A report on

Optimizing Power Despatch

(An initiative towards SCED implementation in Maharashtra)

Maharashtra State Load Despatch Centre
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October 2024

Disclaimer

The findings and recommendations presented in this 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 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.

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Foreword

Maharashtra is advancing steadily on its journey toward an energy transition, preparing to integrate substantial renewable energy resources, especially solar, into the power grid. This transition brings new challenges and opportunities, and with the state's ambitious goals, we recognize the vital role of resources like Pumped Storage Plants in balancing and securing our future energy mix.

The implementation of intra-state SCED (Security Constrained Economic Dispatch) in Maharashtra is a critical step in building the state's capability to manage this evolving landscape efficiently. By optimizing dispatch and enhancing system flexibility, SCED provides a foundation that ensures both cost-efficiency and reliability as we integrate higher shares of renewables.

I commend the proactive, in-house efforts of MSETCL SLDC, as well as the collaborative contributions from IIT Bombay, the World Bank, and various experts. Their commitment has culminated in this evidence-based, data-driven report, which will serve not only as a guide for Maharashtra but for India aiming to achieve a resilient, sustainable energy future.

(Abha Shukla, I.A.S.)

Additional Chief Secretary, Energy, Maharashtra

Foreword

Maharashtra, being one of the largest state power systems in India, plays a crucial role in ensuring energy security and economic optimization for the benefit of consumers. The proactive steps taken by Maharashtra SLDC in launching the intra-state SCED project are commendable.

This forward-looking initiative, supported by MSETCL SLDC, IIT Bombay, the World Bank experts, WRLDC, and NLDC, has culminated in a comprehensive, data-driven report developed over the past six months. This exhaustive effort provides evidence of the substantial savings and numerous intangible benefits achievable through SCED implementation. The report stands as a testament to in-house expertise and India's 'Make in India' and 'Atmanirbhar' vision.

This work will not only benefit Maharashtra but also serve as a valuable reference for other states in India as they embark on similar intra-state SCED initiatives. I am confident that this report will inspire confidence among stakeholders and regulators, offering a solid foundation for a pilot study within a regulatory framework.

Best wishes for the continued success of this remarkable initiative.

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Foreword

As the largest distribution company in Maharashtra, MSEDCL is deeply aware that the cost of power procurement forms the backbone of any DISCOM's financial health. It is imperative that we continuously seek ways to optimize costs while ensuring a reliable supply for our consumers.

The intra-state SCED initiative launched by Maharashtra SLDC marks a pivotal step in this direction. By incorporating advanced techniques such as shadow pricing and marginal cost extraction, this initiative empowers MSEDCL to make informed and optimized buy-sell decisions in the power market. This will not only lead to cost savings but also strengthen our market positioning and operational efficiency.

The collaborative efforts of MSETCL, SLDC, IIT Bombay, the World Bank, WRLDC, and NLDC have resulted in this comprehensive report, which lays out the immense benefits of SCED. The insights gained from this initiative will guide Maharashtra in embracing a more flexible, cost-efficien, and secure energy future.

I extend my best wishes to everyone involved in this forward-thinking endeavour, confident that it will serve as a valuable reference for both MSEDCL and other states exploring similar optimization strategies.

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Message

I am pleased to see that the recent resolution passed in the last Forum of Load Despatchers (FOLD) meeting on My-SCED has been successfully and quickly translated into action by Maharashtra SLDC, with the completion of this case study on implementing intra-state SCED in Maharashtra. This report reflects a significant step toward realizing SCED at the state level, which will serve as a valuable handbook for FOLD as we encourage other states for this initiative.

The security aspects of SCED, including ramp, minimum turn down level, Total Transfer Capability (TTC) and automated scheduling measures, are critical—especially for a large state like Maharashtra. I compliment Maharashtra SLDC for their dedicated efforts in producing this exhaustive and practical guide on SCED implementation. SCED needs to be rapidly implemented by the states; given the high penetration of Variable Renewable Energy (VRE), the scheduling of conventional power plants is increasingly evolving from SCED to include security constrained unit commitment (SCUC), flexibility measures, and energy storage management.

On behalf of Grid-India, we extend our full support and best wishes in obtaining the necessary regulatory orders and advancing intra-state SCED implementation. I also commend everyone who has contributed to this endeavor. We look forward to its full—fledged implementation, thereby helping to strengthen both the economy and security of India's power system.

Best wishes for continued success.

