitoring. Figure 51 illustrates the average availability of generators contributing to system reserves under decentralized MOD and SCED, arranged in ascending order of variable cost. It is observed that low-cost units offer limited reserve availability, as they are primarily despatched to meet demand on a priority basis. In contrast, higher-cost plants exhibit moderate reserve availability. Notably, mid-merit plants emerge as the most valuable contributors to system reserves, supplying the majority of reserve capacity.

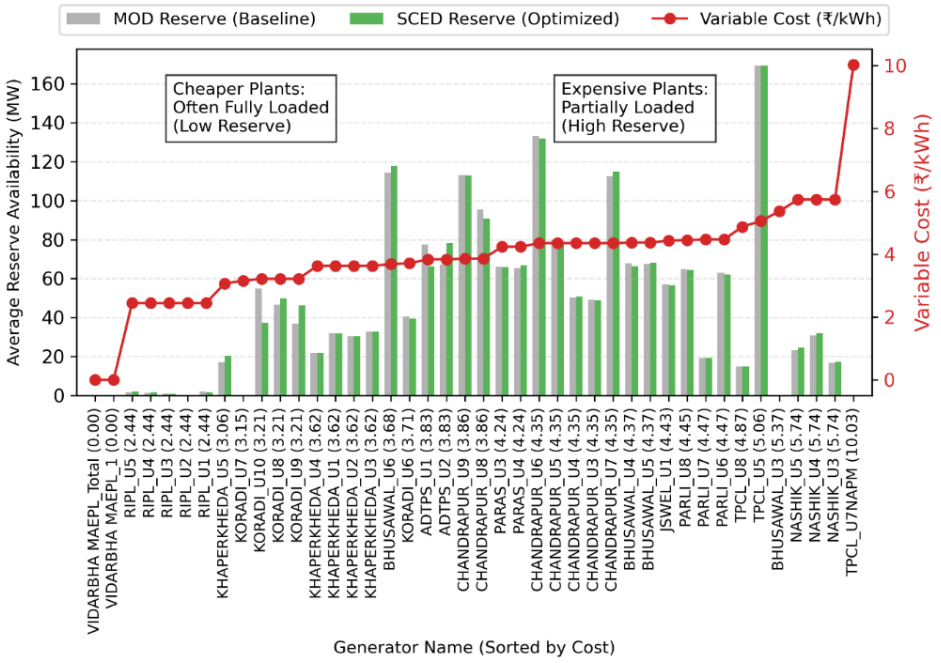


Figure 51 Average spinning reserve availability (generators are in the increasing order of VC)

7.2.1. Spinning Reserve (Up/Down)

The spinning up/down reserve availability on 12th December 2025 is highlighted in the Figure 52. During low-demand periods, the system has higher spinning reserve-up available, while spinning reserve-down availability is correspondingly lower. Throughout the study period, reserve-up and reserve-down clearly follow complementary trends, reflecting how system flexibility shifts with changing demand levels.

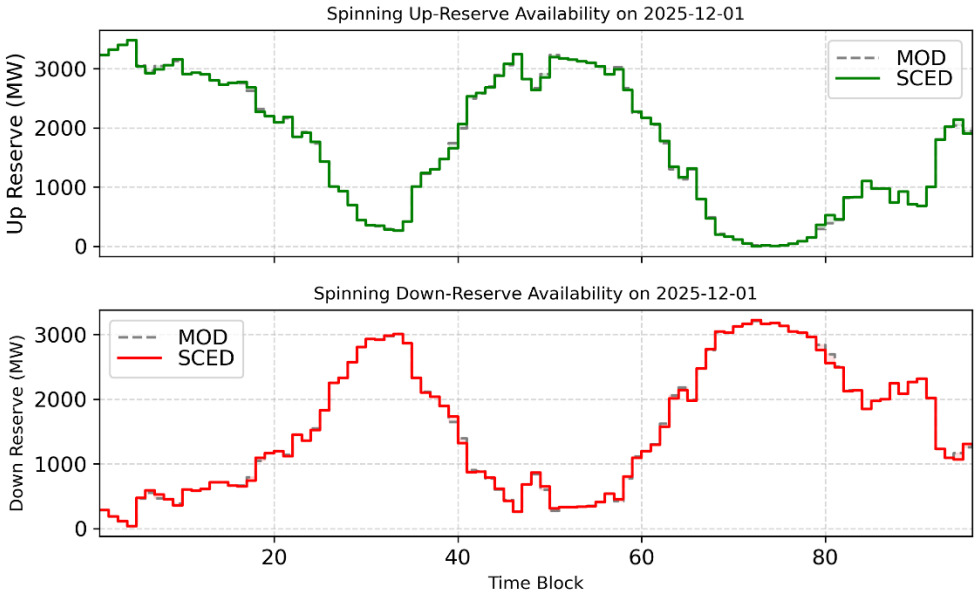


Figure 52 Spinning up/down reserve under MOD and SCED scheduling mechanism

7.2.2. Ramping Reserve (Up/Down)

Similar to the spinning up/down reserve, the ramping up/down reserve are also monitored and for the 12th December 2025 the available ramping up/down reserve is shown in Figure 53. During the morning ramp-up period, when most generators increase output to meet rising demand, ramping-up reserve availability becomes constrained, while ramping-down reserve shows a complementary pattern. During daytime hours, ramping-up reserve availability increases due to a higher contribution from renewable generation and other sources supplying the state demand, followed by a similar trend during the evening ramping period.

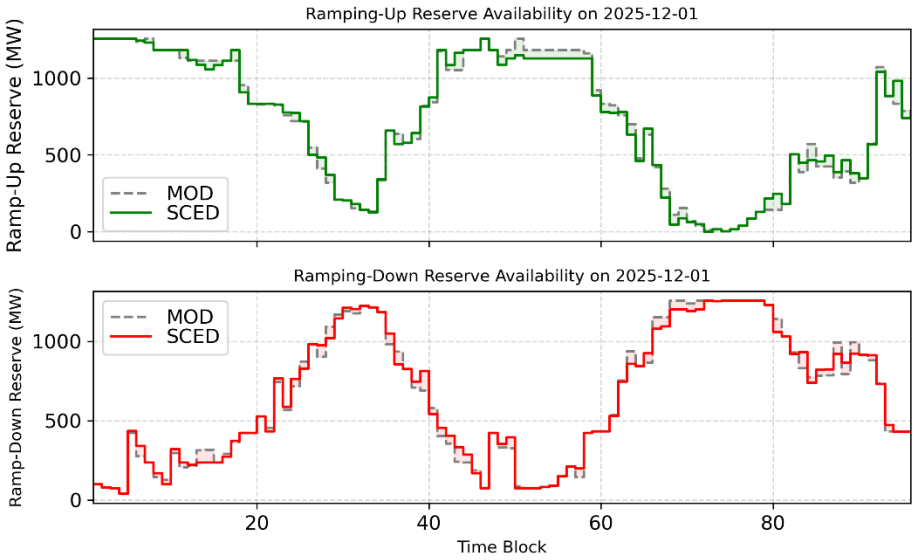


Figure 53 Ramping up/down reserve under MOD and SCED scheduling mechanism

7.2.3. Ramp Limited Reserve

As illustrated in Figure 54, the stranded capacity is explicitly highlighted, showing that during demand transitions, particularly the morning and evening ramps, a substantial portion of available reserves remain unutilized.

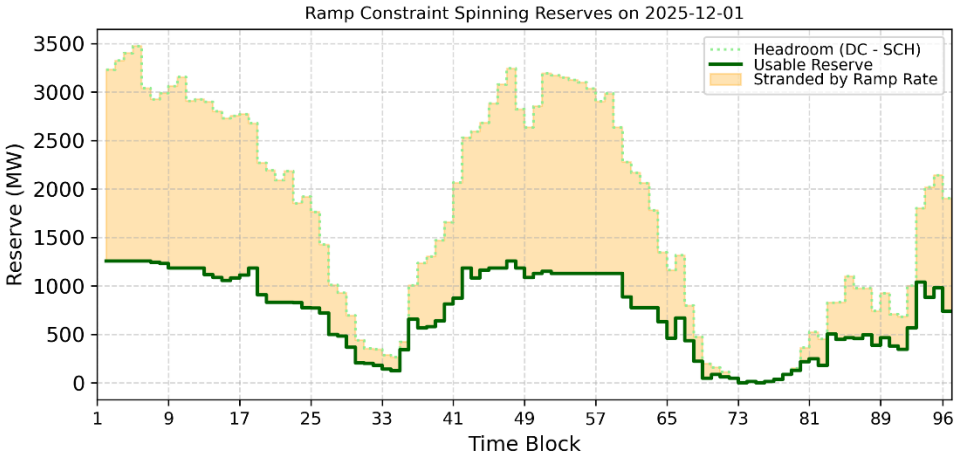


Figure 54 Stranded Spinning-Up reserve due to ramp limitation

7.2.4. Cold Reserve

The cold reserve availability is also monitored. The cold reserve from one of the units, CHANDRAPUR_U7, under reserve shut down is shown in Figure 55.

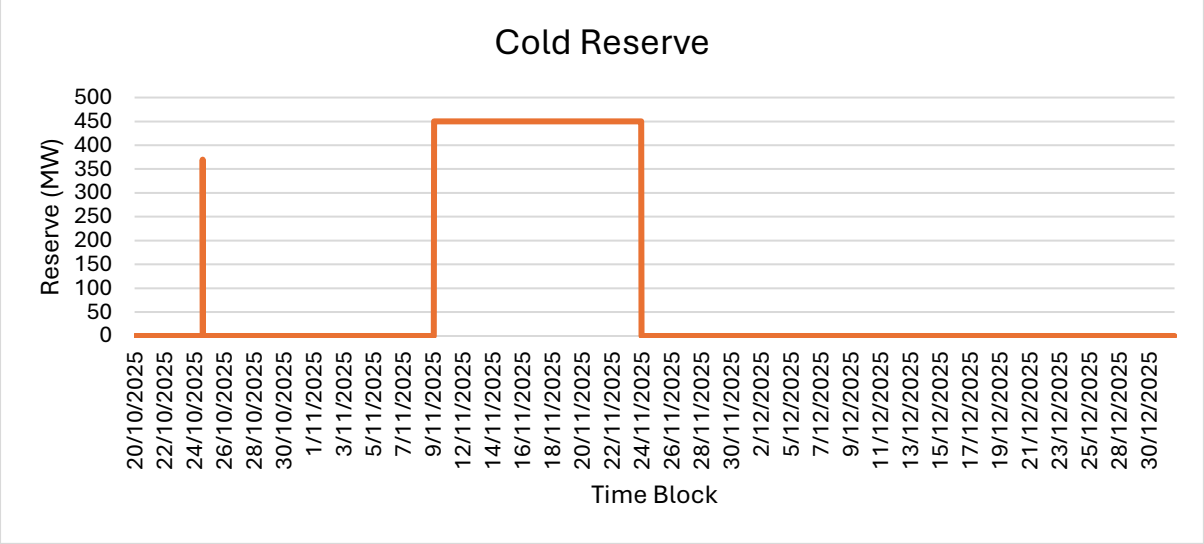


Figure 55 Cold reserve from the CHANDRAPUR_U7 unit, under reserve shut down

7.3. Generator Performance Assessment

Generator performance is assessed through the monitoring and analysis of the number of perturbations, mileage, and differences in scheduling between the MOD and SCED mechanisms.

7.3.1. Generator Schedule Comparisons

While SCED inherently adheres to generator constraints embedded within its framework, the developed SCED engine, under both centralized and decentralized implementations, explicitly care has been taken of these constraints while committing and de-committing units across successive time blocks. An illustrative unit schedule in Figure 56 and Figure 57 is presented to demonstrate this behavior CHANDRAPUR_U3 and NASHIK_U4 on 04 December and 06th December, respectively.

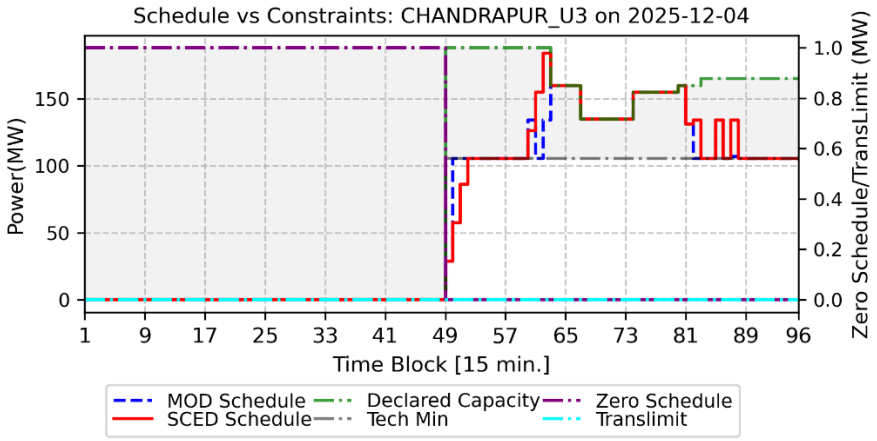


Figure 56 Comparison of schedule of CHANDRAPUR_U3 under MOD and SCED mechanism

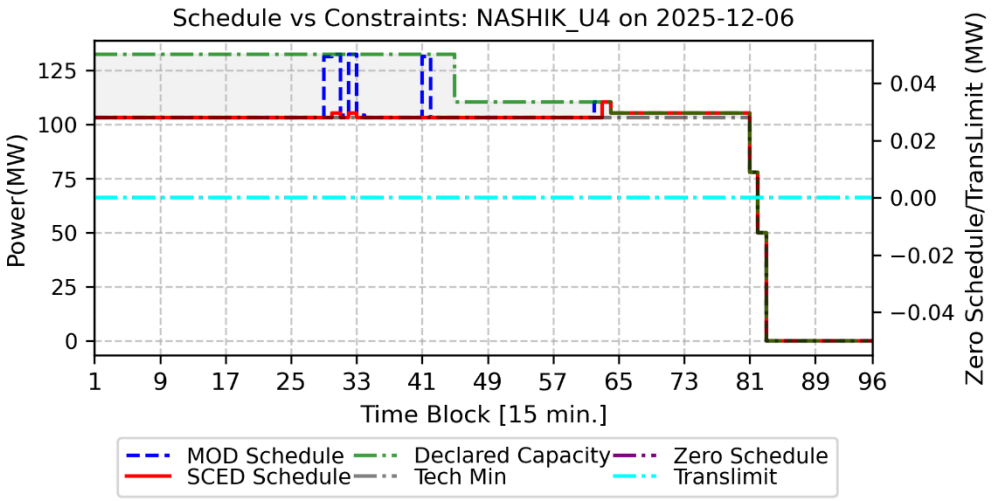


Figure 57 Comparison of the schedule of NASHIK_U4 under MOD and SCED mechanism

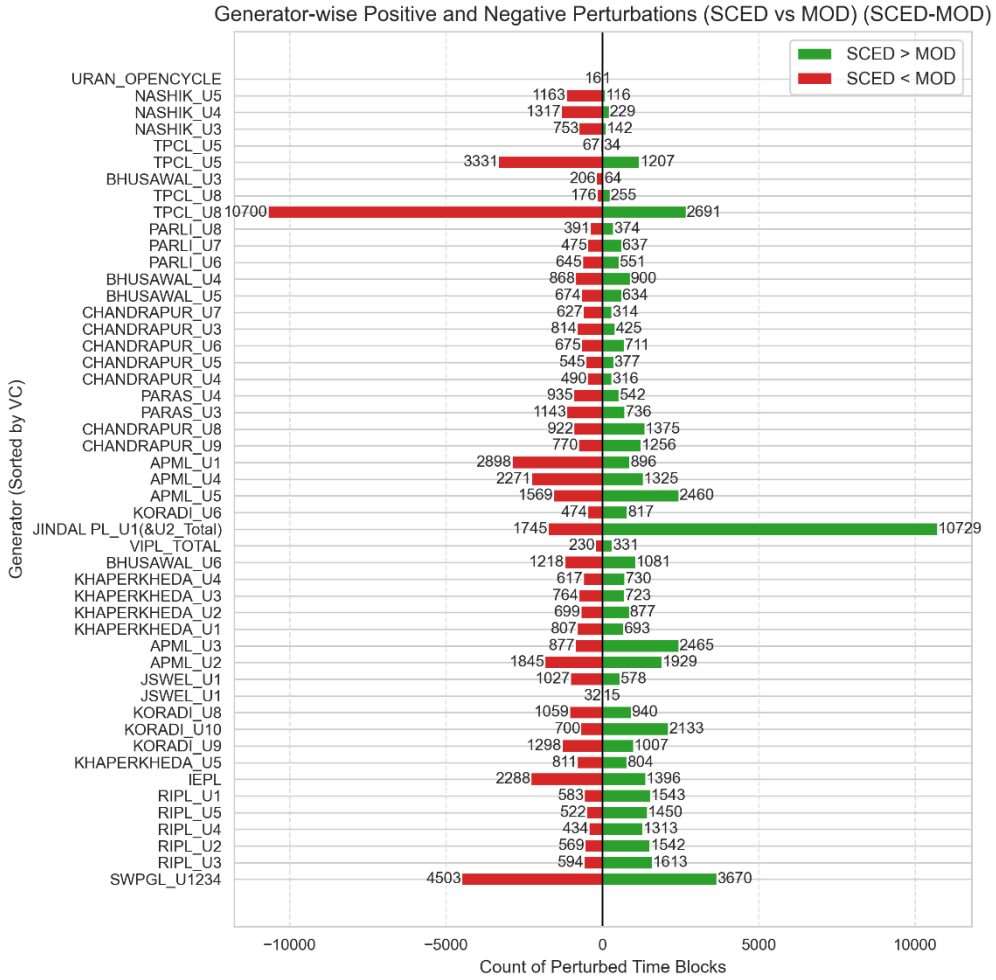


Figure 58 MOD and SCED perturbation difference (Generators are in increasing order of VC)

7.3.2. Ease of Operation

The generator-wise perturbation analysis in Figure 58 indicates that of all generators experience both positive and negative perturbations under SCED operation. On average, positive and negative perturbations are comparable in magnitude, at approximately 7%, with median values below 5%, suggesting that most adjustments are moderate. However, a small subset of generators exhibits significantly higher perturbations, with maximum deviations exceeding 60%, as reflected in the relatively high standard deviations. This indicates that while SCED broadly maintains stable dispatch, flexibility requirements are concentrated on a limited number of units.

7.3.3. Generator Utilization Factor

The generator utilization factor is also monitored and summarised in the Figure 59 and Figure 60. In both figures, lower-cost generators consistently exhibit higher utilisation levels, reflecting their priority in dispatch. In contrast, higher-cost generators operate with moderate utilisation, typically in the range of approximately 40–60%.

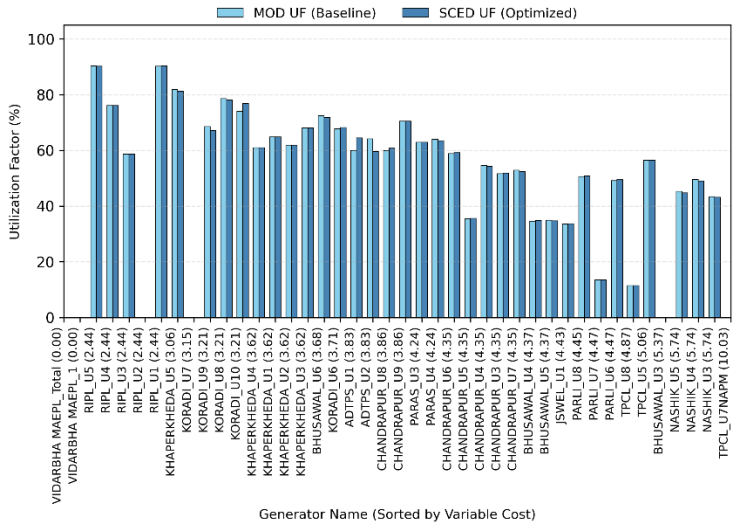


Figure 59 Generator utilization factor with respected to installed capacity

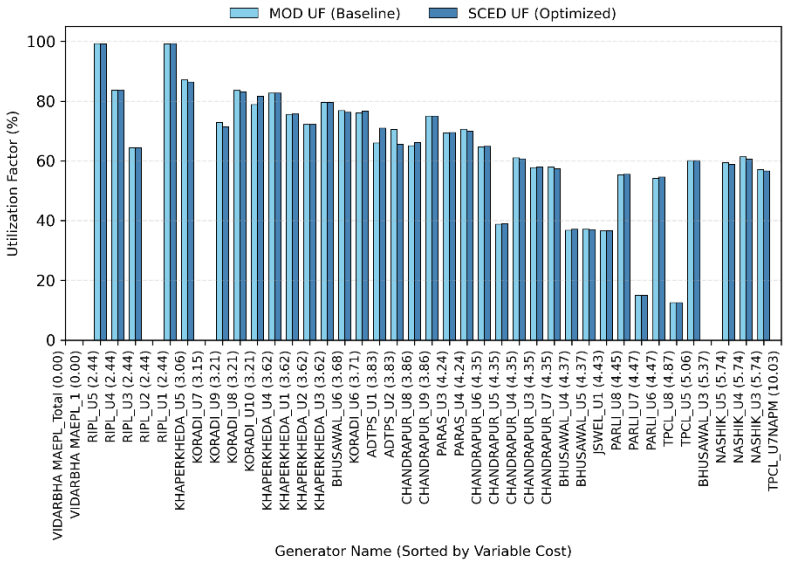


Figure 60 Generator utilization factor with respect to the Declared Capacity

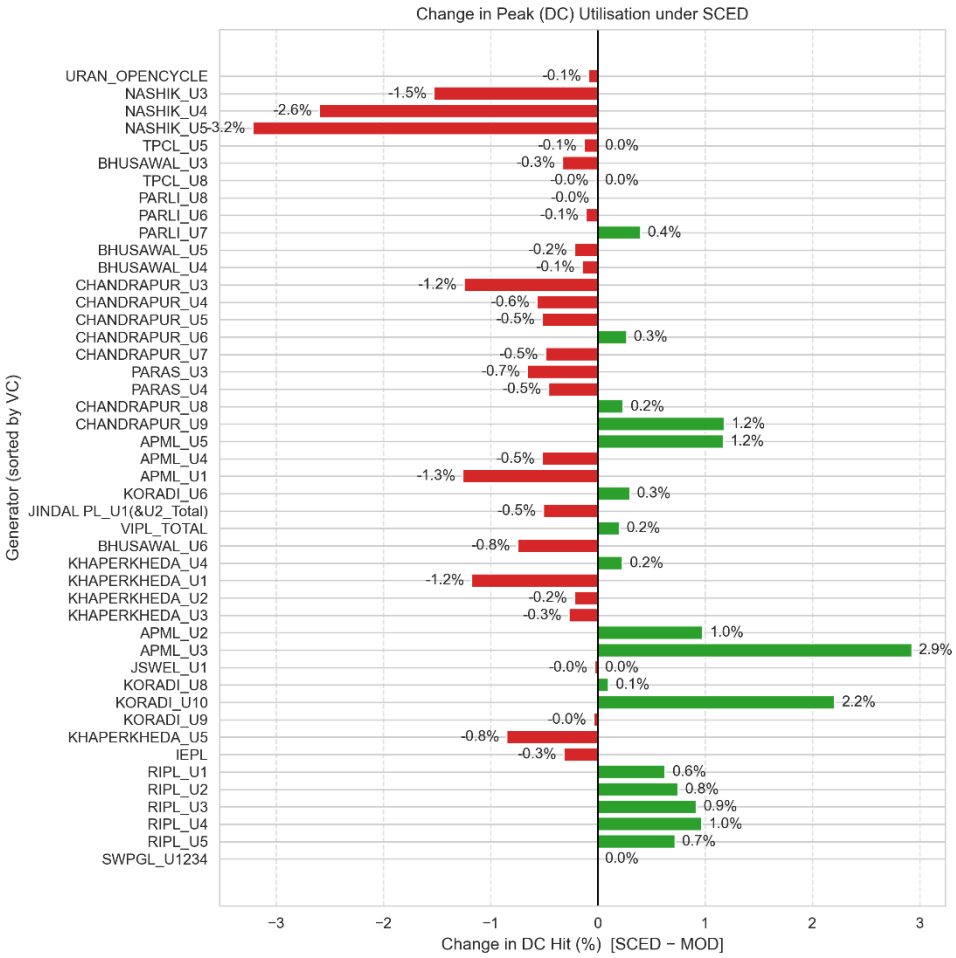


Figure 61 Percentage change in Declared Capacity utilization

7.3.4. Generator Ramping

The generator ramping has been compared between the decentralized and centralized SCED scheduling. As shown in the Figure 62, decentralized SCED consistently results in lower ramping requirements compared to MOD. Additionally, for approximately 20% of the study period, generator schedules remain unchanged under SCED, indicating periods of stable dispatch with no ramping adjustments required.

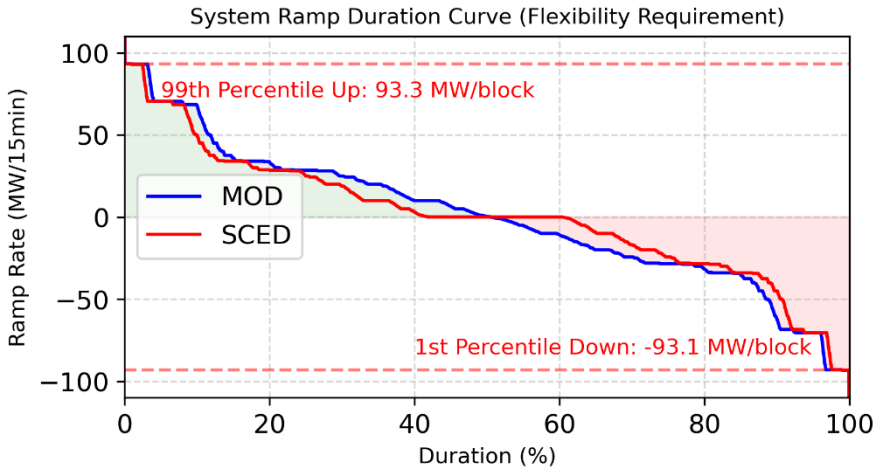


Figure 62 System flexibility requirements (determined based on the MOD schedule)

Along with the total ramping requirement, the generator wise mileage is determined and shown in the Figure 64 through Figure *65*.

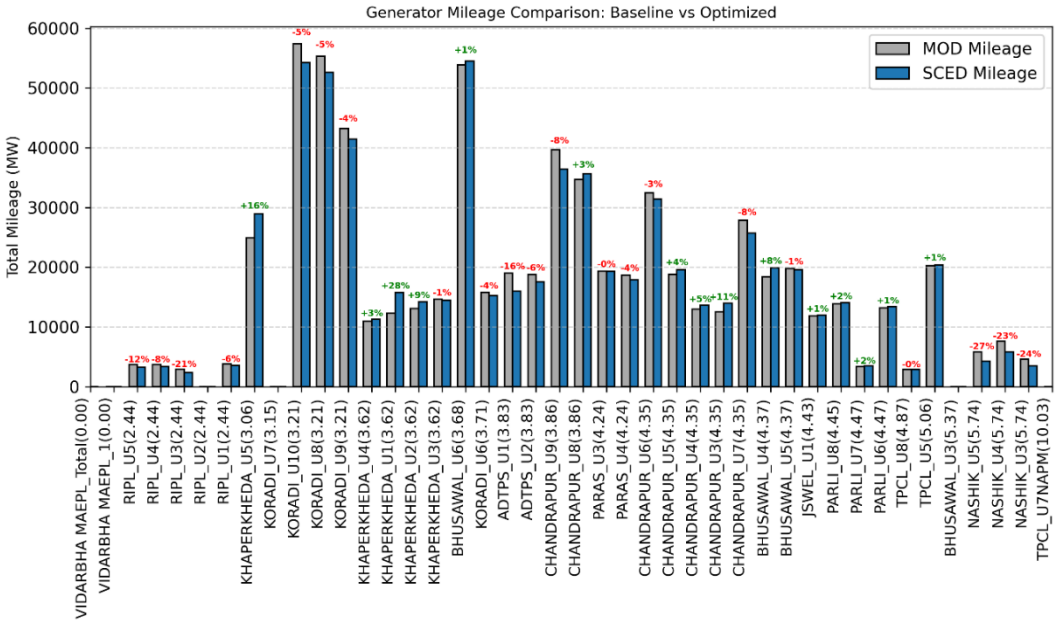


Figure 63 Generator mileage between MOD vs SCED (generators are in increasing order of VC)

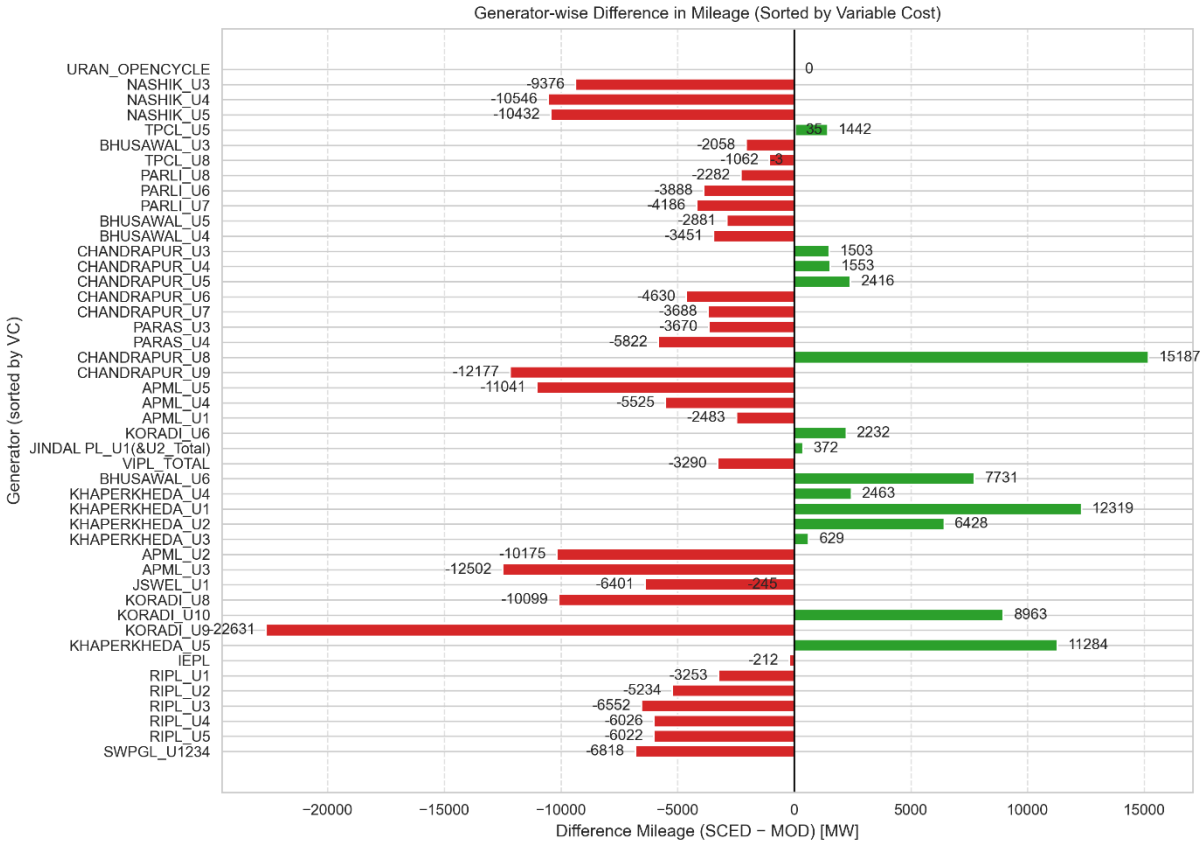


Figure 64 Generator wise difference in the mileage

The mileage analysis across generators indicates that the majority of units (approximately 69%) experience a reduction in mileage under SCED, while about 31% observe an increase. Overall, the average and median changes in mileage are negative (−4.27% and −3.91%, respectively), suggesting a net reduction in generator movement. The interquartile range spans from −7.34% to 1.16%, indicating that most generators experience limited changes. However, a small number of units show larger deviations, with the maximum mileage increase and reduction reaching 21.78% and −26.60%, respectively.

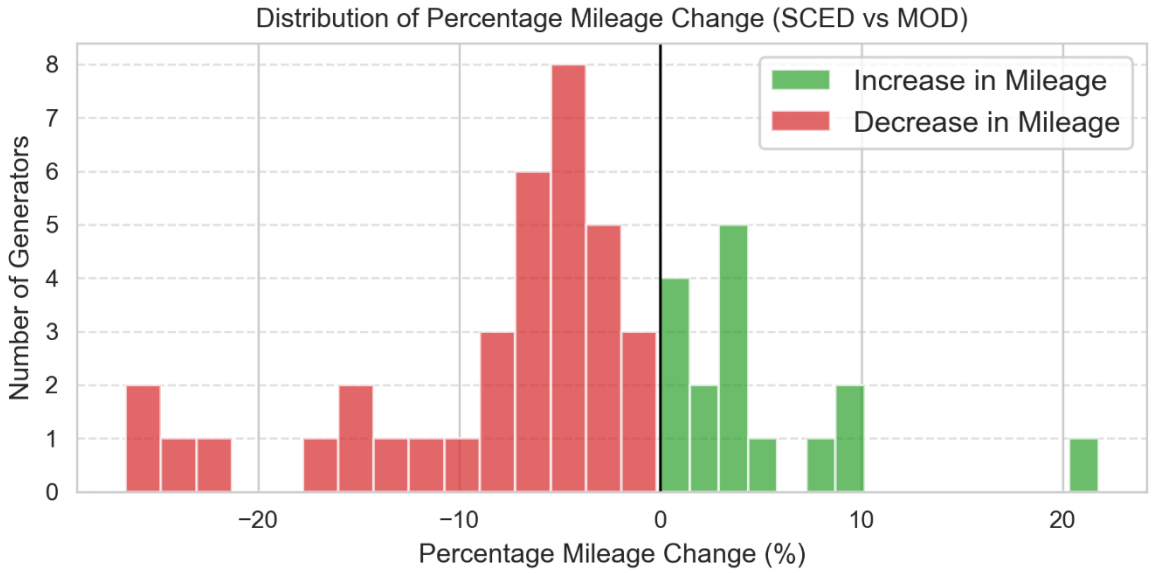


Figure 65 Distribution of the percentage mileage change

7.4. Infeasibility Analysis

The infeasibility in ramping limit under MOD is shown in the Figure 66 for JSWEL. As observed the ramping up limit is hit for the MOD for the block 59 while for the SCED the ramping limit is adhered for the same block.

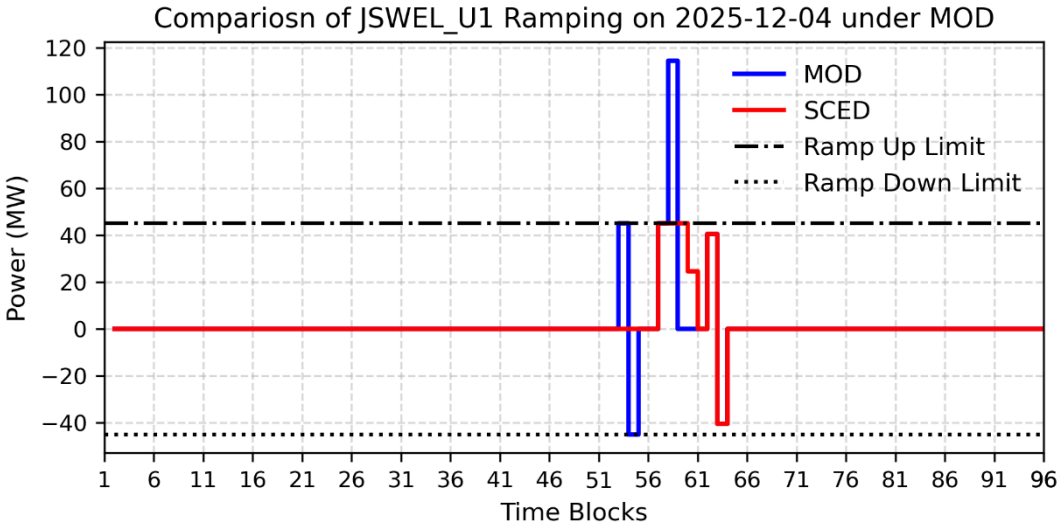


Figure 66 Infeasibility for JSWEL under MOD

7.5. Solution time of SCED Engine

The solver time for the SCED engine is shown in the Figure 67. The engine converges to the optimal solution within ten iterations and requires 0.02s as the total solve time. Further the post processing of the optimization outcomes require total requires ~49 s for execution. Figure 68 shows the solver log for the SCED engine for one month data.

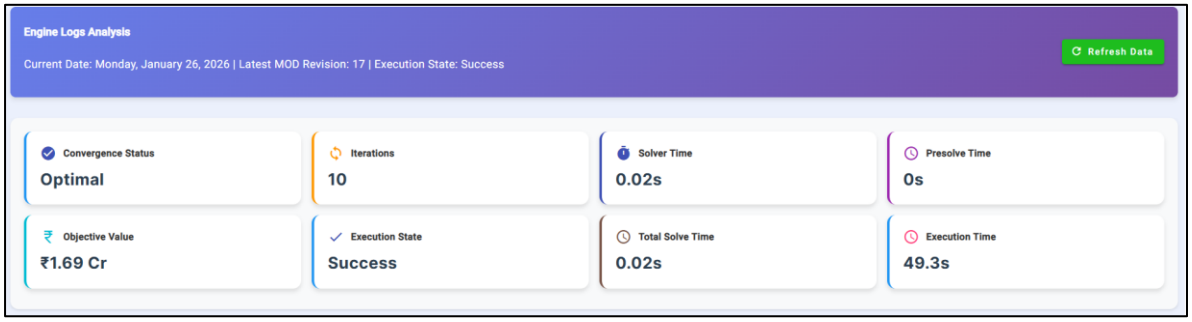


Figure 67 Solve log of online SCED engine

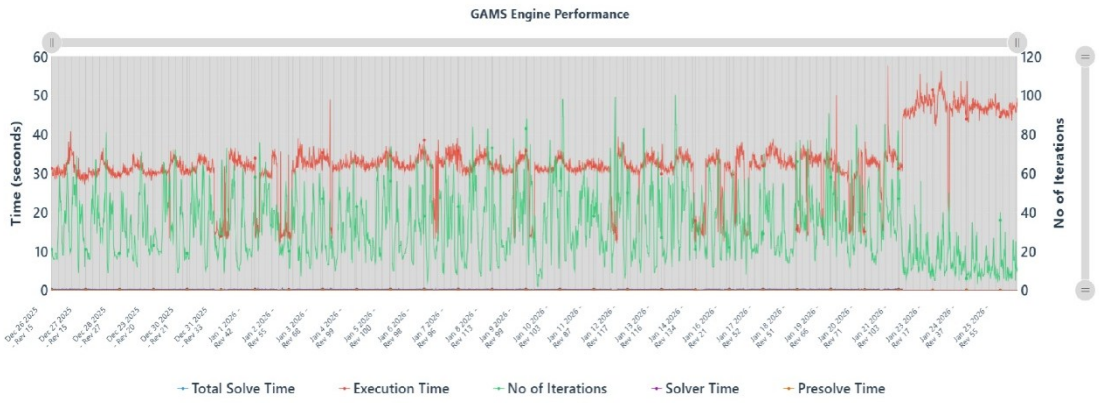


Figure 68 SCED engine solver log of one month data

8. Cost-Benefit and Operational Impact Analysis

This chapter presents a detailed cost-benefit and operational impact assessment of the intra-state SCED pilot, based on a structured comparison of existing MOD-based scheduling and optimization-driven SCED frameworks. The analysis is designed to quantify the economic gains and operational improvements attributable to optimization, and to assess the incremental value of transitioning from decentralized to centralized despatch. To enable a structured assessment, multiple comparative cases have been analyzed. These cases are designed to progressively highlight the impact of optimization, ramp coordination, and system-wide centralization on despatch outcomes and system costs. The following cases have been considered for cost-benefit and operational impact assessment.

Table 3 Summary of Scenarios for Cost Benefit Analysis

Cases	Remarks
MOD-Based Scheduling	Scheduling based on the existing decentralized MOD framework, serving as the baseline for comparison.
Decentralized SCED	Optimization-based scheduling implemented in a decentralized manner, aligned with DISCOM-wise scheduling practices, to assess the benefits of optimization without altering institutional structure.
Centralized SCED	State-level optimization using a centralized SCED framework, designed to evaluate the incremental economic and operational benefits of system-wide coordination over decentralized optimization.

All cases have been evaluated on a like-to-like basis using identical input datasets, including demand forecasts, declared capacities, variable costs, and technical constraints. The analysis focuses on variable generation costs and operational feasibility, with settlement implications kept outside the scope of this assessment. The SCED runs have been executed in parallel to existing scheduling processes, ensuring that the results represent indicative efficiency gains rather than changes to actual despatch. The results presented in this chapter have been generated using the final version of the SCED model developed under the pilot, which continues to undergo incremental refinement as part of the ongoing development process. These refinements are not expected to alter the directional insights or comparative conclusions drawn from the analysis.

Comparison of MOD-Based and SCED-Based Scheduling

In this section a consolidated summary of the cost impact of transitioning from the existing decentralised MOD framework to decentralised and centralized SCED is covered.

8.1.1. Comparison of Decentralized SCED and MOD Cost

As depicted in detailed in *Table 4*, decentralised SCED delivers total savings of ₹6.07 crore relative to the MOD baseline. The consistent monthly savings underscores the structural efficiency gains introduced by optimisation-based scheduling. A large majority of time blocks exhibit positive savings, indicating that optimisation-based scheduling consistently improves economic efficiency. Specifically, over 68% of time blocks show positive savings in both comparisons, while the remaining show blocks incurs the additional cost for system security.

Table 4 Comparison of saving potential

	Total Saving (Crore ₹)	Average Saving (₹/TB)	Max Saving (Lakh ₹)	Min Savings (Lakh ₹)	Positive Savings Instance (%)	Blocks incurring security cost (%)
Decentralized SCED vs Decentralized MOD	~6.07	~3433	~1.43	~0.55	~68.10	~31.90

8.1.2. Comparison of the Centralized and De-centralized SCED

In comparing decentralised SCED with centralised SCED, a direct comparison of absolute system cost is not sufficient, as aggregation at the state level alters the net served energy due to consolidation of DISCOM schedules and State OD/UD components. Under the centralised framework, the optimisation may marginally serve additional or reduced energy compared to the decentralised case, purely as an artefact of aggregation rather than economic efficiency. To ensure a fair and like-to-like comparison, the analysis therefore normalises costs on a per-unit basis. Accordingly, the average cost of supply (₹/kWh), computed as the ratio of total system cost to total energy served, is used as the primary comparison metric. The centralised SCED cost is then imputed to the decentralised energy quantum, thereby eliminating distortions arising from minor differences in despatched energy.

Table 5 Cost comparison of the Centralized and De-Centralized SCED for 6 months

Metric for 6 months	Decentralized	Centralized	Savings
Total Energy (TWh)	42.678	42.667	0
Total Cost (₹ Cr)	15,903.82	15,865.14	~38.68
Avg Rate (₹/kWh)	3.727	3.718	~0.009

As summarised in Figure 69 and Table 5, while the decentralised SCED serves a total energy of 42.667 TWh at an aggregate cost of ₹15,903.83 crore, the centralised SCED achieves a lower total cost. After adjusting the centralised cost to the decentralised energy level, the effective system cost reduces to ₹15,865.16 crore, translating into a net saving of ₹38.68 crore over the pilot period. On a per-unit basis, this corresponds to a reduction in the average procurement cost from ₹3.727/kWh under decentralised SCED to ₹3.718/kWh under centralised SCED.

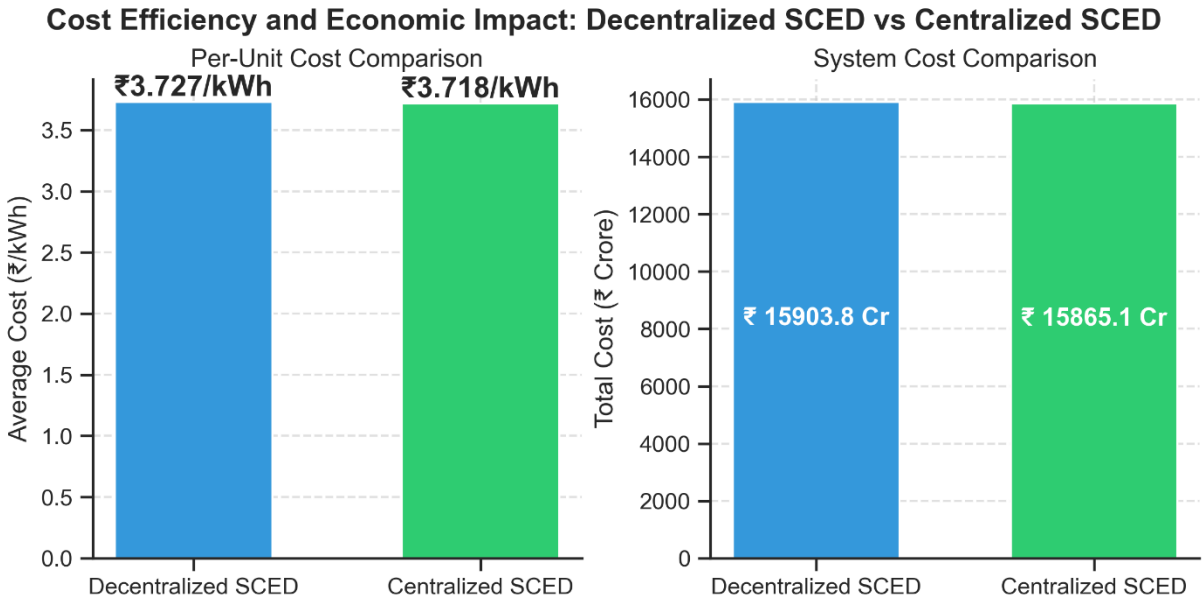


Figure 69 Per-unit cost efficiency and savings in Centralized SCED over De-centralized SCED

Table 6 Cost comparison of the Centralized SCED and De-Centralized MOD for 6 months

Metric for 6 months	*Decentralized*	*Centralized*	*Savings*
Total Energy (TWh)	42.678	42.667	0
Total Cost (₹ Cr)	15,909.88	15,865.14	~44.74
Avg Rate (₹/kWh)	3.729	3.718	~0.010

Similarly, as summarised in Table 6 and Figure 70, centralised SCED results in net saving of ₹44.74 crore compared to the Decentralised MOD for the pilot period.

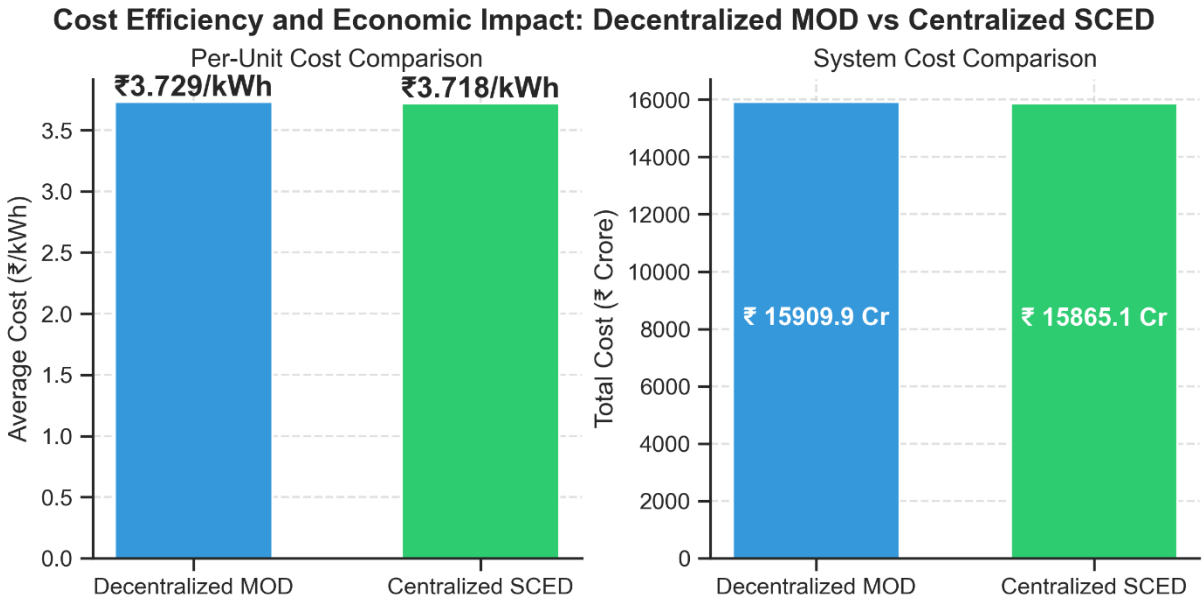


Figure 70 Per-unit cost efficiency and saving in Centralized SCED over De-centralized MOD

This reduction, though modest in per-unit terms, is systemically significant when viewed at scale. It reflects the efficiency gains achieved through centralized SCED, where generation despatch decisions are coordinated across DISCOM boundaries, enabling better utilisation of low-cost resources and more efficient management of flexibility.

8.2. System Cost Savings and Efficiency Gains

In addition to the aggregated savings and this section examines the temporal distribution of cost savings achieved under decentralized SCED relative to the existing MOD-based despatch. The analysis focuses on block-wise and intra-day patterns, highlighting operational conditions under which optimization delivers the maximum benefit. The block-wise variation in total cost difference between MOD and decentralised SCED is shown in Figure 71. The daily savings exhibit a wide dynamic range, ranging up to ₹6.5 lakh per day, depending on system conditions. Across the pilot period from July to December 2025, the average saving consistently exceeds ₹2,000 per time block in every month, indicating that the observed benefits are not sporadic but structurally embedded in SCED mechanism.