Narasimhan

S R Narasimhan

MAHATRANSCO
Maharashtra State Electricity Transmission Co. Ltd

Message

As Maharashtra's State Load Despatch Centre (SLDC), we are entrusted with two primary responsibilities—ensuring system security and promoting economic efficiency. Both of these are crucial in today's rapidly evolving energy landscape. The despatch processes we historically followed have served us well; however, with the increasing penetration of renewable energy and the introduction of a dynamic market mechanisms, we recognize the need for continual improvement and modernization.

Our state's power system is large, constantly growing, and increasingly complex. Managing the massive volumes of data, while addressing the evolving constraints, demands the adoption of more advanced, scientific tools. After a thorough review, we are confident that implementing an intra-state Security-Constrained Economic Dispatch (SCED) framework is essential for Maharashtra, aligning with recommendations from the committee that analyzed grid disturbances in the Mumbai Metropolitan Region (MMR). This SCED approach will enhance our ability to secure and optimize the grid, especially with the influx of renewables.

Introducing intra-state SCED will require us to develop new skill sets, and I am grateful for the expert assistance from the World Bank and IIT Bombay, which has been invaluable in building our in-house capability. This effort marks just the beginning of our journey toward a more resilient and efficient power system. I look forward to the cooperation and support of all stakeholders as we work together to take Maharashtra's power system to new heights.

As a proud member of FOLD, Maharashtra SLDC is committed to advancing the My-SCED initiative, ensuring that Maharashtra remains at the forefront of innovation in India's power sector.

Jewalikar

Shashank Jewalikar
Executive Director,
SLDC, MSETCL

Acknowledgments

The successful completion of this report on optimizing power dispatch would not have been possible without the invaluable contributions and support of several individuals and organizations.

We extend our heartfelt gratitude to all concerned particularly to Maharashtra State Electricity Authorities, for motivating us for this study on the intra-state Security Constrained Economic Dispatch and their encouragement in producing this 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 report.

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

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

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Abbreviations

ABT	Availability Based Tariff
ADTPS	Adani Thermal Power Station
AEML	Adani Electricity Mumbai Limited
AMPL	A Mathematical Programming Language
API	Application Programming Interface
APML	Adani Power Maharashtra Limited
BESS	Battery Energy Storage System
BEST	Brihanmumbai Electric Supply & Transport
CEA	Central Electricity Authority
CPLEX	Complex Programming Linear Expert
CSGS	Central Sector Generating Stations
CTU	Central Transmission Utility
DC	Declared Capacity
DISCOM	Distribution Company
DR	Demand Response
DSM	Demand Side Management
EV	Electric Vehicle
F&S	Forecast & Scheduling
FERC	Federal Energy Regulatory Commission
FOLD	Forum of Load Despatchers
FOR	Forum Of Regulators
GAMS	General Algebraic Modelling System
GIL	Grid Integration Laboratory
GW	Giga Watts
HR	Human Resources
IEGC	Indian Electricity Grid Code
IEPL	Ideal Energy Projects Limited
IITB	Indian Institute of Technology Bombay
InSTS	Intra-State Transmission System
ISGS	Inter-State Generation Station
IT	Information Technology
JSWEL	Jindal Southwest Energy Limited
KKT	Karush-Kuhn-Tucker
VoLL	Value Of Lost Load
LMP	Locational Marginal Price

LP	Linear Programming
MCP	Market Clearing Price
MEGC	Maharashtra Electricity Grid Code
MERC	Maharashtra Electricity Regulatory Commission
MMR	Mumbai Metropolitan Region
MOD	Merit Order Dispatch
MSEDCL	Maharashtra State Electricity Distribution Co. Ltd.
MSETCL	Maharashtra State Electricity Transmission Co. Ltd.
MSLDC	Maharashtra State Load Despatch Centre
MW	Mega Watts
NLDC	National Load Dispatch Centre
OA	Open Access
OPF	Optimal Power Flow
OS	Operating System
PLF	Plant Load Factor
PPA	Power Purchase Agreement
PSP	Pumped Storage Plant
PX	Power Exchange
RE	Renewable Energy
REMC	Renewable Energy Management Centre
RIPL	Real Ispat and Power Limited
RLDC	Regional Load Despatch Centre
RTM	Real-Time Market
SCED	Security Constraint Economic Dispatch
SCUC	Security Constraint Unit Commitment
SERC	State Energy Regulatory Commission
SLDC	State Load Dispatch Centre
SMP	System Marginal Price
TB	Time Block
TPCL	Tata Power Co. Ltd.
VRE	Variable Renewable Energy
VSE	Virtual State Entity
WRLDC	Western Region Load Dispatch Centre

List of Annexures

Executive Summary

This report provides an in-depth analysis of power dispatch optimization methods in Maharashtra, focusing on a transition from traditional Merit Order Dispatch (MOD) to Linear Programming (LP)-based Security Constrained Economic Dispatch (SCED). The objective is to enhance cost efficiency, grid reliability, and flexibility, essential for accommodating increasing renewable energy integration.