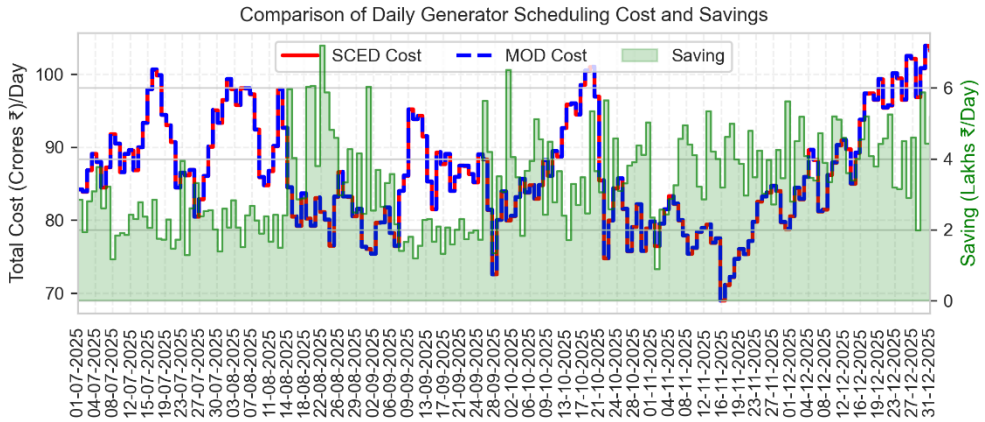


Figure 71 Comparison of MOD and SCED scheduling cost

To visualise the temporal concentration of these savings, Figure 72 illustrates a heatmap with month on the y-axis and time blocks on the x-axis. The intensity of each cell represents the magnitude of cost savings achieved under SCED for that specific block. It demonstrates that savings are concentrated during morning and evening ramping periods, when rapid changes in net load and generator ramping requirements impose binding operational constraints. During these periods, the coordinated optimisation under SCED enables more efficient utilisation of available generation flexibility compared to rule-based MOD scheduling.

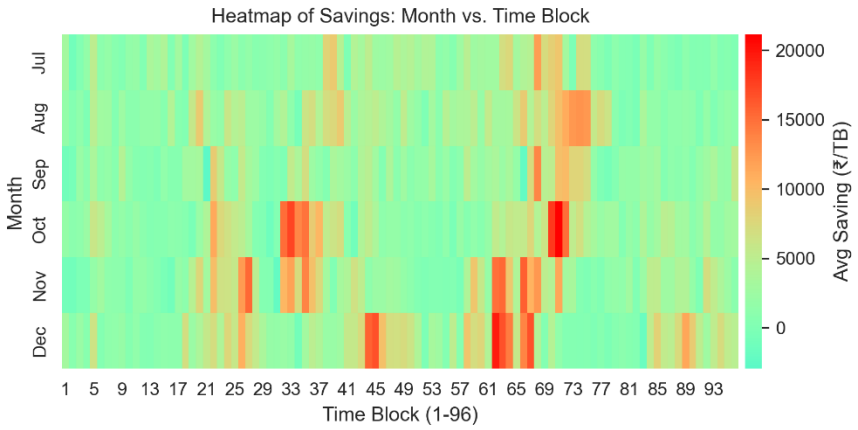


Figure 72 Saving potential across the time block in Decentralised SCED over MOD

The time-block heatmap analysis further demonstrates that savings are concentrated during morning and evening ramping periods, when rapid changes in net load and generator ramping requirements impose binding operational constraints. During these periods, the coordinated optimisation under SCED enables more efficient utilisation of available generation flexibility compared to rule-based MOD scheduling.

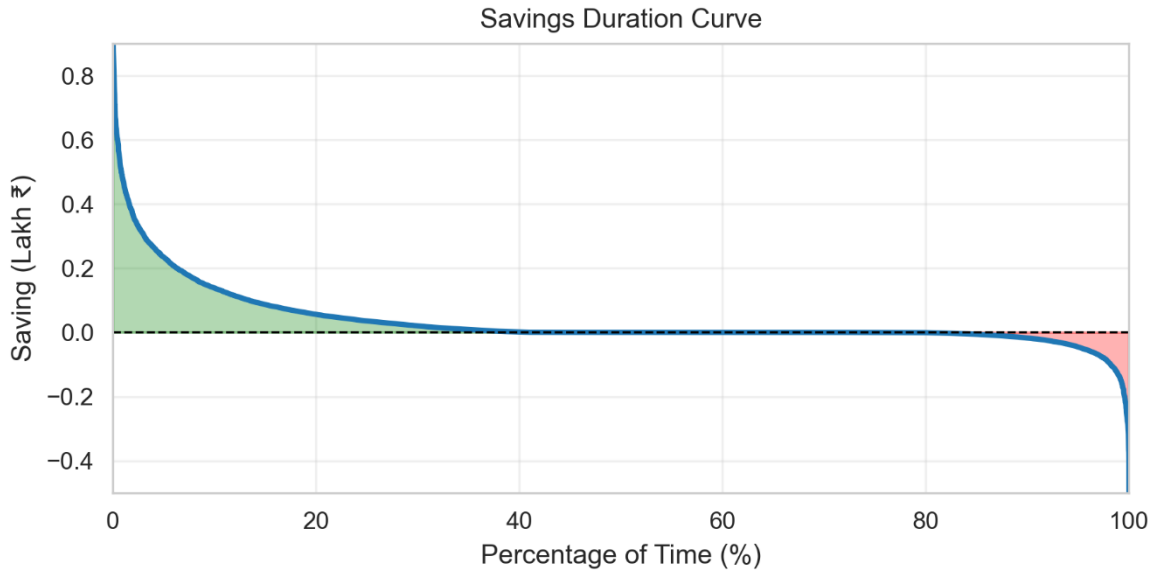


Figure 73 Saving duration curve over the pilot period

Additionally, it is also shown in savings duration curve, Figure 73, that positive cost savings were realised in approximately 30% of the operating time blocks. For nearly 50% of the time blocks, the cost outcomes under MOD and SCED were broadly comparable, reflecting periods where existing schedules were already close to the system-wide economic optimum. In the remaining instances, approximately 10% of time blocks exhibited marginally higher costs under SCED, primarily attributable to the enforcement of security constraints, ramping limits, and other operational constraint. These instances highlight that SCED appropriately prioritises system security and load-generation balance over short-term cost minimisation.

8.3. Impact on DISCOM Power Procurement Costs

Since the SCED optimization operates on the physical generation stack while respecting contractual mappings, the distribution of savings across DISCOMs reflects their respective

generator allocations and exposure to marginal cost optimization,. MSEDCL, which holds the predominant share of intra-state generation resources and bears the largest system demand responsibility, captures the majority of the economic gains from SCED implementation. As reflected in the analysis, MSEDCL accounts for an average saving of ₹3,283 per time block over the six months of pilot period (July-December 2026). This outcome is consistent with its extensive generator mapping and higher participation in marginal despatch adjustments. Positive savings are observed in nearly 51% of the operating blocks, with remaining attributed to the system security, underscores sustained economic benefits despite occasional additional cost for honoring system security .

Other DISCOMs also realise measurable benefits aligned with their resource portfolios. AEML records average savings of ~102₹/block, with positive savings observed in about 31% of blocks. BEST and TPCL demonstrate higher proportions of positive saving blocks, approximately 66% and 70% respectively. Across all DISCOMs, the presence of both positive and additional cost of system security highlights the fact that SCED outcomes are driven by system-wide optimisation and security considerations, rather than uniform gains in every time block.

Table 7 Comparison of savings across the DISCOMs

DISCOM	Avg Saving (₹/Block)	Positive Blocks (%)	Blocks Incurring Security Cost (%)
AEML	102.09	30.72	31.02
BEST	36.38	66.03	33.67
MSEDCL	3283.04	50.89	35.76
TPCL	25.88	70.21	27.3

8.3.1. SCED benefit to MSEDCL

The daily savings profile shows consistently positive outcomes across the pilot period, with savings ranging from upto ~₹6 Lakhs on high-impact days. The average daily savings remain consistently positive throughout the pilot period. Notably, no instances of negative daily savings are observed for MSEDCL.

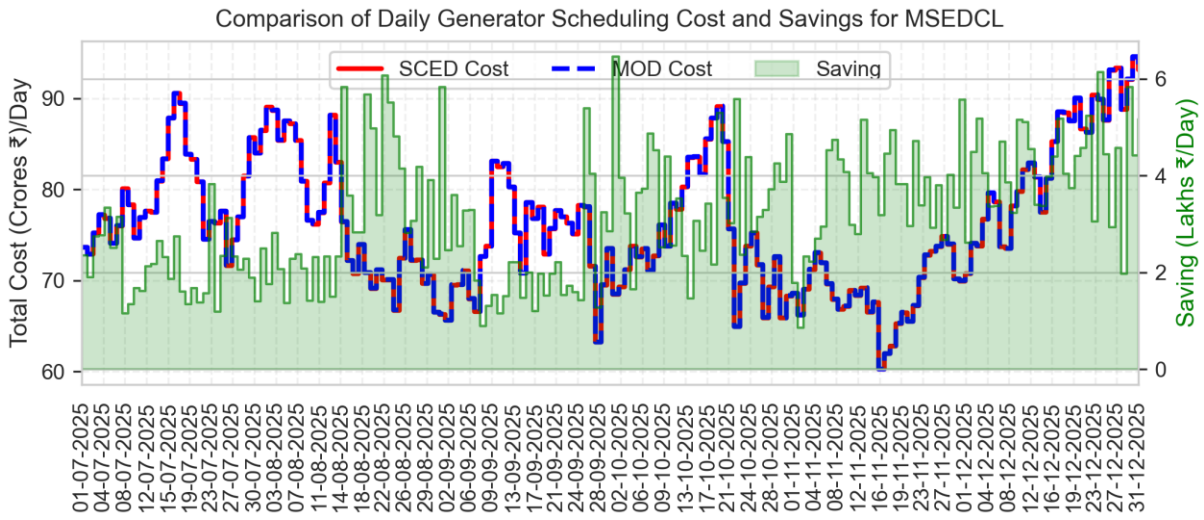


Figure 74 Daily cost and saving potential through SCED for MSEDCL

8.3.2. SCED benefit to AEML

The daily savings, as shown in Figure 75 remain positive, indicating recurring efficiency gains under SCED without adverse cost impacts. On high impact days, the savings accounts up to ~₹1 Lakh.

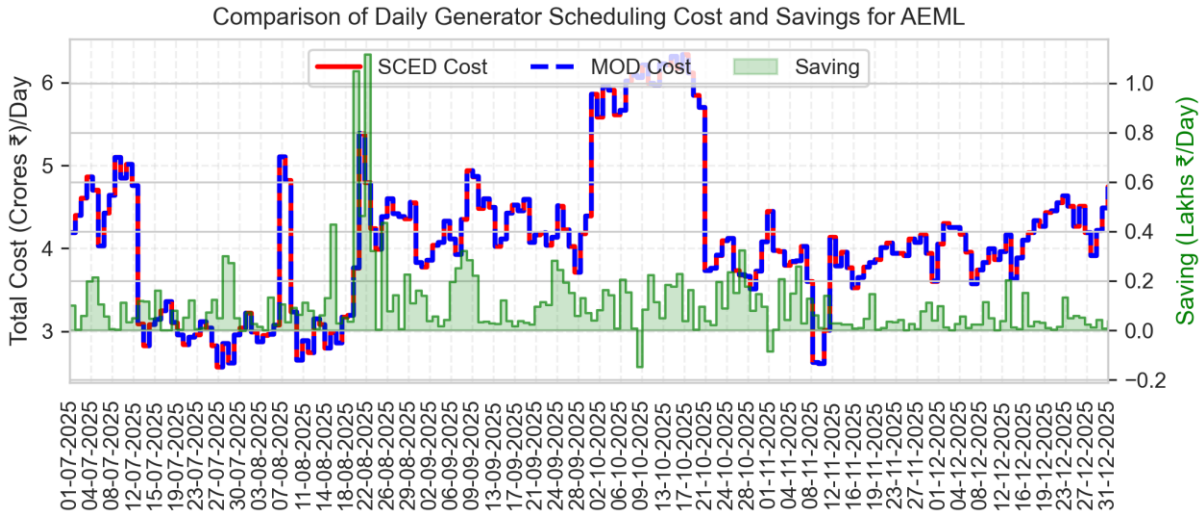


Figure 75 Daily cost and saving potential through SCED for AEML

8.3.3. SCED benefit to TPCL

The day-wise saving for TPCL is shown in Figure 76, indicate savings within the ranges of up to approximately ~₹40 thousand with daily average savings positive throughout the pilot period.

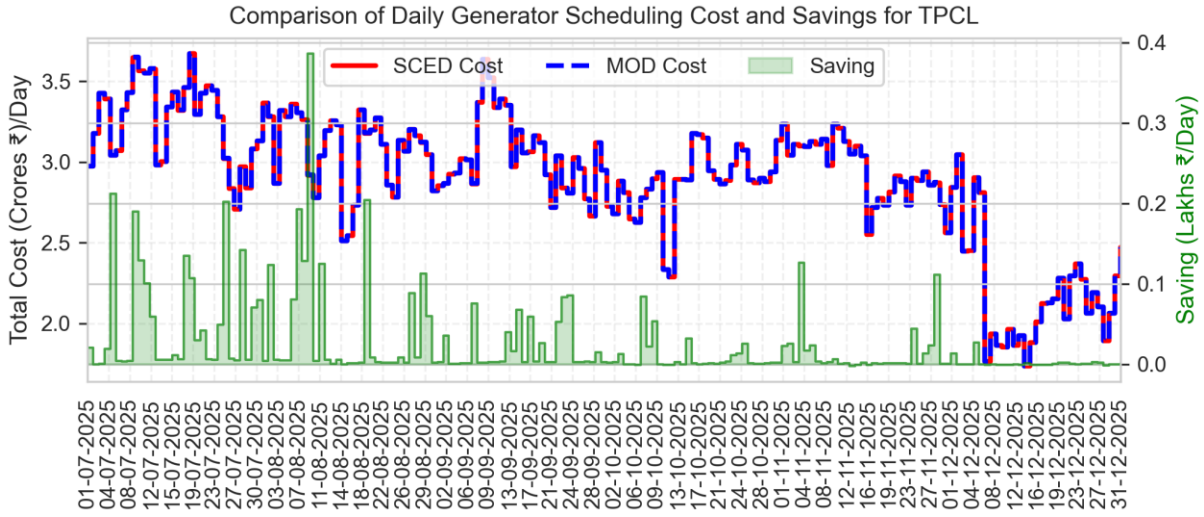


Figure 76 Daily cost and saving potential through SCED for TPCL

8.3.4. SCED benefit to BEST

The day-wise saving for BEST is shown in Figure 77, indicating savings within the ranges of up to approximately ~₹60 thousand with daily average savings for licensees remain positive across the assessment period.

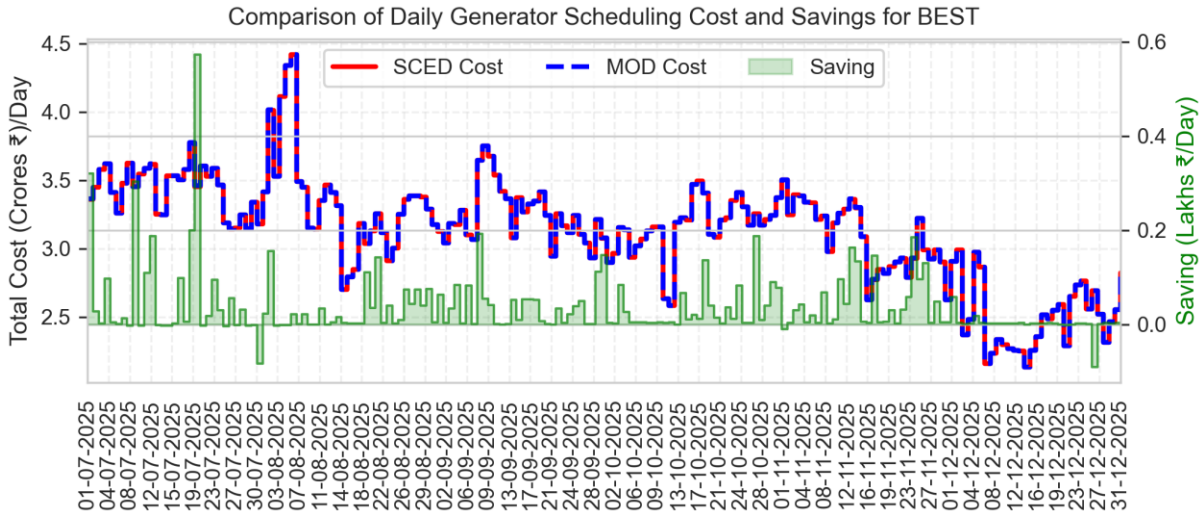


Figure 77 Daily cost and saving potential through SCED for BEST

8.3.5. Energy Arbitrage Potential

The difference duration curves presented in Figure 78 compare the per-unit energy cost under RTM outcomes against the corresponding per-unit energy cost under the SCED framework. Per-unit energy cost has been chosen as the comparison metric to ensure a consistent and neutral assessment across DISCOMs, independent of differences in absolute energy volumes, contract sizes, or aggregation effects. Across all DISCOMs, the per-unit energy cost duration curves indicate that SCED delivers measurable energy-arbitrage benefits relative to RTM outcomes over a substantial portion of operating time blocks. Positive per-unit cost differences are observed for roughly 15-35% of the time blocks, reflecting periods where SCED enables procurement at a lower marginal cost.

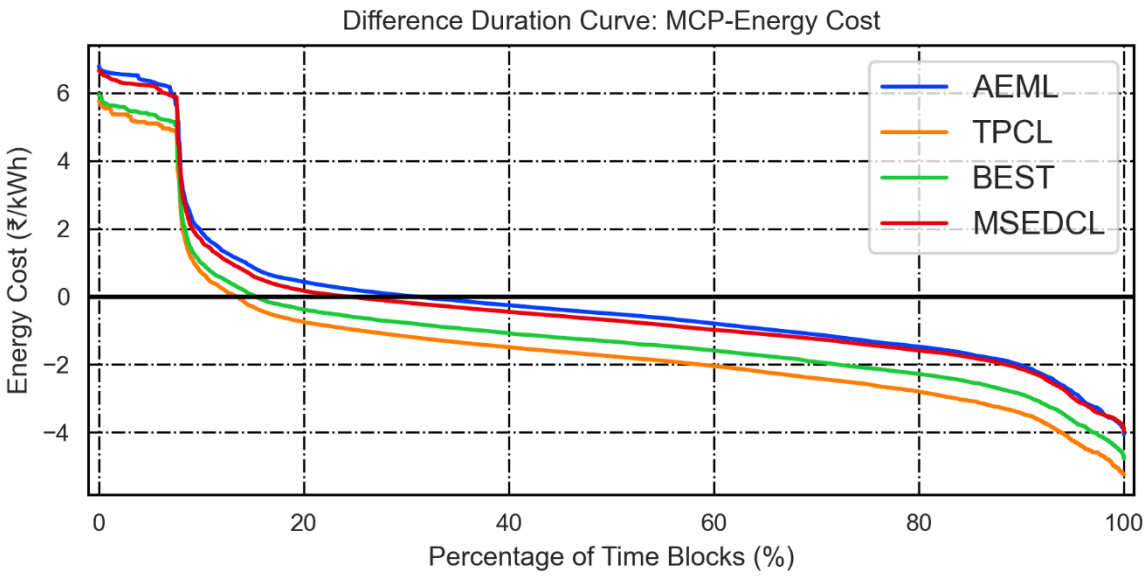


Figure 78 RTM and per unit energy cost difference duration curve

8.4. Impact on Generator Economic Efficiency

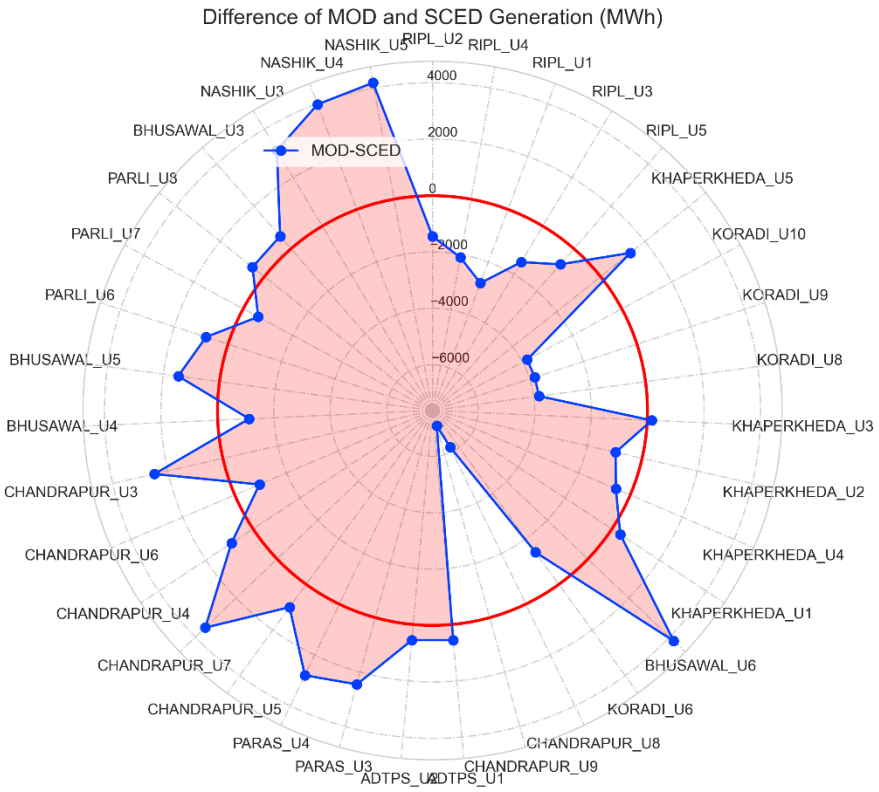


Figure 79 Generator wise energy difference between MOD and SCED

The spider plot in Figure 79 illustrates the generator-wise difference in energy despatch between MOD and SCED, showing only the generators without open access subcontracts. Each radial axis represents a generating unit, arranged in ascending order of variable cost, enabling. Positive values indicate higher utilization under MOD relative to SCED, while negative values indicate increased despatch under SCED. The plot clearly demonstrates that

SCED systematically reduces energy allocation to higher-variable-cost generators while increasing utilization of relatively lower-cost units. The positive value for the expensive generators indicates that in SCED, they are backed down when cheaper alternatives are available and operationally feasible. Certain lower-cost units, such as *KHAPERKHEDA_U5* and *BHUSAWAL_U6*, are observed to be scheduled at higher levels under MOD than under SCED, particularly during ramping periods. Other units in the mid-merit range show mixed behaviour, reflecting the interaction between variable cost, ramping capability, and constraints.

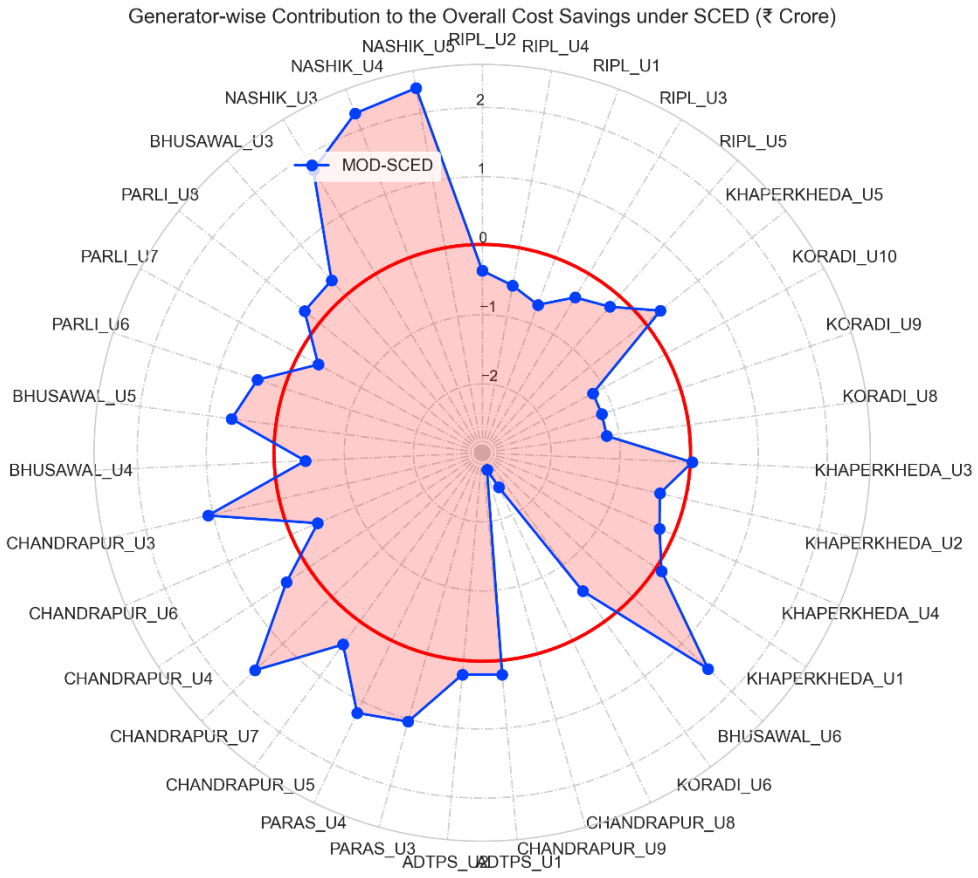


Figure 80 Generator-wise Contribution to the overall Cost Savings under SCED

The generator-wise cost savings plot in Figure 80 complements the energy reallocation observed in the previous Figure 79. Each radial axis represents a generating unit arranged in ascending order of variable cost, while the plotted values indicate the difference in generation cost under SCED relative to MOD. The cheaper plants experience higher and more sustained utilisation under SCED, translating directly into positive cost savings at the generator level. In contrast, higher variable cost units exhibit reduced generation and corresponding cost savings. Notably, the CHANDRAPUR units are predominantly utilised for ramping and flexibility support under SCED.

8.5. Implications for Consumers

The duration curve in Figure 81 represents the per unit energy cost deviations between the SCED and MOD, highlighting the net-positive economic benefit for the end-consumer. The unit energy cost difference curve presents a consumer-relevant view of the economic impact of SCED relative to the existing MOD framework. Positive values for 25-30% time indicate

periods where SCED delivers lower unit energy cost than MOD, while negative values for ~20% time reflect instances where SCED results in a marginally higher unit cost. A substantial portion of operating time blocks experience either cost reduction or cost neutrality under SCED.

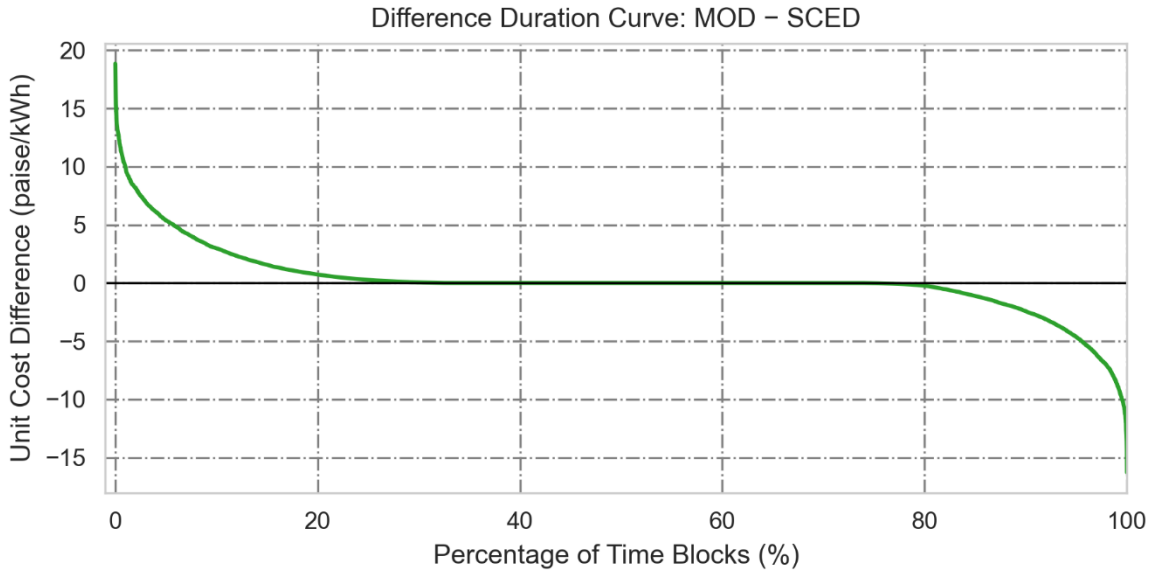


Figure 81 MOD and SCED unit cost differences

The DISCOM wise summary is give in the Table 8. For MSEDCL, which represents the largest share of the state's consumer base, SCED results in positive cost outcomes in 45.0% of the time blocks, with a further 13.8% of blocks remaining cost neutral. The average unit cost reduction of 0.16 paise/kWh indicates sustained, though moderate, efficiency gains over the pilot horizon. The 90th percentile gain of 2.98 paise/kWh reflects recurring savings during favourable system conditions. The worst-case increase of 16.27 paise/kWh occurs in a limited number of blocks and is attributable to security-driven constraints rather than inefficiencies, while best-case reductions reach 18.84 paise/kWh.

Table 8 DISCOM-wise distribution of the unit energy cost impact under SCED

	TPCL	BEST	AEML	MSEDCL
Average Reduction (paise/kWh)	0.12	0.16	0.27	0.16

For AEML, a relatively higher share of blocks (42.8%) shows near-zero difference between MOD and SCED, indicating tariff neutrality across a large portion of operations. Positive savings are observed in 27.9% of blocks, with an average reduction of 0.27 paise/kWh, the highest among the DISCOMs. Although the worst-case increase reaches 43.13 paise/kWh, such instances are infrequent and offset by best-case reductions of 33.96 paise/kWh, suggesting that SCED improves procurement efficiency without introducing persistent adverse impacts.

The outcome is also favourable for TPCL and BEST. TPCL experiences positive savings in 71.8% of time blocks, with very few zero-difference periods, reflecting consistent benefits from optimization; the average reduction of 0.12 paise/kWh and a best-case reduction of 63.7 paise/kWh highlight significant gains during specific system conditions, while the worst-case increase is limited to 2.49 paise/kWh, indicating minimal and infrequent adverse impact. In the case of BEST, positive savings occur in 58.2% of time blocks, with an average reduction of

0.16 paise/kWh; although higher costs are observed in 41.5% of blocks, the best-case reduction of 48.16 paise/kWh demonstrates meaningful savings potential, and the worst-case increase of 35.78 paise/kWh remains limited and largely driven by security-related operational constraints.

8.6. Reliability and Security Enhancements

The key operational advantage of SCED in enforcing technical constraints that are difficult to manage consistently under the existing MOD framework, particularly during periods of sharp transitions such as day cross-over blocks has been highlighted in Figure 82. It is observed for JSWEL-U1, where MOD scheduling allows the unit to absorb rapid net-load changes despite being ramp-constrained. In contrast, under SCED, the ramping capability of JSWEL-U1 is explicitly respected, and the optimization redistributes the ramping requirement across other available resources. While this may result in marginally higher short-term costs in certain blocks, it avoids infeasible schedules and reduces operational stress on individual units.

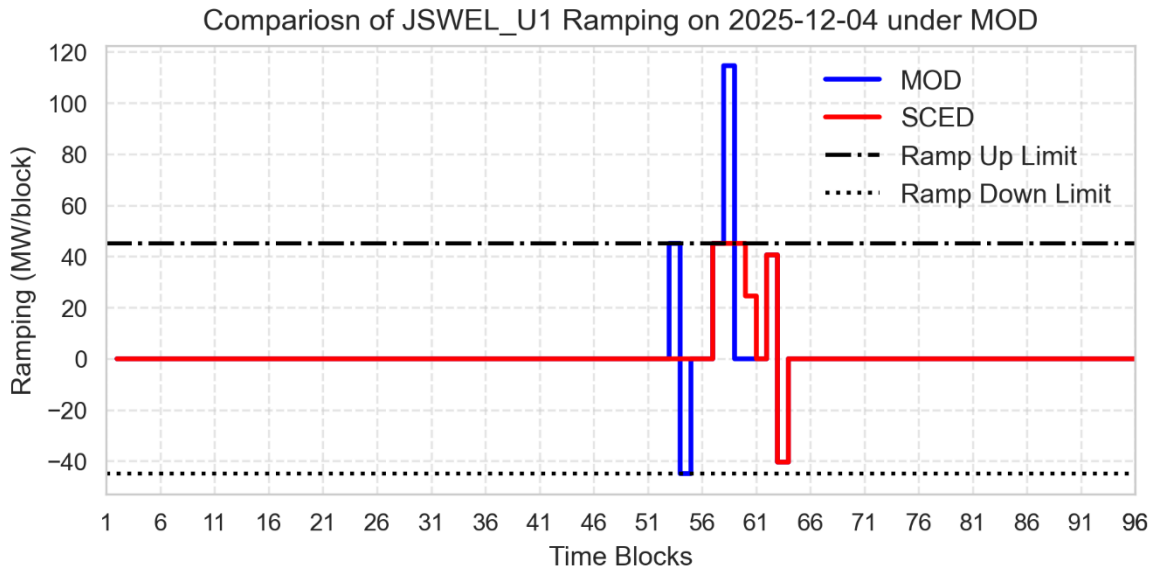


Figure 82 Ramping for JSWEL under MOD and SCED

Importantly, these cases also underscore the need for gate closure harmonization. Misalignment between data cut-off times, schedule finalization, and real-time operational execution exacerbates ramping issues, especially during block transitions. While the SCED framework itself strictly honours system-level technical constraints, its effectiveness is influenced by the quality and timing of inputs determined through the prevailing gate-closure mechanism. When schedules and data are finalized through a well-defined and consistent gate-closure process, SCED is able to operate on stable inputs, thereby reducing frequent schedule switching and smoothing inter-block transitions. Such harmonization mitigates artificial ramping spikes, improves schedule feasibility, and enhances overall system reliability. Conversely, inconsistencies in gate closure directly affect SCED outcomes and can dilute potential cost benefits, underscoring the importance of aligned gate-closure practices for maximizing both economic and security gains.

9. Stakeholder-Specific Insights and Takeaways

Based on the six-month operational assessment of the intra-state SCED pilot, the outcomes extend beyond aggregate cost savings to reveal differentiated impacts across stakeholder groups. The analysis demonstrates that the implications of optimization-based scheduling are not uniform; rather, they vary by institutional role, operational responsibility, and exposure to system risks. While system-level efficiency improvements form the common foundation, the nature of benefits differs for DISCOMs, generating companies, system operators, regulators, and ultimately consumers. A consolidated overview of the key benefits observed during the pilot, mapping system-level efficiency gains to stakeholder-specific outcomes is shown in Figure 83.

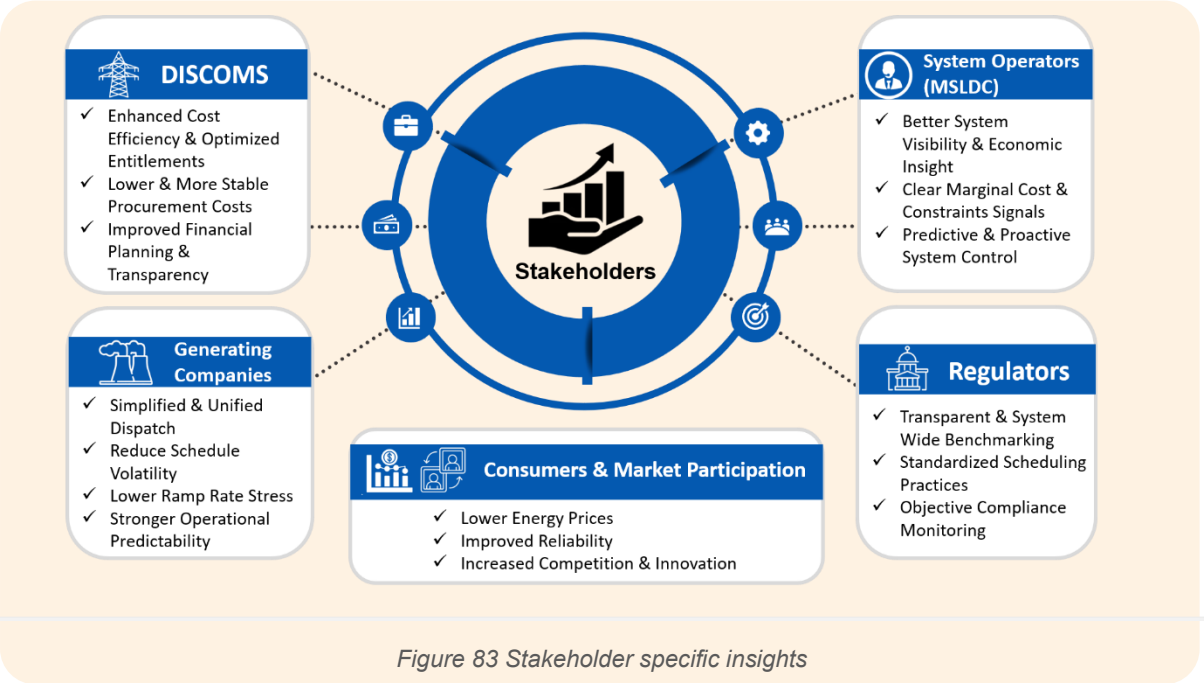


Figure 83 Stakeholder specific insights

9.1. Insights for DISCOMs

Under the existing decentralized scheduling framework, SCED delivers constrained benefits to DISCOMs. While optimization improves despatch efficiency within participating generators, fragmented scheduling prevents full system-wide least-cost outcomes. As a result, cost savings materialize intermittently and vary across DISCOMs depending on their generation mapping and entitlement portfolio. Limited visibility into marginal prices, congestion drivers, and despatch rationale further reduces predictability in procurement outcomes. The analysis indicates that meaningful and sustained cost efficiency for DISCOMs emerges only under centralized SCED, where system-wide merit order is enforced and which further can be improved by optimization of central sector entitlements. The transition towards centralized despatch represents a strategic shift for DISCOMs from short-term scheduling adjustments to portfolio-level risk management, with significant potential to enhance financial predictability, reduce procurement volatility, and support long-term sustainability.

9.2. Insights for Generating Companies

The SCED scheduling mechanism provides partial operational relief compared to MOD, including reduced ad-hoc (manual) coordination and smoother despatch signals. However, coexistence with non-SCED scheduling continues to expose generators to schedule volatility, ramping stress, and fragmented commercial signals. The pilot shows that under de-centralized and/or centralized SCED offers a structural improvement, delivering a coherent despatch instruction, significantly lower ramp stress, reduced cycling, and improved unit stability. Clear marginal cost signals under de-centralized and/or centralized SCED also enhance fuel planning, maintenance scheduling, and long-term asset utilization, supporting both operational efficiency and asset longevity.

9.3. Insights for System Operators (MSLDC)

From a system operations perspective, SCED provides improved analytical visibility compared to the traditional MOD framework by introducing cost-based optimization and constraint-aware despatch signals. However, when implemented alongside decentralized scheduling (not co-optimizing the central section entitlement), this visibility remains incomplete, as a significant portion of generation and load continues to be managed outside the optimization framework. As a result, system operators receive fragmented economic and operational signals, limiting the ability to fully internalize network constraints, ramping requirements, and flexibility needs into proactive system management. Further in existing MOD framework, Operators lack a unified SMP, explicit marginal values of constraints, and economic signals for reserves and flexibility. Consequently, system management remains largely corrective, and experience driven. SCED fundamentally enhances operator capability by delivering clear SMPs, shadow prices of binding constraints, and explicit valuation of reserves and ramping. This enables predictive system management, better anticipation of stress conditions, and informed prioritization of remedial actions marking a shift from rule-based control to optimization-supported decision-making.

9.4. Insights for Regulators

In the decentralized MOD framework, regulators face inherent challenges in objectively assessing economic efficiency, enforcing uniform practices, and designing performance-linked incentives. SCED equips regulators with transparent economic reference points, including SMPs and marginal constraint values, enabling evidence-based oversight. This helps harmonize the scheduling standards, objective compliance assessment, and improved incentive design. Importantly, it strengthens alignment between real-time operations, day-ahead operation and long-term planning, and policy objectives, facilitating a transition from principle-based regulation to outcome-oriented regulation.

9.5. Benefits for Consumers

Consumers emerge as the ultimate beneficiaries of SCED. By minimizing total system generation costs while maintaining security, SCED lowers aggregate procurement costs that feed directly into tariffs. The analysis demonstrates improvements in unit energy cost outcomes, reduced exposure to inefficient despatch, and enhanced reliability through better coordination of ramps and reserves.

9.6. Insights for Market Participation

SCED also creates a structured framework to recognize and integrate demand flexibility as a system resource, allowing operators to assess trade-offs between supply-side and demand-side responses in an economically consistent manner. Transparent marginal pricing under SCED improves market credibility, strengthens price discovery, and encourages participation and innovation. Over time, these outcomes translate into enhanced social welfare through lower system costs, improved reliability, and a more transparent and economically coherent market framework.

10. Governance, Transparency, and Regulatory Relevance

10.1. Alignment with Regulatory Objectives

The implementation of Security Constrained Economic Despatch (SCED) at the intra-state level represents a structural shift in how power system operations, regulatory oversight, and institutional accountability are organized pan India. Unlike incremental operational reforms, intra-state SCED requires coordinated action across governance layers, regulatory instruments, operational institutions, and supporting digital infrastructure. Its relevance therefore extends beyond operational efficiency to the broader domains of market design, regulatory harmonization, and system governance.

At the national level, SCED was first conceptualized and operationalized as a centrally coordinated optimization mechanism for shared Interstate Generating Stations (ISGS), administered through the National Load Despatch Centre (NLDC). The national SCED pilot demonstrated that optimization across balancing areas could deliver measurable economic benefits besides enhancing system security. Importantly, it also established a governance template driven by an independent system operator, transparent and optimized despatch, and pool settlement outside bilateral contracting structures as per Regulatory order. This national experience provided the conceptual and institutional foundation for extending SCED principles to the intra-state domain, where fragmentation of despatch decisions and uneven operational practices had historically constrained optimization.

The formal recognition of SCED within the Indian Electricity Grid Code (IEGC), 2023 marked a significant regulatory milestone. By explicitly acknowledging optimization-based despatch mechanisms, the Grid Code moved beyond prescriptive operational rules toward outcome-oriented system operation. This inclusion effectively legitimised SCED as a recognised system operation function rather than an experimental or discretionary initiative. For intra-state implementation, this was critical: it provided SLDCs and State Electricity Regulatory Commissions (SERCs) with a clear regulatory anchor to initiate pilots without requiring ad-hoc exemptions or special approvals.

The subsequent reference to SCED and market-oriented despatch principles in the draft National Electricity Policy 2026 further elevated its governance relevance. Policy-level recognition signals long-term intent and continuity, reducing regulatory uncertainty for states contemplating deeper reforms. It also places intra-state SCED within a national transition narrative, linking optimization, renewable integration, and resource adequacy, rather than treating it as a standalone efficiency tool.

10.2. Role of SCED in Strengthening Market-Based Despatch

From an institutional perspective, the coordination role played by the Forum of Load Despatchers (FOLD) and Forum of Regulators (FOR) has been central. Intra-state SCED cannot be implemented through isolated state actions alone; it requires alignment across SLDCs, RLDCs, NLDC, generators, regulators, and settlement agencies. FOLD has provided a neutral platform for sharing pilot experiences, harmonizing design choices, and resolving cross-jurisdictional issues such as interface scheduling, deviation handling, and data

standards. This collective approach has reduced the risk of divergent state-specific implementations that could otherwise undermine interoperability and scalability.

Regulatory intervention at the state level has emerged as both an enabler and a disciplining mechanism. SERCs have had to address questions that extend beyond conventional tariff regulation: the legal status of SCED schedules vis-à-vis existing PPAs, treatment of variable cost declarations, allocation de-pooling of savings, and compliance obligations for generators. Regulatory Sandbox, Pilot approvals, procedural directions, and settlement frameworks issued by SERCs have to progressively clarify these issues, demonstrating that SCED implementation is as much a regulatory design exercise as a technical one.

One of the most consequential governance challenges has been gate closure harmonization. Intra-state SCED operates at the intersection of multiple scheduling timelines: ISGS requisition gate closures, state-level scheduling, and real-time market operations. Misalignment among these timelines can dilute optimization benefits or introduce operational risk. The ongoing effort to rationalize and harmonize gate closure times reflects a broader governance imperative, aligning institutional processes across market and non-market mechanisms to ensure consistency and predictability.

10.3. Transparency, Audit Trails, and Data Availability

Data quality and integration have emerged as foundational enablers of intra-state SCED governance. Optimization outcomes are only as robust as the data inputs on demand forecasts, generator availability, technical constraints, and network limits. Variability in data practices across states has highlighted the need for standardised data protocols, validation processes, and accountability frameworks. In this context, LP, MILP SCED and SCUC has acted as a forcing function, exposing latent data deficiencies that were less visible under manual or heuristic despatch practices.

The reliance on advanced IT systems and digital platforms represents another governance shift. Intra-state SCED requires real-time data ingestion, optimization engines, automated schedule generation, and settlement interfaces. This has moved SLDCs from predominantly manual or semi-automated operations toward technology-intensive system operation. Governance implications include cybersecurity considerations, system auditability, vendor management, and long-term system ownership, all of which require regulatory and institutional clarity.

10.4. Enablers for Regulatory Oversight

Settlement design has similarly required careful regulatory oversight. SCED-based despatch introduces top up INC and DEC, besides deviations between contracted schedules and optimized outcomes, necessitating transparent and auditable settlement mechanisms. Ensuring that settlements are timely, verifiable, and insulated from discretionary adjustments has been essential to building stakeholder confidence. This has reinforced the need for clear separation between operational decision-making and financial settlement, supported by well-defined regulatory rules.

Finally, capacity building and in-house skill development are central to sustainable implementation. SCED SCUC is not a “plug-and-play” solution; it demands system operators capable of interpreting optimization outputs like DUALS etc , understanding constraint binding, and exercising informed operational judgement. Regulatory frameworks have increasingly recognised this by encouraging structured training programmes, pilot-phase learning, and gradual scaling. Over time, the development of in-house analytical and modelling capability

within SLDCs will be as important as the LP based optimization software itself, Made in India, ensuring that SCED remains a tool for informed decision-making rather than a black-box process.

In summary, the governance and regulatory relevance of intra-state SCED lies not merely in cost optimization, but in its ability to institutionalize coordinated decision-making, data discipline, and transparent accountability across the power system. Its evolution from national implementation to Grid Code recognition and policy endorsement, reflects a deliberate shift toward more integrated and resilient system operation, with intra-state SCED emerging as a critical bridge between operational reform and market evolution.

11. Capacity Building and Training Programme

To support the successful implementation of intra-state SCED and ensure long-term institutional readiness, a structured capacity building programme was undertaken for MSLDC officers. The training initiative was designed to strengthen conceptual understanding of optimisation-based despatch, build practical modelling skills, and enable informed operational decision-making. The programme was conducted by the GIL, IIT Bombay, under Continuing Education Programme (CEP), ensuring academic rigor and formal certification to the MSLDC operators. The training was implemented over a period of two months primarily focused on applied learning and hands-on driven skill development in the SCED modelling and its implementation. The training program enabled the participants to first build theoretical foundations and subsequently reinforce learning through practical exposure and real system applications.

11.1. Objective of the Training Program

The primary objective of the training programme was to build a deep technical capacity within MSLDC by equipping officers with a strong conceptual and practical understanding of optimisation theory, power system economics, and SCED principles. The focus was not limited to theoretical exposure but extended to application-oriented learning aligned with real-world system operations in Maharashtra, enabling participants to code the optimisation models, interpret optimisation outputs in the context of operational constraints such as ramping limits, reserve requirements, transmission congestion, and contractual obligations. A total of eighteen officers from key functional areas, scheduling, market operations, IT systems, and real-time grid operations, participated in the programme. Participants were nominated by MSLDC management, ensuring alignment with institutional requirements and succession planning. A key objective was to develop inhouse capability of independently running optimisation models, validating results, diagnosing infeasibilities, and interpreting marginal prices and shadow costs from a system operator's perspective. The training programme was designed around below mentioned objectives.

- To develop a strong foundational understanding of power system operations, generation-load balancing, unit commitment, and economic despatch principles relevant to real-time system operation.
- To enable officers to conceptually understand SCED and translate operational intuition into mathematical optimisation formulations.
- To expose participants to international best practices in optimisation-based despatch through case studies and expert lectures, including experiences from global markets.
- To build competency in identifying key components of SCED models, including technical and economic data requirements and formulation of operational constraints.
- To strengthen analytical skills in linear programming, including understanding primal-dual relationships, feasibility, optimality conditions, and solver behaviour.

- To develop familiarity with different modelling platforms and software tools used for SCED implementation, including comparative assessment of open-source and commercial tools.
- To impart hands-on programming skills, including model development, syntax, execution, debugging, and interpretation of results.
- To enable participants to develop and validate base-case SCED models for single time-step economic despatch and extent it to solve multi-time-step SCED models incorporating inter-temporal constraints.
- To train officers in end-to-end SCED model development using actual MSLDC data formats, including data pre-processing, constraint modelling, execution, and result validation.
- To strengthen understanding of dual variables and their economic interpretation, including system marginal prices and shadow costs of constraints.
- To build competency in modelling network constraints using DC load flow formulations and understanding their impact on despatch outcomes and analyse Locational Marginal Prices (LMPs), including congestion impacts and node-wise pricing behaviour
- To equip officers with the ability to independently assess model feasibility, diagnose constraint binding issues, and suggest data or formulation refinements.
- To develop institutional capability for transitioning from decentralised MOD-based scheduling to optimisation-based SCED frameworks.