Comparative Performance: MOD vs. SCED

The report compares MOD, which dispatches generation based on variable costs, with SCED, which optimizes by incorporating economic and system security constraints. Key advantages of SCED include; (i) **Cost Savings:** SCED reduces total generation costs over MOD, resulting in potential savings for DISCOMs. (ii) **Operational Efficiency:** Reduced dispatch instructions and enhanced management of ramping and other constraints lead to more efficient grid operations. (iii) **Computational Efficiency:** The LP-based approach handles multiple complex variables like ramp rates, transmission limits, and technical minima, ensuring grid stability.

Value to Stakeholders

SCED benefits all key stakeholders:

(i) DISCOMs: Achieve cost-effective power procurement knowing their system marginal price (SMP) and optimized generation schedules.
(ii) Generators: Benefit from improved asset utilization and grid access, especially for renewables.
(iii) System Operators: Gain enhanced grid stability and operational efficiency, reducing the need for real-time interventions.
(iv) Consumers: Experience lower costs, increased reliability, and access to cleaner energy, supporting environmental sustainability.
(v) Regulators: Enable Regulators to design right incentives for the constraints looking at the shadow prices and improves transparency in despatch
(vi) Policy makers: Facilitate necessary decisions on the required technical interventions looking at the marginals and decide the course of action for the future.
(vii) Planners: Facilitate plan the network expansion looking at the transmission constraints and the price for congestions.

SCED's Support for Renewable Energy and National Policies

SCED aligns with India's renewable energy and market transparency goals, promoting competition, reducing costs, and supporting grid modernization and decarbonization policies. Its capacity to adapt to evolving grid scenarios ensures that the framework is future-proof and conducive to a competitive energy market.

Study Methodology and Findings

Conducted by the Maharashtra State Load Dispatch Centre (MSLDC) using 32 days of historical data (August 9 – September 9, 2024), the study tested SCED under various constraints, ramp rates, and DISCOM demand-supply balances. The findings confirm SCED's ability to lower operational costs and enhance grid stability.

Implementation Challenges and Recommendations

SCED's deployment requires improvements in data integration, computational infrastructure, and capacity building among human resources. To address this, a six-month SCED pilot is recommended for MSLDC to assess benefits across different seasons and operating conditions, focusing on real-time dispatch optimization, infrastructure needs, and value distribution among stakeholders.

Implementation Challenges and Recommendations

SCED's deployment requires improvements in data integration, computational infrastructure, and capacity building among human resources. To address this, a six-month SCED pilot is recommended for MSLDC to assess benefits across different seasons and operating conditions, focusing on real-time dispatch optimization, infrastructure needs, and value distribution among stakeholders.

The recommended pilot will gather essential input data, and disseminate the results, enabling stakeholders to refine generation scheduling, enhance real-time dispatch and security and observe SCED's full benefits under varying grid conditions.

Key parameters of the study

Table 1: Key Parameters & observations of the study

Sl. No.	Description	SCED
1.	Period of study	9th Aug-2024 – 9th Sept-2024
2.	No. of time blocks	3072
3.	No. of generating units	246
4.	No. of units considered for optimisation	44
5.	Total installed capacity (MW)	29738
6.	Net demand profile (MW) (Demand met – RE Generation – ISGS Alloc. - Hydro – non-MOD Contracts)	Min: 6217 Max: 11752
7.	Variable cost (₹/ unit)	2.9 to 11.6
8.	System Marginal Price (SMP) (₹)	3.50 to 6.00
9.	Perturbation (Nos)	Less in SCED for low-cost generators
10.	%age time Pmax is hit	~60
11.	%age time Tech-min is hit	~20
12.	%age of time Ramp limit hit	~ 2 - 3
13.	Per-day cost savings (₹ lakhs / day)	~ 87
14.	Per unit cost reduction (paise/unit)	~ 1.2