Building on the learning objectives and the competencies developed through the programme, the following section presents the detailed structure of the two-month training engagement. This section outlines the phased delivery approach, thematic progression of modules, and the balance between theoretical instruction and hands-on application adopted during the training period.

11.2. Training Programme Structure

The two-month training programme was designed as a structured, progressive learning journey, combining theoretical grounding with practical application to ensure sustained capacity building within MSLDC. The programme followed a modular format, where each week built upon the knowledge and skills developed in previous sessions, as highlighted in the Figure 84.This approach ensured a smooth transition from foundational concepts to advanced optimisation modelling and real-world applications. The initial phase of the programme focused on strengthening conceptual understanding of power system operations and economic despatch. Participants were introduced to generation-load balancing, unit commitment, and the fundamentals of SCED, with specific emphasis on how these concepts align with day-to-day operational practices at MSLDC. This phase helped establish a common knowledge baseline across participants from diverse functional backgrounds. Subsequently, the programme moved towards understanding the limitations of the existing MOD-based scheduling framework and the rationale for adopting optimisation-based despatch. Through tutorials and case discussions, officers were guided on how operational challenges can be translated into mathematical formulations, enabling them to view system operations through an optimisation lens.

Subsequently, the programme concentrated on developing strong analytical capabilities. Dedicated sessions were conducted on linear programming fundamentals, solver logic, and optimisation theory. Participants learned about primal-dual relationships, feasibility conditions, and convergence behaviour, which helped them interpret solver outputs with confidence rather than treating them as black-box results. A major component of the programme involved hands-on exposure to modelling platforms. Officers were introduced to various software tools used for SCED implementation, followed by in-depth training on the programming environment. Participants learned model structuring, syntax, data handling, execution workflows, and result interpretation through guided exercises.

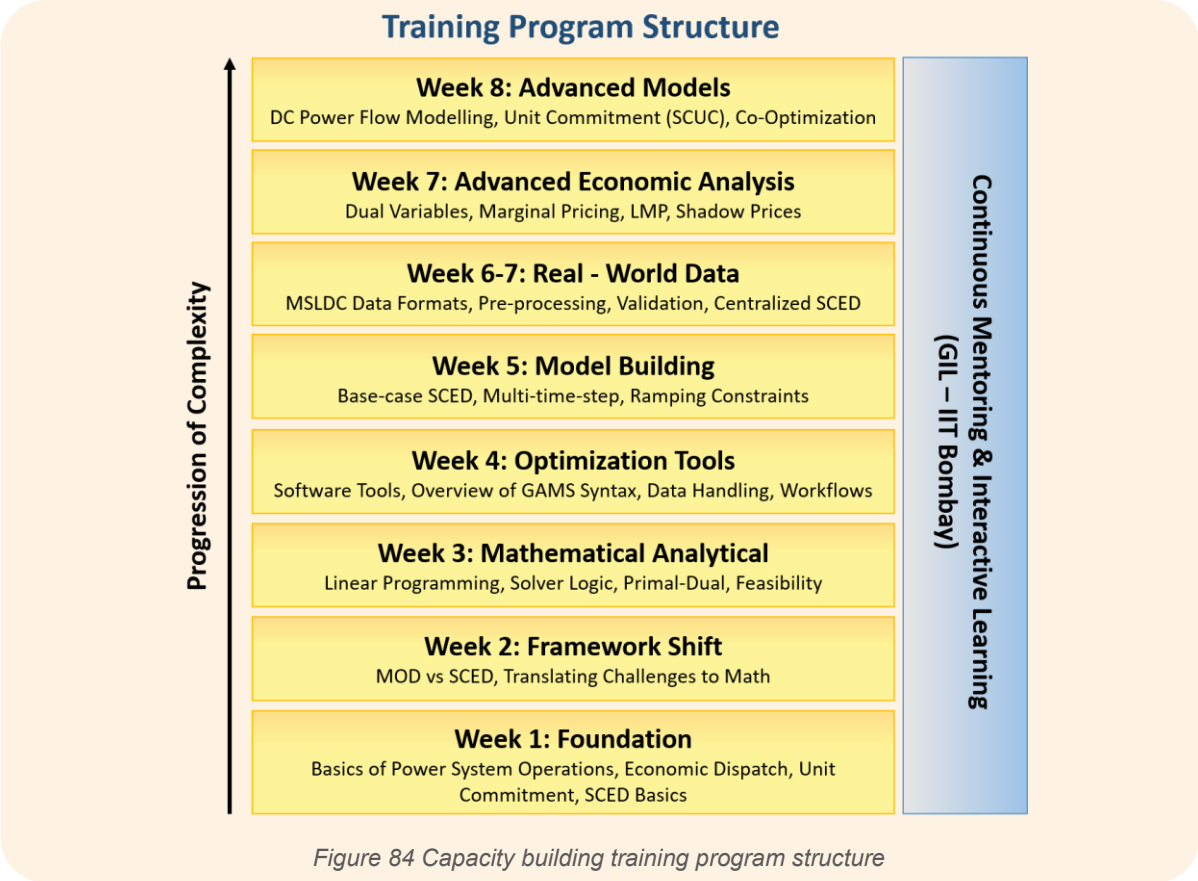


Figure 84 Capacity building training program structure

Building on these skills, participants developed base-case SCED models for single time-step economic despatch and gradually progressed to multi-time-step formulations incorporating inter-temporal constraints. This progression allowed them to understand how system dynamics influence despatch outcomes across time blocks through international case studies. Further, MSLDC officers worked directly with actual operational data formats used in the scheduling process. This included data pre-processing, formulation of operational constraints, model execution, and validation of optimisation results against real system conditions. As part of this hands-on engagement, participants also developed a centralised SCED model, which, after successive refinements, has now been integrated into the live dashboard environment. This has enabled officers to directly observe and analyse centralised optimisation outcomes alongside existing scheduling results, thereby strengthening understanding and operational confidence.

With a strong foundational understanding established, participants were subsequently introduced to state-of-the-art optimisation concepts, including modelling of transmission constraints using DC power flow formulations, locational marginal pricing analysis, and unit commitment frameworks. These advanced modules enabled officers to appreciate the impact of network constraints, congestion, and commitment decisions on despatch outcomes and system economics. The programme also covered advanced economic concepts such as dual variables and marginal pricing. Participants learned to interpret shadow prices of binding constraints, congestion, and spatial price variations through LMP analysis. This strengthened their ability to connect optimisation outputs with market signals. Throughout the two-month engagement, learning was reinforced through interactive discussions, guided self-learning, and do-it-yourself programming exercise. Continuous mentoring by GIL, IIT Bombay ensured that participants could clarify doubts, test new ideas, and deepen their understanding in a practical setting.

11.3. Skill Development Outcomes and Feedback

The structured and progressive design of the training programme resulted in a tangible enhancement of technical, analytical, and interpretative competencies among participating MSLDC officers. The learning outcomes extended well beyond tool familiarity, enabling participants to internalise SCED as an optimisation-driven operational framework and its application under realistic system conditions. A key shift observed during the programme was the transition of system operators from procedural schedule execution to analytical, evidence-based decision-making supported by optimisation outputs and economic signals. Officers gained the ability to translate practical system challenges into mathematical optimisation formulations and benchmarked state practices against international market experiences such as PJM and Singapore. Hands-on training strengthened proficiency in SCED model development, including data preparation, constraint formulation, execution, and result validation. Participants successfully developed both single time-step and multi-time-step models incorporating inter-temporal constraints. Analytical skills were built through exposure to linear programming fundamentals, solver diagnostics, and dual interpretation. Officers are now capable of identifying infeasibilities, tracing binding constraints, and recommending corrective measures. Training on network modelling and locational marginal pricing enhanced their ability to interpret congestion impacts and spatial price variation. From an operational perspective, participants can now systematically compare MOD and SCED schedules, evaluate generator stress, and anticipate system behaviour under high renewable penetration. Economically, officers developed a strong understanding of system marginal price formation and constraint-driven price signals. At an institutional level, the programme has created an internal capability of supporting regulatory engagement, technical studies, and future extensions towards advanced scheduling mechanisms. The training has substantially strengthened MSLDC’s readiness for long-term transition to optimisation-based despatch frameworks.

The photographs captured during the training, Figure 85-Figure 87, showing faculty-led sessions, hands-on exercises, assessment activities, and the closing workshop with participation of the Executive Director (MSLDC), independent consultants, and faculty coordinators, and participants appearing for learning assessment reflect the depth of engagement and institutional commitment to this capacity-building initiative. These interactions further reinforced peer learning, knowledge exchange, and professional development.



Figure 85 MSLDC officers attending sessions of capacity building training at IITB

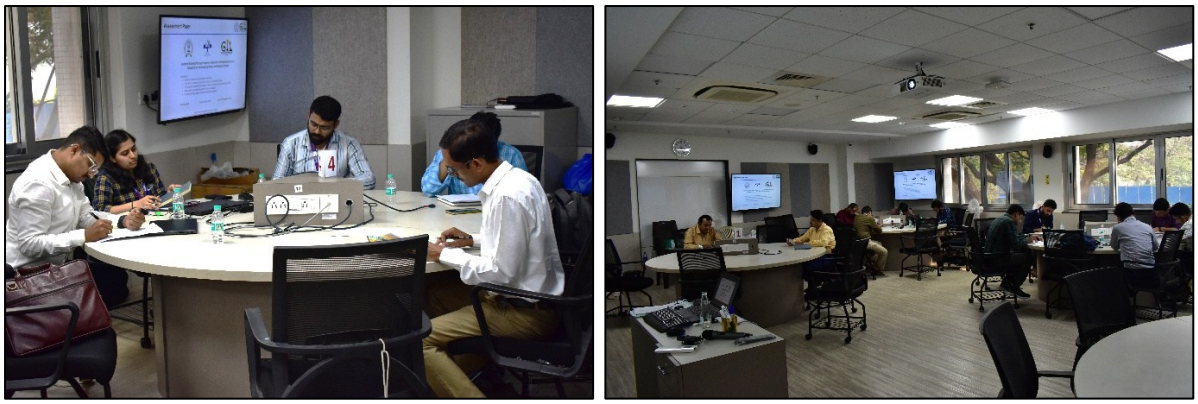


Figure 86 MSLDC officers appearing in assessment test during capacity building training at IITB

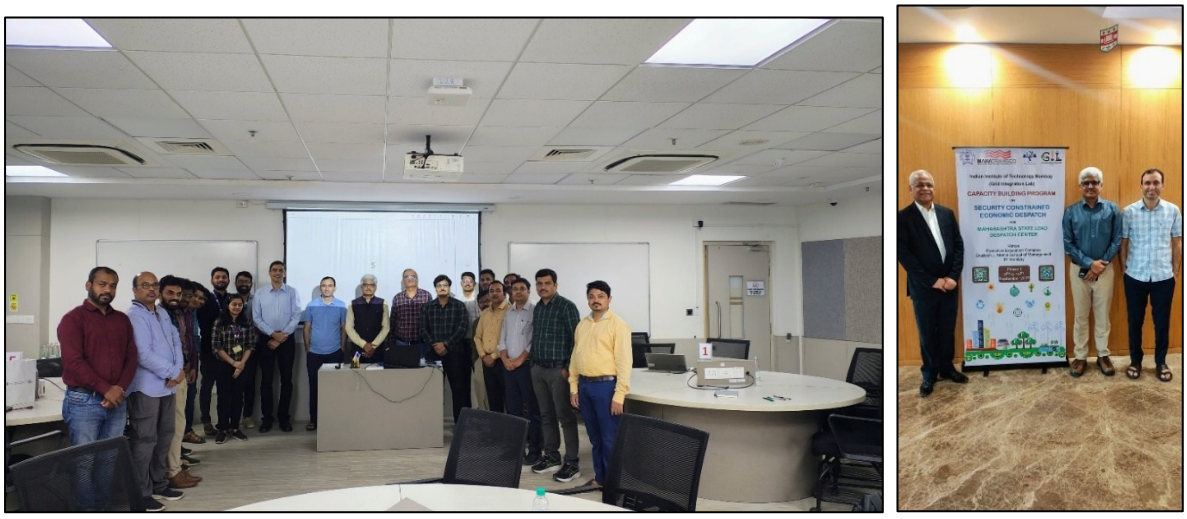


Figure 87 Group Photograph during the SCED Capacity Building Programme at IITB

Participants highlighted that the training significantly enhanced their understanding of optimisation-based despatch and bridged the gap between theoretical concepts and real-world system operation. Many officers appreciated the hands-on sessions, stating that working directly with actual MSLDC data helped them gain confidence in interpreting model outputs and diagnosing infeasibilities. Figure 88 Participants Feedback on SCED Capacity Building programme at IITB is shown in Figure 88.

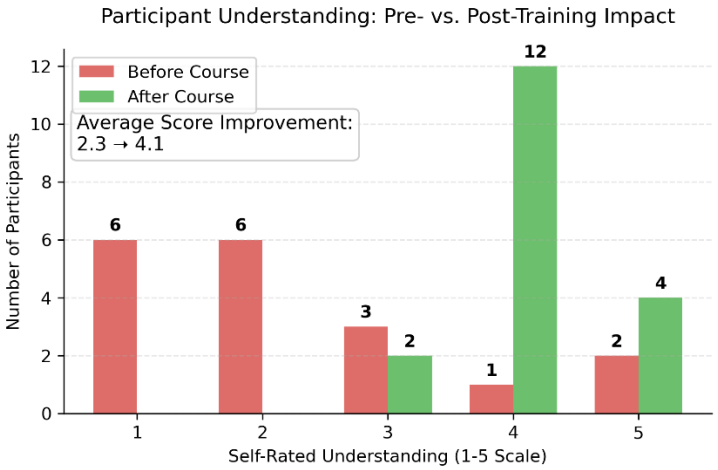


Figure 88 Participants Feedback on SCED Capacity Building programme at IITB

"Participants identified the hands-on application for Power System modelling as the most valuable aspect of the training. The feedback highlights a strong appreciation for moving beyond theory into practical logic development, specifically regarding SCED formulation and transmission constraint modelling. Several attendees specifically praised the pedagogical approach, notably the progression from basic generator examples to complex, real-world data sets, and the patient walkthrough of input data sets. The consensus indicates that the program successfully bridged the gap between raw coding and high-level optimization concepts, offering a clear improvement over traditional scheduling methods like MOD."

Overall, the training programme has significantly strengthened MSLDC's institutional readiness for advanced despatch operations and laid a strong foundation for the long-term transition from decentralised MOD-based scheduling to optimisation-driven SCED frameworks.

11.4. Institutional Readiness

The capacity building programme and pilot implementation have enabled MSLDC to reach a strong level of institutional readiness for optimisation-based despatch. At present, MSLDC has developed a core group of trained officers with hands-on expertise in SCED modelling, data preparation, result validation, and economic interpretation. This in-house capability allows the organisation to independently operate, refine, and troubleshoot optimisation models with minimal dependencies on external consultants. The operators are now able to meaningfully interpret SCED outputs alongside MOD schedules, marking a shift towards evidence-based operational decision-making.

From an IT and systems standpoint, MSLDC has established understanding of functional data pipelines, automation workflows, and a live dashboard environment. Internal teams now possess the competence to manage data integration, requirement of cybersecurity protocols, access control, and system scalability. Governance mechanisms such as audit trails, logging, and performance reporting are in place, enhancing transparency and regulatory confidence. The institutional readiness achieved during the pilots includes

- In-house modelling and analytical capability

- Trained personnel across operations, planning, and IT
- Operational experience through parallel online SCED runs
- Functional dashboard and automation ecosystem
- Structured documentation and auditability

12. Key Learnings from the Pilot

The online intra-state SCED pilot has provided a comprehensive, evidence-based understanding of how optimization-based scheduling performs when applied to a large, contractually complex, and operationally constrained state power system. The learnings extend beyond cost outcomes and offer practical insights across technical modelling, real-time operations, institutional readiness, data governance, and implementation risks. Collectively, it has been realized that the SCED is a systemic reform that requires coordinated technical, operational, and regulatory preparedness.

12.1. Technical Learnings

One of the early technical refinements was the optimization of the first-time block of each day. In the offline study, the first-time block was treated as fixed to avoid infeasibility. During the pilot, this block was explicitly optimized using prior despatch (96th time block schedule) as an initial condition, significantly improving inter-block continuity and reducing artificial ramp violations at block boundaries. The pilot also enhanced visibility of reserve availability, both at the generator level and in aggregate across DISCOM portfolios. Explicit monitoring of ramp-based and spinning reserves provided system operators with quantitative insight into flexibility margins, which were largely implicit under the existing MOD framework.

While modelling SCED, contractual obligations were preserved through the use of virtual units mapped to DISCOM-wise sub-contracts. Unlike the initial offline pilot, DISCOM interdependencies were deliberately de-linked to avoid cross-impact of one DISCOM's demand or scheduling decisions on another. At the same time, contract-level costs and operational limits were retained at the virtual unit level. This modelling approach enabled centralized optimization of system resources while ensuring strict adherence to existing commercial arrangements and avoiding unintended cost or despatch spillovers across DISCOMs.

From a modelling robustness perspective, the pilot highlighted the need for adaptive SCED code capable of operating under short rolling horizons, while remaining extensible to longer planning horizons as system conditions evolve. This adaptability is essential to accommodate future reductions in despatch intervals and increasing renewable variability. Parallel execution of multiple SCED variants, decentralized with transmission constraints, and centralized proved valuable both for validation and for building operator confidence. Independent parallel runs allowed systematic comparison of outcomes and ensured that benefits attributed to SCED were analytically distinguishable.

Another important technical insight was the untapped optimization potential of central sector entitlements. Preliminary offline analysis indicated that treating central allocations as optimizable resources, while respecting entitlement limits, could unlock additional economic efficiency, demanding attention in subsequent work.

The pilot further underscored the importance of data structuring and orchestration for seamless dashboard integration. Standardized input-output schemas, automated logging of runs, and consistent data tagging were necessary to support real-time visualization, post-analysis, and auditability. Dashboard functionality evolved beyond simple result display into an operational decision-support tool. Enhancements such as infeasibility flags, advisory schedules, constraint diagnostics, and soft-start mechanisms were identified as essential to minimize operational disruption and support gradual adoption. Data quality emerged as a

recurring bottleneck. Inconsistencies in declared capacity, ramp rates, and contract mappings directly influenced feasibility and outcomes, reinforcing the need for tighter data validation and governance frameworks. Finally, the integration of SCADA and energy meter data was identified as critical for closing the loop between scheduled and actual despatch. Initiated during the pilot and currently ongoing, this integration is expected to significantly enhance validation of SCED outcomes, improve deviation analysis, and strengthen confidence in optimization-driven despatch decisions.

12.2. Operational Learnings

Operationally, the pilot demonstrated that SCED enhances despatch feasibility, ramp discipline, and inter-temporal consistency when compared with the prevailing MOD-based scheduling framework. Block-wise and heatmap analyses across multiple operating days indicate that MOD schedules tend to exhibit pronounced stress during periods of rapid system transition, such as morning and evening demand ramps and day-boundary crossovers, where frequent schedule adjustments are required. Under SCED, these transitions are handled through coordinated optimization across units and time blocks, resulting in smoother despatch trajectories and improved alignment with declared operational capabilities.

A key operational benefit observed during the pilot is SCED's ability to internalize ramping requirements within the optimization itself. By distributing flexibility across the available generation portfolio and explicitly linking successive time blocks, SCED reduces abrupt inter-block changes and improves consistency between scheduled. This was particularly evident for mid-merit and ramp-constrained thermal units, where SCED schedules exhibited greater stability relative to MOD outcomes. The pilot also highlighted the importance of upstream scheduling discipline for realizing the full benefits of SCED. Outcomes were found to be sensitive to gate-closure alignment, data freezing timings, and revisions in demand, declared capacity, and contractual inputs.

12.3. Institutional and Capacity-Building Learnings

A major outcome of the pilot was the development of in-house institutional capability. Through structured training and hands-on engagement, MSLDC personnel transitioned from procedural schedule execution to analytical interpretation of optimization outputs. Officers demonstrated the ability to understand marginal prices, diagnose binding constraints, evaluate feasibility issues, and suggest data or formulation refinements. During the capacity building it has been emphasized to have ecosystem, combining optimization modelling expertise, system operation experience, IT integration skills, and regulatory understanding.

12.4. Data and Infrastructure Learnings

The pilot underscored that data quality is not a one-time prerequisite but a continuous requirement for reliable SCED operation. Robust data sanity checks at the input stage, covering declared capacity, ramp rates, costs, and contractual mappings, were found to be equally important as post-processing validation of optimization outputs before these results are consumed by downstream systems and visualization layers. Breaks in this circular validation loop can propagate inconsistencies, affecting both feasibility and interpretability of results.

The experience also highlighted the need for sustained and close engagement between domain experts and the visualization development process. While the IT partner effectively enabled data pipelines and dashboard infrastructure, energy analytics and power system interpretation require continuous guidance from system operators and optimization experts.

Without this engagement, visual outputs risk being technically correct but operationally misaligned, limiting their usefulness for decision-making.

A key learning was that robust data interpretation and well-defined performance metrics play an essential role in streamlining troubleshooting efforts. A clear grasp of data enables quicker detection of anomalies and irregular patterns in optimization outcomes, supporting timely analysis and resolution. The pilot demonstrated that system operators and modellers must retain clarity on what data is being ingested, how it is processed, and how each indicator is derived, enabling faster diagnostics and more informed interventions.

Finally, the pilot emphasized the need for a flexible data schema and responsive IT workflows. As SCED models evolve and operational requirements change, the ability to rapidly accommodate new parameters, indicators, and reporting formats becomes critical. Reducing turnaround time for updates, fixes, and enhancements through closer coordination and streamlined development cycles was identified as a key enabler for continuous improvement and long-term system maturity.

13. Recommendations and Way Forward

Maharashtra State is experiencing multidimensional transformation in the State electricity grid, with transition from conventional to RE dominated generation system including rapid increase in the share of rooftop PV system, electrification of transport sector, rising number of inverters based bulk data centre loads coupled with various other policy and regulatory developments. Such overlapping multiple transitions push the State grid to its security limits, thereby highlighting the pressing need to reform the grid operational procedures, market design, identifying the key regulatory intercessions and institutional proactive interventions including capacity building to enhance technical and economic efficiency of evolving complex power systems. The Intra-State SCED pilot outcome so far clearly suggesting that traditional MoD framework, while historically effective in conventional system, can no longer satisfactorily meet operational, economic efficiency and security needs of such complex power system. Therefore, transitioning to SCED driven optimal generation scheduling and despatch is not only a significant improvement over MoD framework, but unavoidable necessity to firm up the secure and economic operation of the State grid. This section, therefore, outlines a potential roadmap for Maharashtra State to transit from pilot to the implementation stage, unlocking economic and operational benefits of centralized generation scheduling, institutional capacity building and enabling regulatory measures for successful transition to modernized smart grid operation in the State.

13.1. Scaling from Pilot to Full-Scale Implementation

The SCED pilot has successfully evolved over the past six months including SCED engine development, dashboard development leading to online deployment in parallel with existing MoD scheduling engine. The near real-time output generated by the SCED engine and displayed over operator oriented SCED user interface along with various features of generating different visualization plots for cost, operational parameters including generator and demand parameters, DISCOM wise figures and State level generation and demand schedule patterns with point-by-point comparisons of SCED and MoD engine output. The enriching experience of developing and running the SCED pilot at MSLDC control centre has not only demonstrated how SCED based generation scheduling can improve operational and economic efficiency of the system, but a lot of insights, experience and learnings have been gathered highlighting the criticalities in integrating the SCED engine into the scheduling system of Maharashtra, however without any change in the existing MoD based scheduling and settling mechanism in the State. The SCED pilot outcome has demonstrated potential additional saving ranging from average value of 1-6 Cr per month for decentralized and centralized SCED scheduling, enhanced security including full compliance with various operational constraints, ease of operation and evidence-based inputs for DISCOMS and generators thereby enabling them to take informed decisions on bidding in the market. The pilot experience gained over past six months supported by favorable results clearly indicates superiority of SCED based scheduling over existing practice of MoD scheduling, both on cost economics and strengthening of security and reliability coupled with promising computational efficiency/speed of SCED engine. However, while decentralized SCED is better than existing practice of decentralized MoD (DISCOM level optimization), it has clearly emerged that centralized SCED based scheduling is having a far additional technical and economic benefits

with the results over the pilot period demonstrating as high as six times cost savings compared to decentralized SCED. Therefore, based on the outcomes/conclusions derived, the below mentioned recommendations are put forward to transit from pilot to the full scale SCED implementation.

Recommendations:

- *Based on the experience of the SCED pilot and derived confidence evidenced by the analysis/pilot outcome, the SCED pilot should be transitioned into full SCED implementation with generator scheduling mechanism including settlement in the Maharashtra State to be realized through SCED framework, thereby advancing from existing bucket filling scheduling approach to a scientific method (LP/MILP) based optimal despatch.*
- *Considering far more potential of optimizing resources through centralized SCED, it is strongly recommended that the SCED to be realized in the State should be centralized SCED based generation scheduling instead of decentralized based framework, with due consideration and compliance of existing contractual obligations of generators and DISCOMs.*
- *Inclusion of central share of ISGS under the centralized SCED framework of the State is likely to further increase the operational and economic efficiency in the Intra-State SCED. This dimensions of the SCED scheduling is being investigated further with its outcome expected to be available before final SCED pilot report. Therefore, subjected to the favourable results, there is potentially a strong case for inclusion of central share of the State in the intra-state SCED framework.*
- *Considering the development of the SCED pilot which has over past six months evolved through different phases of the development into an advanced and stable engine, its recommended that the ongoing SCED pilot be continued for next four to six months to gather more consistent data from the stable SCED engine while advancing the SCED models with new features.*
- *Considering potential of reserve management at the State level, it is recommended to optimize the reserves through a centralized approach at the State level including potential co-optimization of reserves from the intra-State and central share (State entitlement of) ISGS.*

13.2. Strengthening Institutional Capacity

While technical readiness has been established through the pilot development, a full-scale institutionalisation of SCED will require regulatory and systemic enablers. Clear regulatory guidelines are needed on governance structure, cost allocation mechanisms, treatment of marginal prices, and settlement integration. Formal recognition of SCED outputs within the scheduling and settlement framework will be essential to avoid parallel systems and ambiguity in accountability. On the organisational front, dedicated SCED cell within SLDC, sanctioned manpower, and defined career pathways for optimisation specialists will be required to sustain long-term operations. Continuous training and certification programmes must be institutionalised to address staff rotations and skill continuity. From a systems perspective, further integration with SCADA, energy metering, and market platforms is required to enable near-real-time optimisation and automated feedback loops. Standardisation of data formats across generators and DISCOMs will also be critical or scalability and reliability.

Regulatory support will be central to the successful institutionalisation of intra-state SCED. The Commission's role encompasses providing a clear policy roadmap for phased adoption, establishing governance and accountability frameworks, and approving the integration of SCED outputs into existing settlement mechanisms. In addition, the Commission will play a key role in facilitating stakeholder alignment, resolving implementation-related issues, and enabling a structured transition from pilot to full-scale deployment. This proactive regulatory guidance will be critical in ensuring transparency, stability, and long-term sustainability of Intra-State SCED, optimisation-based despatch reforms.

13.3. Enhancements to SCED Models and Dashboards

SCED engine strengthening:

- *Co-optimizing central (ISGS) share*: The SCED engine will be further strengthened by developing SCED mode for inclusion of Central (ISGS) share under intrastate SCED model, thereby allowing to analyze the potential of co-optimizing the ISGS share of the State while respecting the contractual obligations including DISCOM requisition from ISGS.
- *Treatment of same VC generators*: SCED engine will strengthen the treatment of generators/subcontracts with same VC through scientifically supported approach with due consideration of prevailing regulatory and contractual constraints.
- *Hydro generation scheduling*: Hydro scheduling, which is currently treated as must run for the DISCOM requisition quantum with the remaining margin within its DC remains unavailable for optimal scheduling. The unutilized margin from hydro is used as the last resort to maintain LGB. Scheduling of hydro, which is currently coming as a must run input to the SCED engine, will be integrated with the intrastate SCED model.
- *Enhancement of transmission constraint modelling*: Modelling of transmission constraints will be strengthened by incorporation of detailed network constraints/limits in the SCED engine, thereby enabling direct handlining of the transmission constraints instead of indirect treatment.

Strengthening of IT and Data Visualization Infrastructure:

- The dashboard will be further enhanced by developing stakeholder-oriented interface in line with current practice for MoD mechanism.
- Visualization and report generating features of the dashboard will be further strengthened.
- Data handling capability of the dashboard will be strengthened with a dedicated focus on ease of data handling including online plotting, online report generation, streamlining data extraction from the dashboard and/or from the backend data storage.

Annexures

SCED Regulatory Order of MERC

Before the
MAHARASHTRA ELECTRICITY REGULATORY COMMISSION
World Trade Centre, Centre No.1, 13th Floor, Cuffe Parade, Mumbai 400005
Tel. 022 022 6987 6666
Email: mercindia@merc.gov.in
Website: www. merc.gov.in

Date: 29 April 2025

CORAM: Sanjay Kumar, Chairperson
Anand M. Limaye, Member
Surendra J. Biyani, Member

IA 43 of 2025 in Case No. 51 of 2025

Interlocutory Application of Maharashtra State Load Despatch Centre seeking urgent listing of Case No. 51 of 2025 - for seeking approval for a regulatory sandbox to conduct pilot operation of Intra-State Security Constrained Economic Despatch (SCED) for optimizing power despatch in Maharashtra in online mode

Maharashtra State Load Despatch Centre (**MSLDC**) ..... **Petitioner**

Vs

1. Maharashtra State Electricity Distribution Co. Ltd. (**MSEDCL**)
2. Brihanmumbai Electric Supply and Transport Undertaking (**BEST**)
3. Adani Electricity Mumbai Limited – Distribution (**AEML-D**)
4. Tata Power Company Limited – Distribution (**TPC-D**)
5. AEML SEEPZ Ltd. (**ASL**)
6. Indian Railways (**IR**)
7. Gigaplex Estate Pvt. Ltd. (**GEPL**)
8. Mindspace Business Parks Pvt. Ltd. (**MBPPL**)
9. KRC Infrastructure and Project Pvt. Ltd. (**KRC**)
10. Nidar Utilities Panvel Ltd. Liability Partnership (**Nidar**)
11. EON Kharadi Infrastructure Pvt. Ltd. (**EON SEZ Phase I & II**)
12. Maharashtra Airport Development Company Ltd. (**MADC**)
13. Laxmipati Balaji Supply Chain Management Ltd. (**LBSCML**)
14. M/s Jawaharlal Nehru Port Authority (**JNPA**)
15. SEZ Bio-Tech Services Pvt Ltd. (**Manjari SEZ and Manjari SEZ**)
16. Adani Dahanu Thermal Power Station (**ADTPS**)
17. Tata Power Company Limited – Generation (**TPC-G**)

18. Adani Power Ltd. – (**APL**)
19. M/s. Daund Sugar Pvt. Ltd.
20. M/s. Sai Wardha Power Generation Pvt. Ltd. (**SWPGL**)
21. Maharashtra State Power Generation Co. Ltd. (**MSPGCL**)
22. M/s. Jindal Power Ltd.
23. M/s. JSWEL, Ratnagiri,
24. M/s Omsairam Steel & Alloys Pvt Ltd.,
25. M/s. RattanIndia Power Ltd.
26. M/s. Shree Siddheshwar Sahakari Sakhar Karkhana Ltd.
27. M/s. Shri Ambalika Sugar Pvt.Ltd.
28. M/s. Topworth Urja & Metals Ltd.
29. M/s. Ideal Energy Projects Ltd (**IEPL**)
30. M/s Lloyds Metals and Energy Ltd.
31. M/s Sanvijay Alloys & Power Ltd. ..... **Respondents**

Appearance:

For the Petitioner	: Shri Shashank Jewalikar (Rep.)
For MSEDCL	: Adv. Shashwat Kumar
For BEST	: Shri M.M. Rane (Rep.)
For AEML-D	:Shri Ranjit Sawardekar (Rep.)
For TPC -D	: Shri Vidyadhar Wagle (Rep.)
For ADTPS	: Shri Chintan Mankad (Rep.)
For APL	
For IEPL	: Shri Sandip Kawale (Rep.)

Daily Order

1. Heard the Advocates/Representatives for the Petitioner and the Respondents.
2. The Petitioner reiterated its submissions as made in its Interlocutory Application filed for an early hearing in its main Petition in Case No. 51 of 2025 and briefly elaborated on the offline studies it undertook for the introduction of SCED (Security Constrained Economic Dispatch) in the State and the pilot run operation for the said Intra-State SCED, which it intends to commence pilot run for six months before its full-fledged implementation. The Petitioner also stated that the Energy Department of the

Government of Maharashtra has included the SCED Pilot project in its 100 Days implementation and hence requested for urgent interim approval.

3. The Commission notes that none of the respondents present during the E-Hearing raised any objection to the prayer of MSLDC seeking approval to conduct a six months online pilot run operation on Intra-State SCED without affecting existing real-time scheduling operations, which will enable MSLDC to evaluate the potential benefits of SCED and provide key insights for its future full-scale implementation in the State.

4. Accordingly, the Commission allows MSLDC to go ahead with the six-month online pilot run on Intra-State SCED as requested, with due coordination with all the concerned stakeholders and without affecting the present real-time scheduling operations under the MERC (Deviation Settlement Mechanism and Related Matters) Regulations, 2019.

5. After completion of the SCED pilot run operation, MSLDC shall come out with the detailed report on the outcome of the pilot run operation, benefits of SCED implementation, difficulties faced, stakeholders' concerns/feedback and way forward/suggestions for full-fledged implementation of SCED in the State. The report shall be shared with the Stakeholders by MSLDC. In the meantime, the stakeholders may submit their replies on the present Petition and also the responses/feedback on the pilot run implementation. After receipt of the MSLDC's above report and stakeholders' feedback and replies, the Commission shall decide further course of action in the main matter (Case No. 51 of 2025).

With the above, IA No. 43 of 2025 in Case No. 51 of 2025 for urgent listing stands disposed of.

Sd/-	**Sd/-**	**Sd/-**
(Surendra J. Biyani)	**(Anand M. Limaye)**	**(Sanjay Kumar)**
Member	**Member**	**Chairperson**

(Dr. Rajendra G. Ambekar)
Secretary

MSLDC Orders Related to SCED Pilot Implementation

- **MERC Order Case No 202 of 2020**

  Link: https://merc.gov.in/wp-content/uploads/orders_data/2021/Order%201622211917250.pdf

MAHARASHTRA ELECTRICITY REGULATORY COMMISSION
13th Floor, Centre no. 1, World trade Centre, Cuff Parade, Mumbai-400 005
Tel. No. 022-22163964/65/69,
E-mail: mercindia@merc.gov.in
Website: www.merc.gov.in

Case No. 202 of 2020

In the matter of

Report submitted by the High Level Committee appointed by the Commission for enquiry into Grid Failure occurred in the Mumbai Metropolitan Region on 12 October 2020 at 10.02 Hrs.

Coram

Sanjay Kumar, Chairperson
I.M. Bohari, Member
Mukesh Khullar, Member

ORDER

Date: 28 May 2021

1. A partial grid failure occurred in Mumbai Metropolitan Region (**MMR**) on 12 October 2020 at 10:02 hours, due to outages and tripping of multiple 400 kV Extra High Voltage (**EHV**) Transmission Lines interconnected to the Mumbai Transmission System. The outage/tripping of these 400 kV lines also resulted in cascade tripping of several 220 kV lines transmitting electricity to MMR and the embedded generating units within MMR which affected the supply to a large part of MMR (loss of 3508 MW loads) for about 1.5 hours in critical areas of South and North Mumbai (restored at 11.40 Hrs) and about 6 hours in majority areas of Mumbai (restored at 15.24 Hrs) . The complete restoration of loads in MMR took about 32 Hrs(restored at 17.29 Hrs on 13 October, 2020) .
2. As required under the Regulation 46.1.1 and 46.2.4 of MERC (State Grid Code) Regulations, 2020 (**Grid Code Regulations**), Maharashtra State Load Despatch Centre (**MSLDC**) and Mumbai Utilities submitted their respective reports on the aforesaid partial grid failure. Taking cognizance of the occurrence, the Commission initiated a Suo-Motu proceeding in Case No. 202 of 2020 under Regulation 32 of the MERC (Conduct of Business) Regulations, 2004, to identify the primary reasons for the partial grid failure, response, and performance of the Licensees/Generators, and identify the corrective/preventive measures to minimise chances of the recurrence of such events.
3. The Commission in its Suo-motu Order dated 22 October 2020 in Case 202 of 2020 has observed that, it was important to examine as to whether all concerned entities including MSLDC had acted/responded during the grid disturbance effectively and in a timely manner consistent with their respective roles and responsibilities laid down under the Grid Code Regulations. It was necessary to find out the system/infrastructure adequacy (or the improvements required) and also as to what happened at every stakeholder level and what needed to be done in future at individual stakeholder level and collectively at systems level to

18.13. Exploring Avenues for improvement in Embedded Generation Mix and other Innovations.

HLC's Recommendations

18.13.1. Scheduling of embedded generation needs to be done considering the criticality of ATC at that point of time. As one alternative, Security Constrained Economic Despatch (SCED) and Security Constrained Unit Commitment (SCUC) can be implemented while scheduling the embedded generation similar to SCED in operation at the regional level. SCED/SCUC can be used to determine how much embedded generation is required and at which locations in the Mumbai area to ensure survival of the islanding scheme. This is specially to revise the generation schedule due to tripping of lines bringing power to Mumbai, resulting in the reduction of ATC for import of power into Mumbai.

18.13.2. Further, there are limitations for capacity addition to conventional embedded generation within Mumbai, and the transmission capability of interconnections to the Mumbai system is presently limited until the completion of various projects suggested by earlier committees and those planned by the STU. The embedded generation within Mumbai could also be augmented by installing rooftop PV systems, waste to energy power plants, and energy storage devices. The options of virtual transmission systems like BESS may also be explored to meet the partial requirement of peak demand to manage transmission loading. HLC has recommended to explore the avenues for improvement in the embedded generation mix and other innovations by harnessing Rooftop Solar PV potential within the MMR area, installation of waste to energy power plants in the MMR area and use of Battery Energy Storage Systems at critical locations within the MMR transmission network to harness various benefits of ESS for system operations such as ancillary, balancing support and congestion management.

MSLDC's Submission

18.13.3. As regards implementation of SCED, MSLDC submitted that, for Generator scheduling under SCED, Regulation 35 of the Grid Code Regulations needs to be modified.

TPC's Submission

18.13.4. Importance of embedded generation to meet the critical load in Mumbai cannot be ruled out and subjecting Mumbai to heavy load shedding could not be a feasible option. Hence, suitable mechanisms to share this generation among all constituents should be worked out.

18.13.5. With regard to implementation of SCED, TPC submitted that, while implementing the SCED, the commercial interest of Discoms and Generators should be adequately addressed and options for other ancillary services mechanism may also be explored.

Commission's Ruling

18.13.6. The Commission notes the HLC's recommendation as regards SCED/SCUC operations and opines that MSLDC should explore technical feasibility of the same and undertake preparatory steps necessary for implementation of SCED and SCUC while scheduling the embedded generation, especially in view of the limitation of ATC into MMR area under prevalent circumstances. The Commission directs MSLDC to study the feasibility of implementation of SCED and SCUC and approach the Commission for necessary approval within six months from the date of this Order.

18.13.7. As regards long term planning of generation resource and optimal capacity expansion planning and optimal power system operations is concerned, the Commission opines that the same should be guided by Generation Resource Planning framework and Integrated Resource Plans, as specified under Regulation 11 of MERC (State Grid Code) Regulations, 2020. The relevant extracts of the Regulation 11 are as under:

11. Generation Resource Planning

i. Each Distribution Licensee shall ensure demonstrable resource adequacy as specified by the Commission for the next five (5) years starting from 1st April of the next year. Resource adequacy can be met using short-term, medium and long term capacities available for Round the Clock (RTC), peak and off-peak

durations. Adequacy statement containing a list of such resources along with associated capacities shall be submitted to the STU by 31 December of each year and made publicly available on its website. Efforts to shift load, inter-DISCOM banking and storage should also be considered while preparing the adequacy statement. The adequacy statement should be revised every year in the five-year period and monthly reports should be submitted to the STU regarding compliance with the adequacy statement.

ii. Based on the generation resource plans of distribution licensees, STU in consultation with SLDC shall develop Integrated Resource Plan for next five years for the state. While developing such Integrated Resource Plan, STU shall use appropriate power system modelling tools and may consider the following from grid operation perspective:

a. Generation flexibility, ramping and minimum turndown level and start-stops.

b. Requirement of energy storage systems and demand response measures

c. Generation reserve requirement

d. System inertia for grid stability

e. Fuel security

iii. STU shall submit such Integrated Resource Plan for the state to CTU in line with requirements specified under IEGC.

18.13.8. The Commission concurs with the recommendation of HLC for exploring avenues for augmentation in embedded generation within Mumbai by installing rooftop PV systems, waste to energy power plants, and energy storage devices. The Commission observes that regulatory framework for implementation of rooftop PV systems and waste to energy power plants is already in place by way of RE Tariff Regulations, RPO Regulations and several other regulatory orders and there are well established precedents for project implementation based on these technologies and resources. The licensees and stakeholders would benefit from such precedents. However, deployment of energy storage devices, particularly, battery energy storage systems is at nascent stage, for the utility scale storage and transmission/grid applications. Licensees and stakeholders could explore pilot scale projects to assess and ascertain and harness its benefits, particularly at utility scale for power / transmission system applications.

- **FOLD 48th Meeting**

  Link: https://webcdn.grid-india.in/files/fold/uploads/download-manager-files/Minutes%20of%2048th%20FOLD%20Meeting.pdf

9. Agenda-8: "My-SCED" project for implementation of SCED at the State level

A pilot project on Security Constrained Economic Despatch Pan-India covering 52 thermal ISGS with 58 GW capacity was operationalized by GRID-INDIA starting 1st April 2019. A robust, integrated SCED software application was developed in-house, which runs every 15 minutes on 24x7 basis to optimize the all-India variable cost of generation, while fulfilling grid security constraints. The pilot has been expanded w.e.f. 1st June 2020, opening participation to all willing generators. Security constraints have been strengthened with incorporation of bidirectional Available Transfer Capability (ATC) and counter dispatch for correcting inter-regional ATC violations. Generator minimum and maximum evacuation limits have been introduced for addressing local security violations. For ensuring that generators do not see any ramp violation in schedules when they are excluded, soft landing feature has been developed and introduced. For handling of different SCED stop under different scenarios, scheduled and emergency stop functionalities have been developed.

The schedules of beneficiaries are not changed on account of SCED. Buyers or beneficiaries continue to pay the charges for the scheduled energy directly to the generating stations participating in the SCED. Gains from the SCED process shall be accumulated into the "SCED Account" and are being shared with generating stations and their beneficiary states. For any increment in the generation schedule on account of SCED, the participating generator is paid from the 'SCED Account' at the rate of its energy charge or SCED Compensation Charge declared upfront by the generator. For any decrement in the generation schedule on account of SCED, the participating generator pays to the 'SCED Account' at the rate of energy charge or SCED Compensation Charge, as applicable. The net savings shall be shared between the beneficiaries or buyers and the generating stations as per a gain sharing mechanism. Part load compensation for a reduction in the schedule on account of SCED is paid from the savings in the SCED Account.

National Load Despatch Centre (NLDC) has prepared and submitted several detailed feedback reports to CERC covering various aspects of the SCED operation. With the implementation of Indian Electricity Grid Code 2023 from 1st October 2023 onwards, SCED has moved from pilot phase and is now an inherent part of the scheduling and despatch process. In addition to SCED, the IEGC-2023 also contains provisions for Security Constrained Unit Commitment (SCUC), which has been implemented from April 2024 onwards.

As of August 2024, a total of 52 plants with installed capacity of 63420 MW form part of the SCED optimization. Around ₹4000 crores national savings have been done through SCED since April 2019. These savings have been transparently shared between the generating stations and beneficiaries transparently. All the accounts and records are available in public domain.

A rough estimation of the potential of intra-state SCED by Grid-India is valued at around ₹4000 crores per annum at the all-India level, which roughly translates to 0.5%-0.7% of the annual variable production cost. More than the savings, the intangible benefits that are provided by SCED implementation hold vital importance –

a. SCED is an advanced application to merit order despatch (MOD) as it simultaneously factors constraints viz., ramp rates, energy charges, load generation balance, transfer capability margins, and any other limits needed. SCED is also superior to MOD in handling congestion and retrieving the marginal cost information.
b. Optimization algorithm used in SCED justifying and covering any inefficiency in manual load despatch decision.
c. Improved automation for facilitating SCED
d. SCED implementation also gives by products such as the improved reporting infrastructure through customized charts, tables, and duals (shadow prices) of the constraints, which would be helpful for the senior management in taking policy level decisions.

e. Strict gate closures timelines can be implemented, which can open new doors for Ancillary Services, flexibility initiatives, efficient grid management considering high penetration of renewables.

Implementation of Intra-state SCED has huge potential of economic savings and therefore, a new collaborative project titled "My-SCED" is proposed by FOLD. In this project, FOLD welcomes all the interested states to take initiatives for implementing SCED in-house customized at the state level. Each State may kindly create a dedicated group constituting of executives/officers from these preferable backgrounds-

- Scheduling and Despatch – for facilitating scheduling changes
- Market operations and regulatory aspects
- Computer Science, IT, Communication – for facilitating data exchange, and developing portals, cybersecurity.
- Heads, contracts/procurement departments – for facilitating any procurement requirements or changes in the existing scheduling software, although SCED algorithm can be preferably developed in-house

The following activities are proposed to be taken up during the "My-SCED" project –

i. Technical support through online workshops
ii. Interactions with national and international experts
iii. Shared resources, publications folders, and sample code directories would be made available
iv. Short deputations of resource personnel for training/brainstorming
v. Regular progress tracking will be done through FOLD secretariat. The intra-state SCED project may be targeted to be completed in a time bound fashion at all the interested states by 2025

The information regarding the nominated officers may be provided to FOLD Secretariat at the earliest by the interested states through Head of SLDC.

FOLD Secretariat

- **FOLD 49th Meeting**

  Link: https://webcdn.grid-india.in/files/fold/2025/10/Final%20Agenda_49th%20FOLD%20Meeting_449_458.pdf

E) Agenda-3: Intra-State SCED Implementation in Maharashtra (MySCED Project)

SLDC Maharashtra gave a presentation to share the findings from the studies related to intrastate SCED (using one-month historical data) under the MySCED project. He said that the pilot project was undertaken in collaboration with IIT Bombay, World Bank and GRID-INDIA. He highlighted the economic and operational benefits of transitioning from a merit-order dispatch (MOD) to a security-constrained economic dispatch (SCED) in the State of Maharashtra. He shared that key observations include cost savings of ₹2-4 lakhs per hour during peak operations and better integration with real-time electricity markets, such as RTM and power exchanges. The project is expected to unlock ₹300 Cr in annual savings while aligning Maharashtra's dispatch strategies with IEGC 2023 standards.

The project has identified significant opportunities to reduce system operation costs, improve renewable energy integration, and enhance the reliability of Maharashtra's grid. SLDC Maharashtra plans to integrate SCED in real-time operations, allowing better grid management and cost savings.

All members appreciated the efforts being done by SLDC Maharashtra and emphasized the replication of this model in other states.

Action Points:

- All SLDCs could consider implementation of intra State SCED in their respective States.
- Intra-state SCED with multiple States could also be explored.

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Security Constrained Economic Despatch - Indian Context

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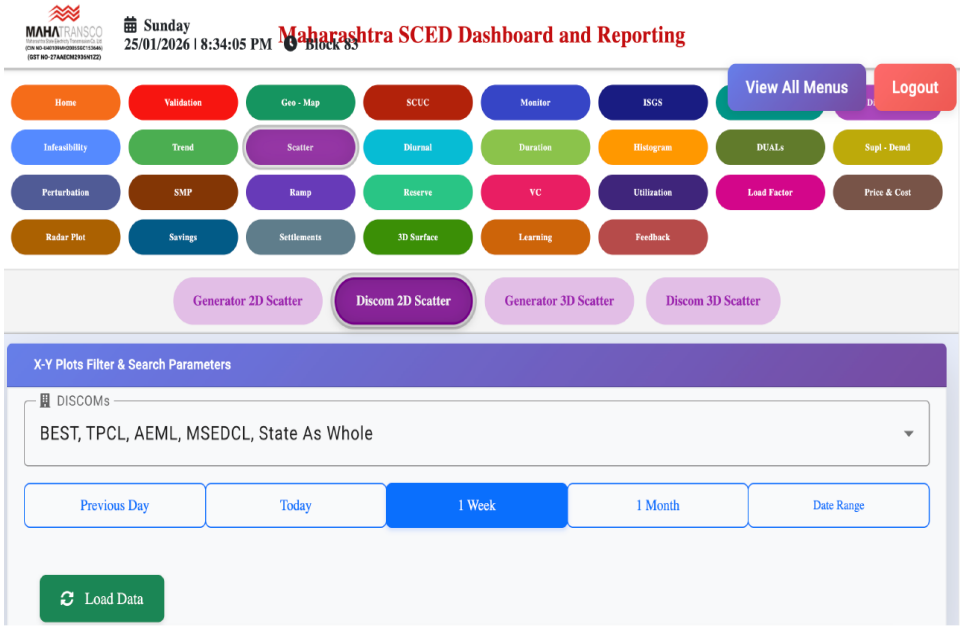
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Dashboard Snapshots and Descriptions

SCED Dashboard Reporting





Drop down list for Generators

Generator-wise (X-Axis and Y-Axis)

C. DC Marginal (₹/unit)	D. Ramp Down Penalty (₹)
C. MOD Schedule (MW)	D. Ramp Down Short (MW)
C. Non Spin Reserve Up (MW)	D. Ramp Up Marginal (₹/unit)
C. Ramp Down Marginal (MW)	D. Ramp Up Penalty (₹)
C. Ramp Down Short (MW)	D. Ramp Up Short (MW)
C. Ramp Down Short Penalty (₹)	D. Savings (₹)
C. Ramp Up Marginal (MW)	D. SCED Cost (₹)
C. Ramp Up Short (MW)	D. SCED Perturbation (MW)
C. Ramp Up Short Penalty (₹)	D. SCED Ramp Reserve Down (MW)
C. SCED Cost - D. SCED Cost (₹)	D. SCED Ramp Reserve Up (MW)
C. SCED Cost (₹)	D. SCED Schedule - D. MOD Schedule (MW)
C. SCED Perturbation (MW)	D. SCED Schedule (MW)
C. SCED Ramp Reserve Down (MW)	D. SCED Spin Reserve Down (MW)
C. SCED Ramp Reserve Up (MW)	D. SCED Spin Reserve Up (MW)
C. SCED Schedule - C. MOD Schedule (MW)	D. TechMin Marginal (₹/unit)
C. SCED Schedule (MW)	D. Translimit Marginal (₹/unit)
C. SCED Spin Reserve Down (MW)	Date
C. SCED Spin Reserve Up (MW)	DC MOD Engine (MW)
C. SCED VSE (MW)	DC SCED Engine (MW)
C. TechMin Marginal (₹/unit)	Ex-bus Capacity (MW)
C. Translimit Marginal (₹/unit)	Installed Capacity (MW)
D. DC Marginal (₹/unit)	MOD Rate (₹/kWh)
D. MOD Cost (₹)	MOD VSE (MW)
D. MOD Perturbation (MW)	Non Spin Reserve (MW)
D. MOD Ramp Reserve Down (MW)	PMax (MW)
D. MOD Ramp Reserve Up (MW)	PMin (MW)
D. MOD Schedule (MW)	Ramp Down (MW/TB)
D. MOD Spin Reserve Down (MW)	Ramp Up (MW/TB)
D. MOD Spin Reserve Up (MW)	Tech Min (MW)
D. Ramp Down Marginal (₹/unit)	Time Block

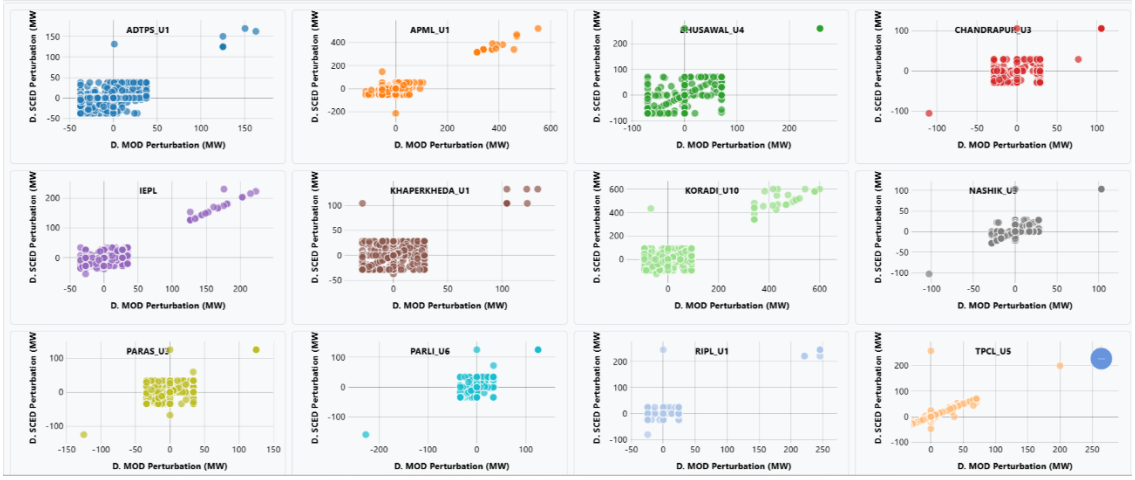
Drop down list for DISCOMS

DISCOM-wise (X-Axis and Y-Axis)

Average MOD Rate - Average SCED Rate (₹/kWh)	D. MOD Ramp Reserve Up (MW)
C. Excess Generation (MW)	D. MOD Spin Reserve Down (MW)
C. Excess Generation Penalty (₹)	D. MOD Spin Reserve Up (MW)
C. Non Spin Reserve Up (MW)	D. SCED Average Rate (₹/kWh)
C. Ramp Down Penalty (₹)	D. SCED Cost (₹)
C. Ramp Down Short (MW)	D. SCED Cost Without Penalty (₹)
C. Ramp Up Penalty (₹)	D. SCED Ramp Reserve Down (MW)
C. Ramp Up Short (MW)	D. SCED Ramp Reserve Up (MW)
C. SCED Cost - D. SCED Cost (₹)	D. SCED Schedule (MW)
C. SCED Cost (₹)	D. SCED Spin Reserve Down (MW)
C. SCED Ramp Reserve Down (MW)	D. SCED Spin Reserve Up (MW)
C. SCED Ramp Reserve Up (MW)	D. Shortfall (MW)
C. SCED Schedule (MW)	D. Shortfall Penalty (₹)
C. SCED Spin Reserve Down (MW)	D. SMP (₹/kWh)
C. SCED Spin Reserve Up (MW)	DAM (MW)
C. SCED Total VSE (MW)	Date
C. Short Fall (MW)	Forecasted Demand (MW)
C. Short Fall Penalty (₹)	Hydro Requirement (MW)
C. SMP (₹/kWh)	Intra DISCOM Trade (MW)
Centre (MW)	Intra State Non-MOD (MW)
D. Excess Generation (MW)	MOD & Non-MOD Total Schedule (MW)
D. Excess Generation Penalty (₹)	MOD Schedule (MW)
D. MOD Average Rate (₹/kWh)	MOD Surplus/Shortfall (MW)
D. MOD Cost - D. SCED Cost (₹)	Non Spin Reserve REMC (MW)
D. MOD Cost (₹)	RTM (MW)
D. MOD Ramp Reserve Down (MW)	Time Block

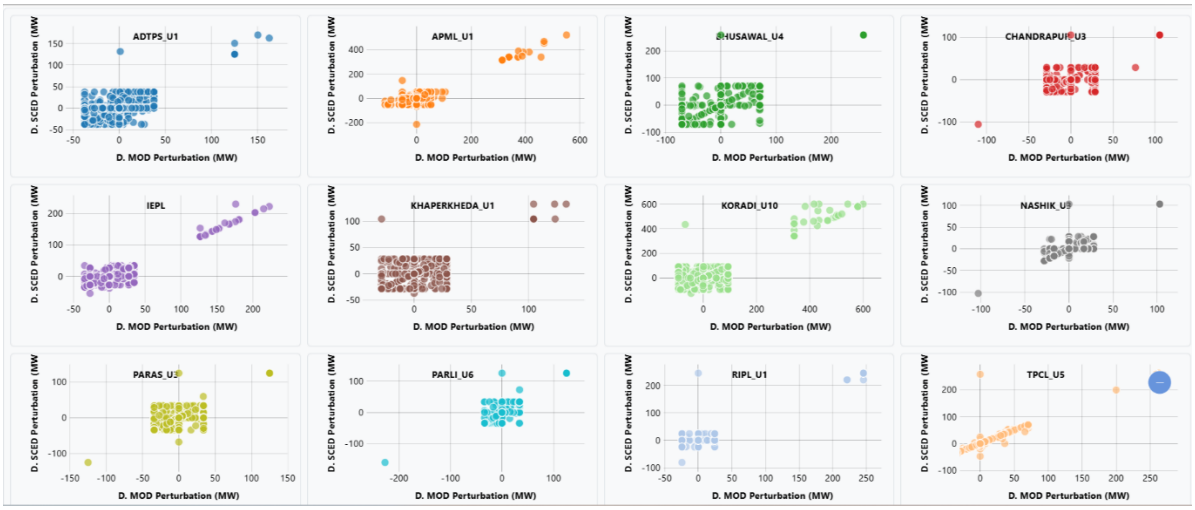
Generator-wise SCED cost vs MOD Cost

01.12.2025 to 31.12.2025



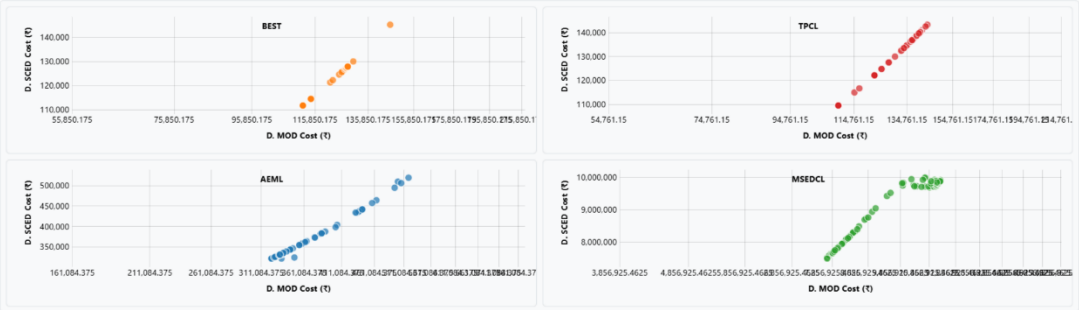
Generator-wise SCED vs MOD Perturbations

01.12.2025 to 31.12.2025



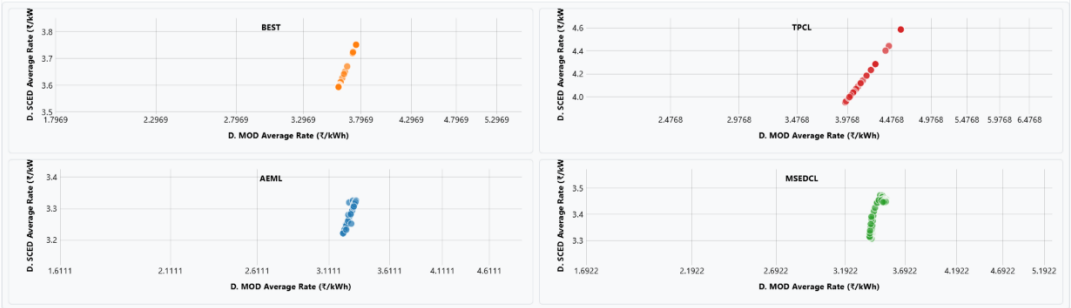
DISCOM-wise SCED vs MOD Cost

01.12.2025 to 31.12.2025

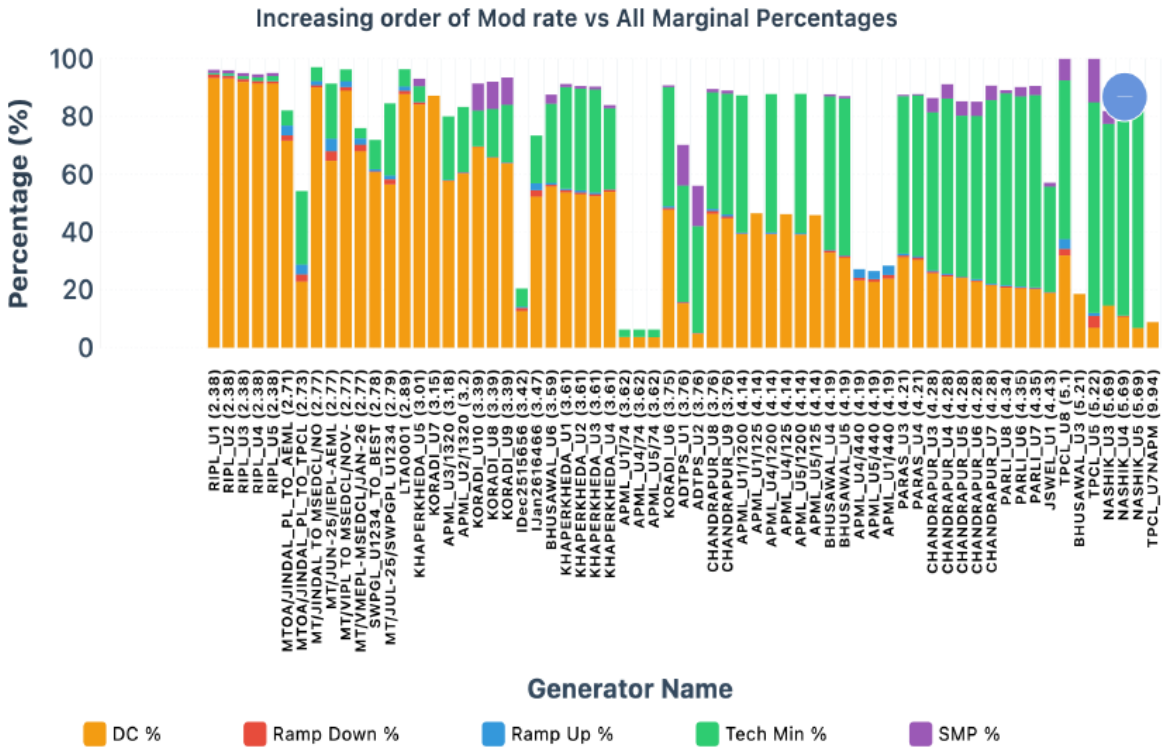


DISCOM-wise SCED vs MOD Average rate

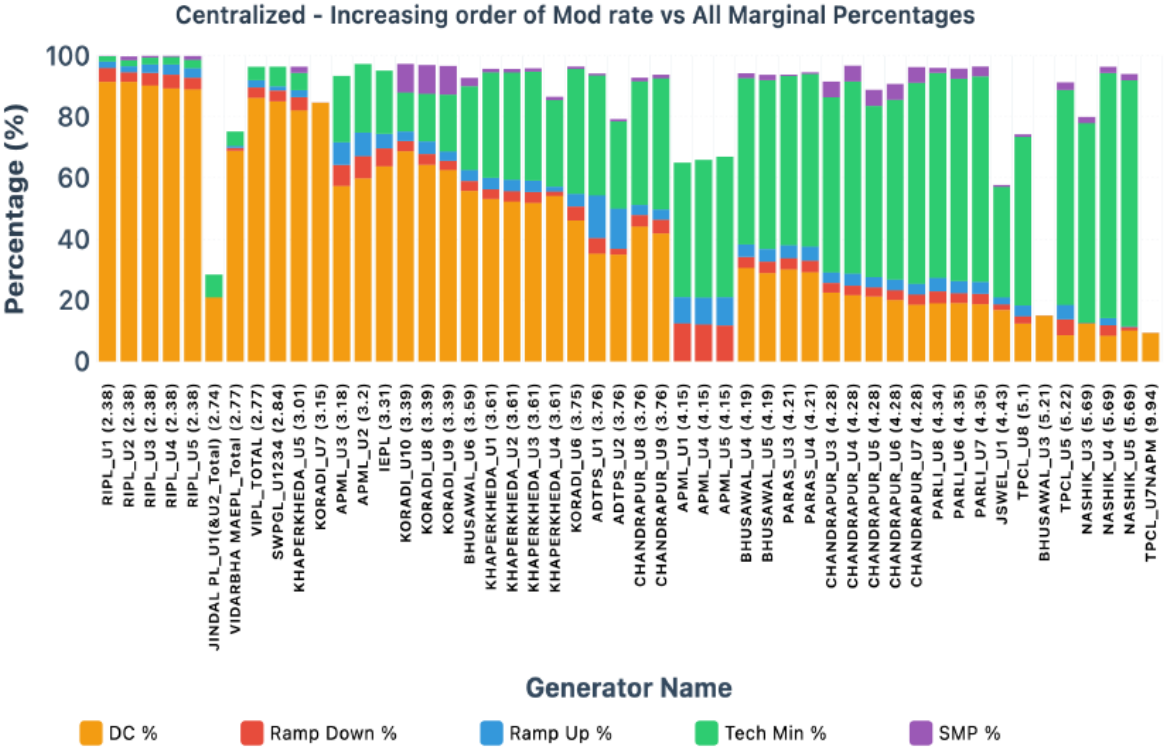
01.12.2025 to 31.12.2025



Decentralized - Histogram Analysis (25/12/2025 - 25/1/2026)

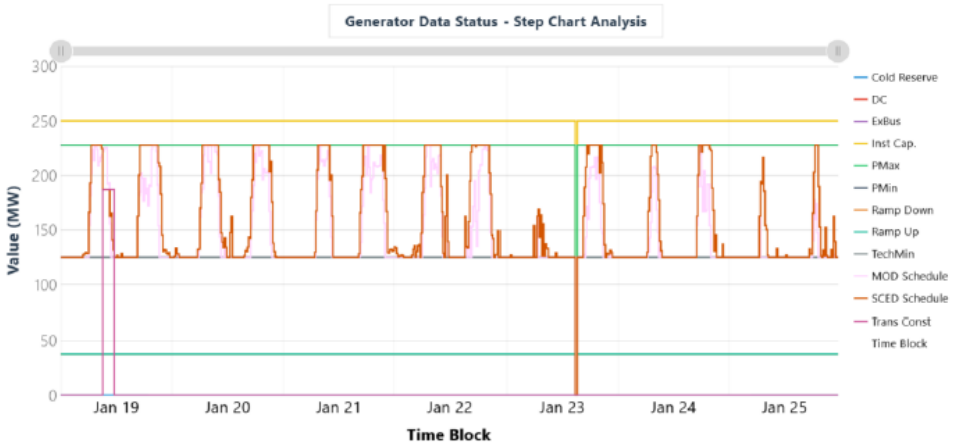


Centralized - Histogram Analysis (25/12/2025 - 25/1/2026)



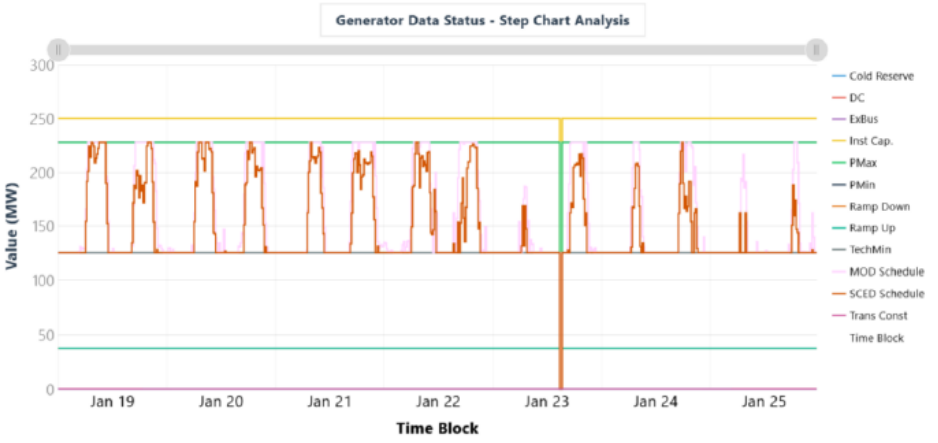
Generator data status - ADTPS_U1

From: 19-Jan-2026 To: 25-Jan-2026



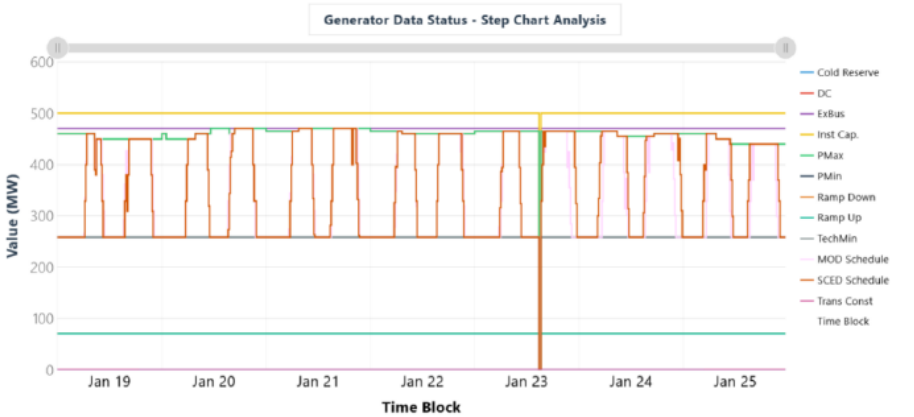
Generator data status - ADTPS_U2

From: 19-Jan-2026 To: 25-Jan-2026



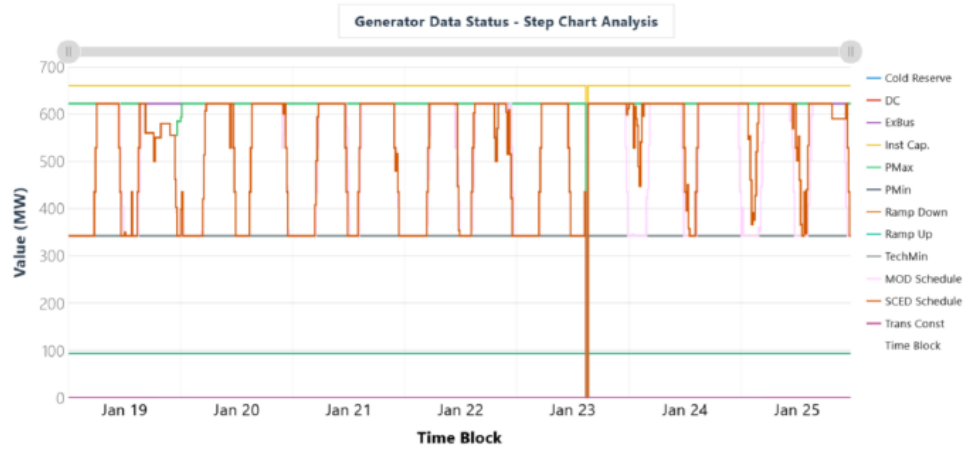
Generator data status - BHUSAWAL_U5

From: 19-Jan-2026 To: 25-Jan-2026



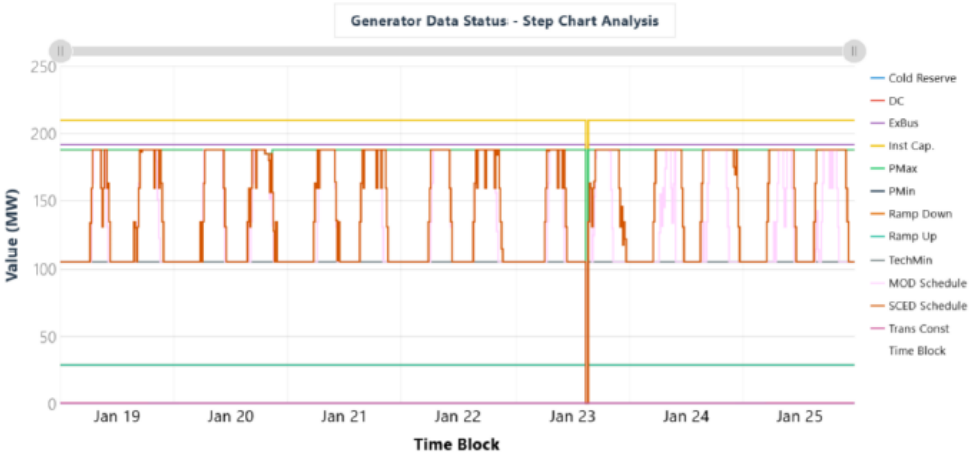
Generator data status - BHUSAWAL_U6

From: 19-Jan-2026 To: 25-Jan-2026



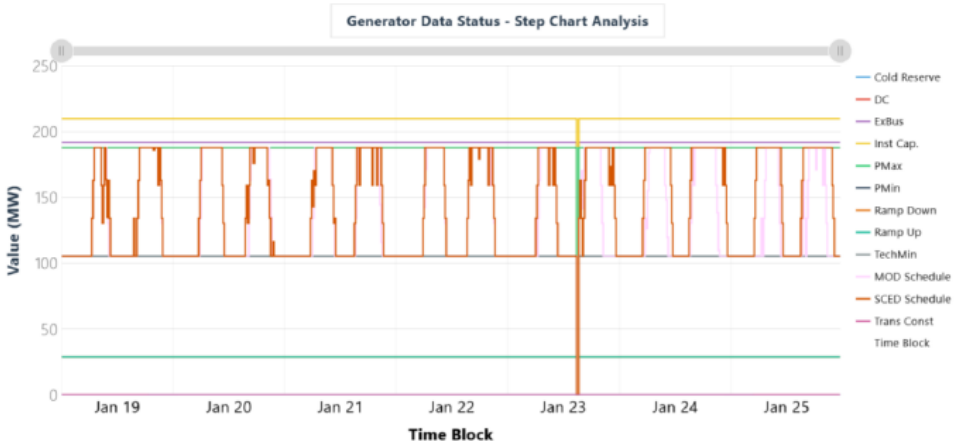
Generator data status - CHANDRAPUR_U3

From: 19-Jan-2026 To: 25-Jan-2026



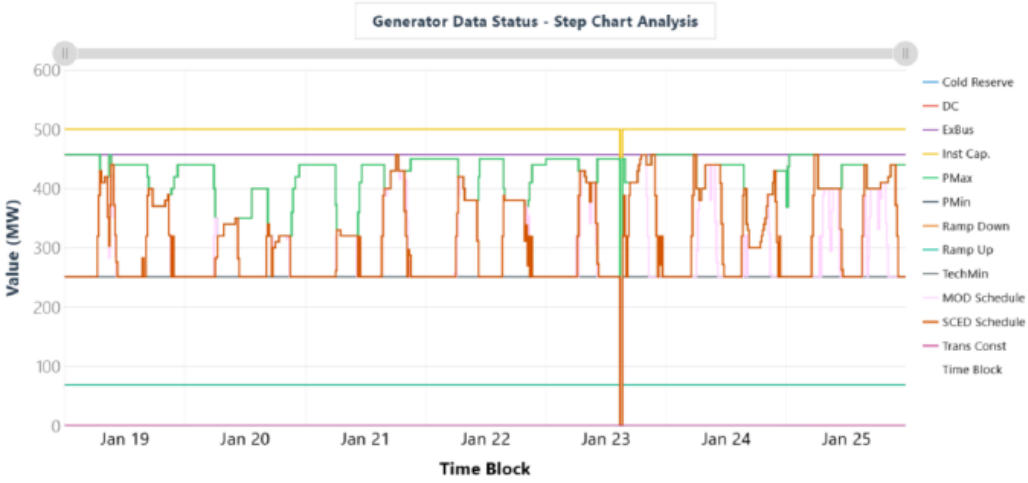
Generator data status - CHANDRAPUR_U4

From: 19-Jan-2026 To: 25-Jan-2026



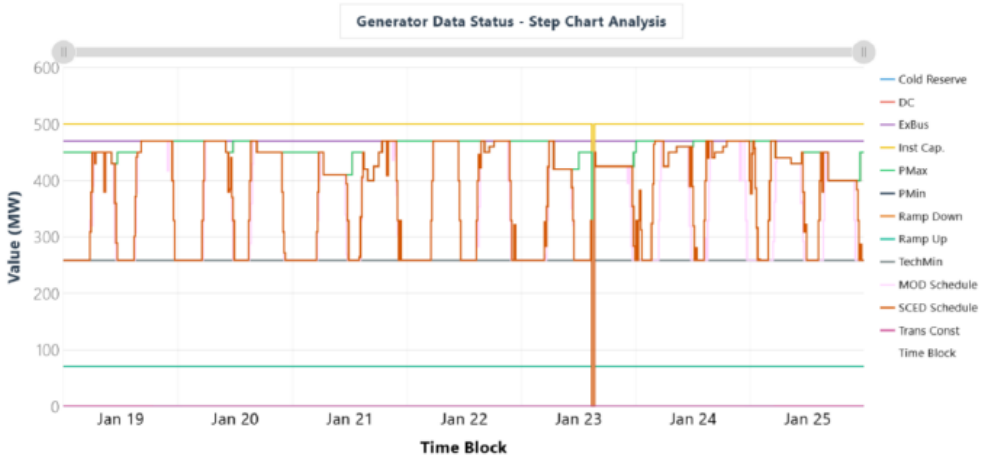
Generator data status - CHANDRAPUR_U7

From: 19-Jan-2026 To: 25-Jan-2026



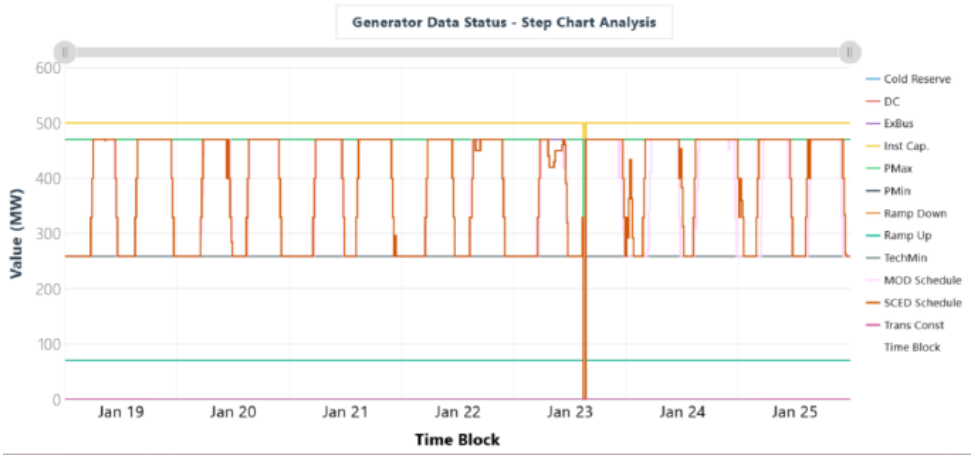
Generator data status - CHANDRAPUR_U8

From: 19-Jan-2026 To: 25-Jan-2026



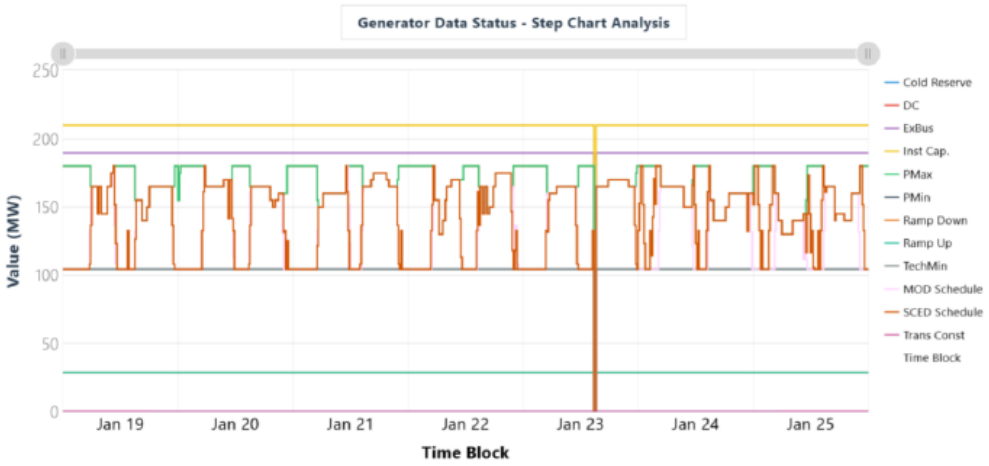
Generator data status - CHANDRAPUR_U9

From: 19-Jan-2026 To: 25-Jan-2026



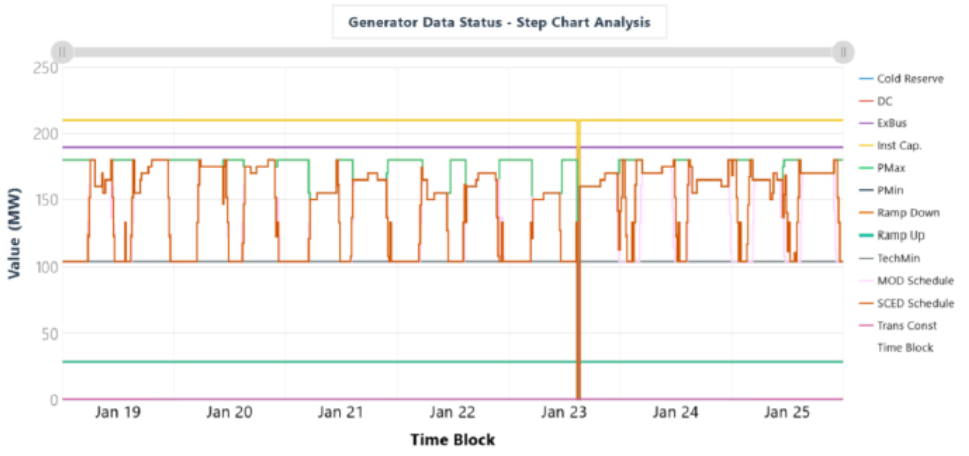
Generator data status - KHAPERKHEDA_U1

From: 19-Jan-2026 To: 25-Jan-2026



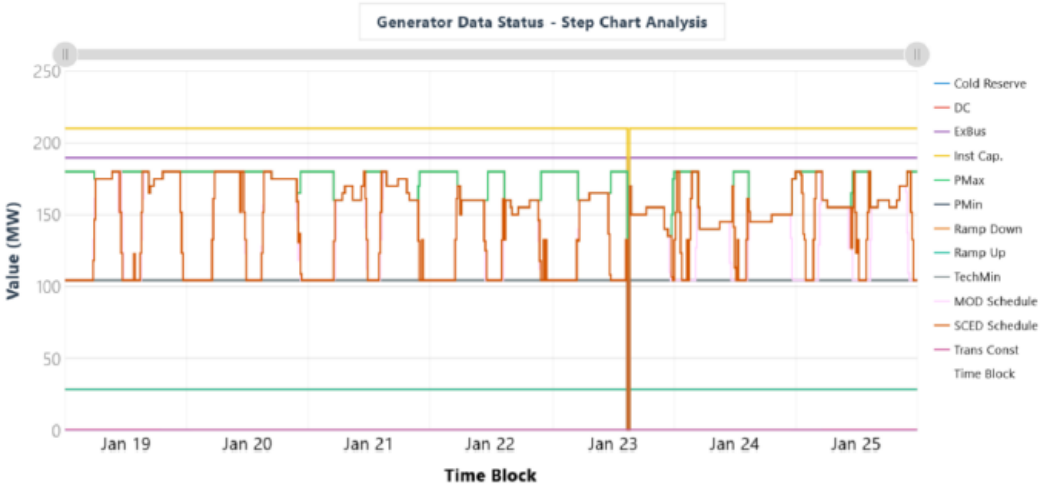
Generator data status - KHAPERKHEDA_U2

From: 19-Jan-2026 To: 25-Jan-2026



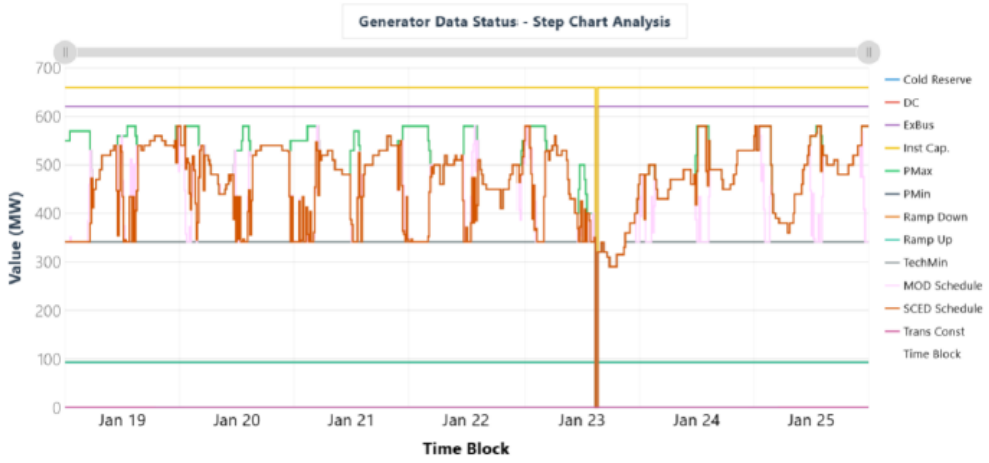
Generator data status - KHAPERKHEDA_U3

From: 19-Jan-2026 To: 25-Jan-2026



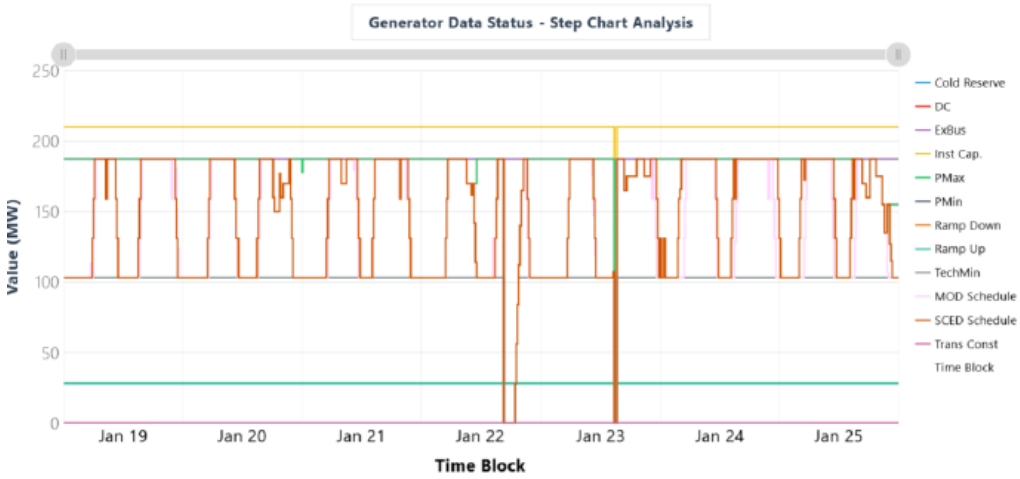
Generator data status - KORADI_U10

From: 19-Jan-2026 To: 25-Jan-2026



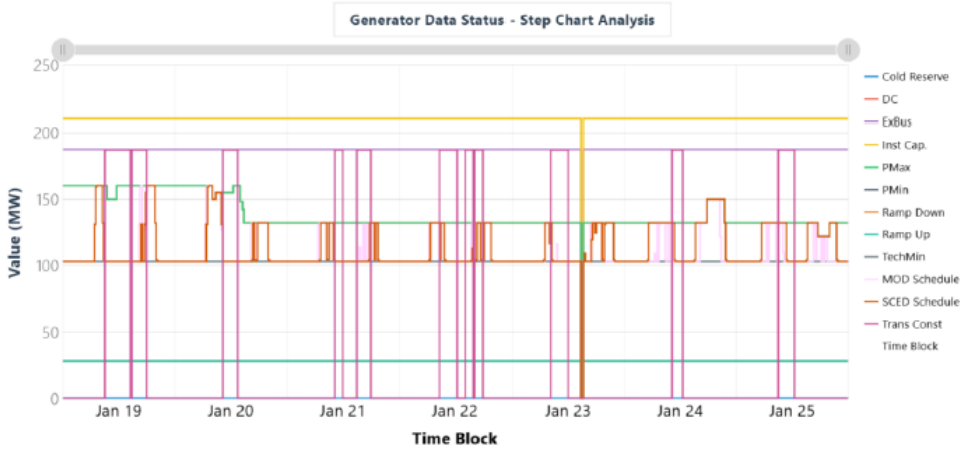
Generator data status - KORADI_U6

From: 19-Jan-2026 To: 25-Jan-2026



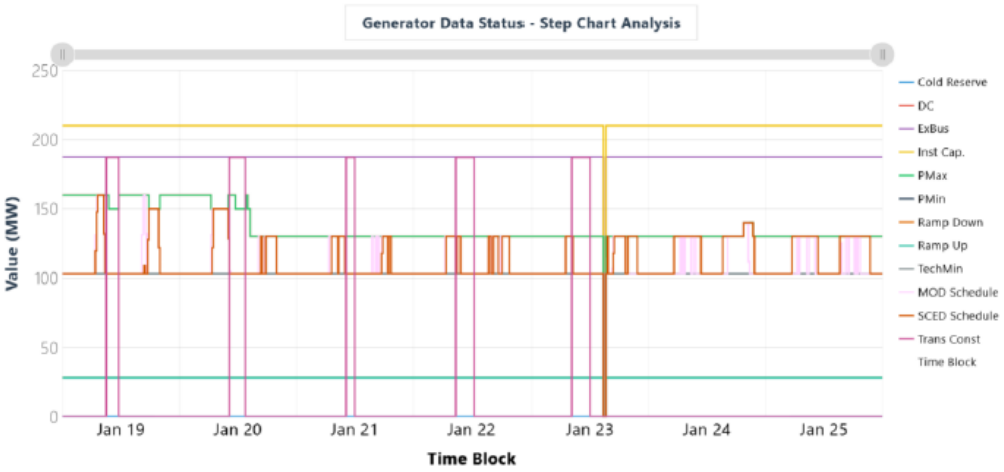
Generator data status - NASHIK_U4

From: 19-Jan-2026 To: 25-Jan-2026



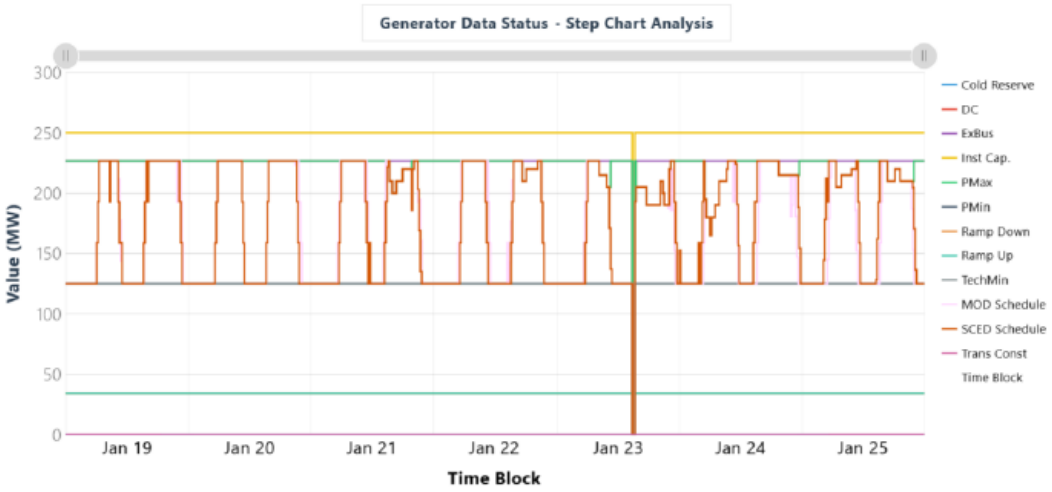
Generator data status - NASHIK_U5

From: 19-Jan-2026 To: 25-Jan-2026



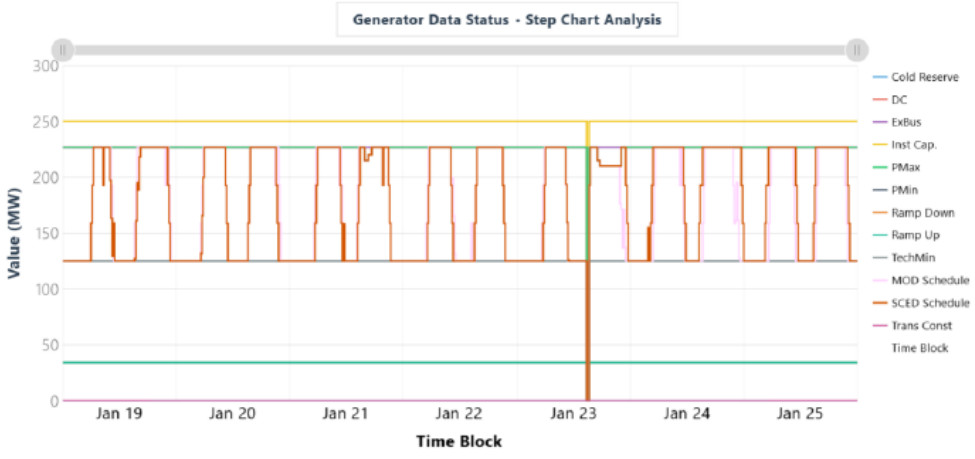
Generator data status - PARAS_U3

From: 19-Jan-2026 To: 25-Jan-2026



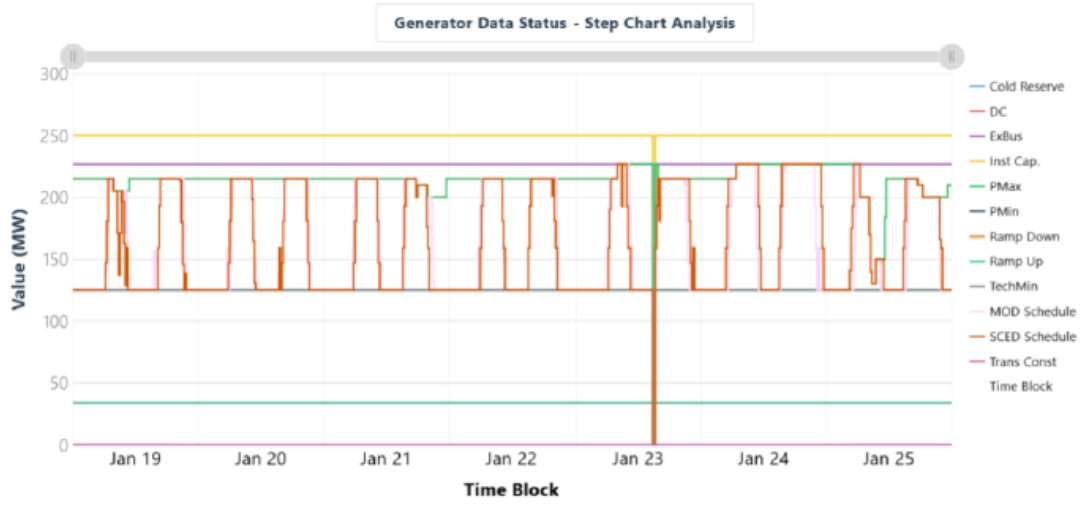
Generator data status - PARAS_U4

From: 19-Jan-2026 To: 25-Jan-2026



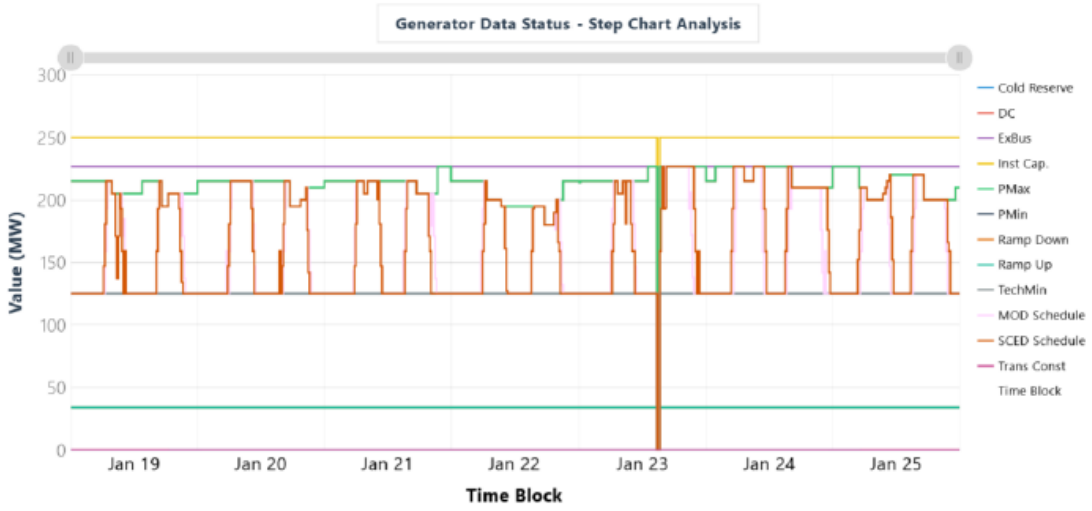
Generator data status - PARLI_U6

From: 19-Jan-2026 To: 25-Jan-2026



Generator data status - PARLI_U7

From: 19-Jan-2026 To: 25-Jan-2026



Acronyms

AEML	Adani Electricity Mumbai Limited
API	Application Programming Interface
BEST	Brihanmumbai Electric Supply & Transport
CCE	Centre for Continuing Education
CEA	Central Electricity Authority
CERC	Central Electricity Regulatory Commission
CSGS	Central Sector Generating Stations
DAM	Day-Ahead Market
DC	Declared Capacity
DISCOM	Distribution Company
DSM	Demand Side Management
FOLD	Forum of Load Despatchers
GAMS	General Algebraic Modelling System
GIL	Grid Integration Laboratory
IEGC	Indian Electricity Grid Code
IEX	India Energy Exchange
IITB	Indian Institute of Technology Bombay
InSTS	Intra-State Transmission System
ISGS	Inter-State Generation System
IT	Information Technology
LMP	Location Marginal Price
LP	Linear Programming

LTOA	Long Term Open Access
MEGC	Maharashtra Electricity Grid Code
MERC	Maharashtra Electricity Regulatory Commission
MOD	Merit Order Despatch
MSEDCL	Maharashtra State Electricity Distribution Co. Ltd.
MSETCL	Maharashtra State Electricity Transmission Co. Ltd.
MSLDC	Maharashtra State Load Despatch Centre
MTOA	Medium Term Open Access
MW	Mega Watts
NLDC	National Load Despatch Centre
OA	Open Access
PX	Power Exchanges
PXIL	Power Exchange India Limited
RE	Renewable Energy
REMC	Renewable Energy Management Centre
RLDC	Regional Load Despatch Centre
RTM	Real-Time Market
S&D	Scheduling and Despatch
SCED	Security Constrained Economic Despatch
SCUC	Security Constrained Unit Commitment
SERC	State Electricity Regulatory Commission
SLDC	State Load Despatch
SMP	System Marginal Price
TB	Time Block
VSE	Virtual State Entity
WRLDC	Western Region Load Despatch Centre

Published by:
MSLDC in Collaboration with Grid Integration Lab (GIL), IIT Bombay

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January 2026

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