Key findings

Table 2: Key findings

Sl. No	Metric	Key findings	Outcomes from the case study (No. of Days : 32)
1	**Cost Efficiency**	SCED produced significant reductions in production costs by optimizing the dispatch of lower-cost power plants and reducing the reliance on higher-cost plants. The study noted an overall reduction in operational costs compared to the traditional MOD process.	MOD Cost: ₹ 11,444.56 Cr. SCED Cost: ₹11,415.75 Cr. Net Reduction: ₹28.81 Cr. % Saving: 0.25%
2	**Management of Ramping requirements**	SCED provided better adherence to ramp rate limits and efficiently managed generation output by adjusting schedules in real-time, reducing the number of ramp violations observed in MOD.	SCED provides dual of the ramps from which technical interventions to the plants could be decided.
3	**Operation of thermal plants**	SCED enhances generation stability by prioritizing low-cost generation, minimizing high-cost plants, and efficiently managing ramping requirements, which reduces stress on generators and improves thermal plant efficiency. As SCED optimizes schedules, low-cost plants tend to see an increase in Plant Load Factor (PLF), while high-cost plants may experience a decline, leading to more balanced and cost-effective power plant operations.	It is observed that a steady plant dispatch for cheaper generation was facilitated with less perturbations in dispatch, which will lead to an increase in efficiency in plant operation and thereby reduce the maintenance cost.
4	**Grid Reliability**	SCED demonstrated an ability to maintain grid security even during peak demand periods and unpredictable fluctuations in renewable generation, ensuring	The generation dispatch constraints defined, e.g. Pmax, Pmin, Ramp-up & Ramp-down, were honored during the total period of observations.

		reliable power delivery without compromising security.	Hence, the security is better ensured in SCED framework.
5	**Identification of constraint violations**	SCED can effectively identify any potential constraint violation in the schedule, thereby allowing the grid operator to manage it in a better manner.	Any violation of the constraints is penalized by the model and corresponding marginal value is given for making decisions by the grid operators.
6	**Computational performance**	Execution time of Optimization engine is faster than the MOD execution time.	At least 40 times faster. (2 min for MoD & 2.5 sec for SCED)
7	**Ease of development and flexibility to Change**	The optimization through LP provides full flexibility to accommodate changes to be incorporated due to continuous changes in the power system as well as the constraints without any major effort.	The current GAMS code consists of 50 lines in comparison to hundreds in MOD. Extending it to multiple days or a year can be done by looping the existing code. Adding new constraints and creating scenario models remains straightforward.

Other observations of the study:

Observation 1: There is a potential for cost savings of ₹2 to ₹4 lakhs per hour during low demand periods when SMPs range between ₹4 and ₹6. By maximizing low-cost generation, the reliance on high-cost generation can be reduced, further driving down costs.

Observation 2: The State SMP changes by ~ 7 paise/unit for each 100 MW change in net demand.

Observation 3: An arbitrage opportunity of ~₹1 between the SMPs of the DISCOMs with respect to State SMP was observed..

Observation 4: There is a potential for arbitrage in the SMP of the State and MCP of the market during ~80% of the time during the period of study.

Observation 5: SCED could generate savings specially during ramping either up or down while following the given constraints.

Observation 6: Normally, SCED generated cost savings during ~49% of the time blocks. However, there are ~1% for the time blocks when SCED production cost is more than that of MOD. Unlike MOD, SCED strictly honours the security constraints.

Observation 7: The production cost saving through SCED is 0.25% during 50% time of the duration of the study. As already mentioned, higher cost savings is possible during the low demand.

Observation 8: The cost of production increases significantly with the increase in demand, as the number of high-cost generators committed increases during high demand periods.

Observation 9: The savings are negligible beyond 11000 MW net demand whereas the savings is ₹1 lakh to ₹6 lakhs per time block during the period when the net demand varies from 6000 MW to 8000 MW.

Observation 10: Around 40% of the generators on bar (under MOD) experienced schedule changes in SCED, with the maximum generator-wise deviation of 100 MW. Low-cost generators experienced positive adjustments, while high-cost generators experienced negative adjustments with respect to the MOD schedule. However, only 20% of the generators had a high likelihood of schedule changes.

Observation 11: SCED provides key information like shadow price for binding constraints like Pmax, Pmin. Ramp-up and Ramp-down based on which actions for technical interventions could be initiated.

Observation 12: SCED also provides the System Marginal Price (SMPs) DISCOM-wise as well as for the whole of Maharashtra as a State. The SMP varies from ₹3.5 to ₹6.0 with the net demand varying from 7000 MW to 11000 MW.

1. Introduction

"Grid of the future isn't just about power—it's about optimization, integration, and innovation"

India's power system is undergoing a significant transformation, driven by rising electricity demand, a growing focus on renewable energy, integration of new and emerging technologies such as electric vehicles, electrolysers and data centres, and the need for enhanced grid efficiency and reliability. As the country pursues its ambitious renewable energy goals and aims to provide sustainable energy for all, optimizing power system operations becomes crucial. A major step in this direction is the shift from traditional methods like the bucket-filling Merit Order Dispatch (MOD) to more advanced Linear Programming (LP)-based optimization techniques.

Maharashtra State has one of the largest and most complex power grids in India, that relies on a diverse mix of generation sources, from conventional fossil fuels to an increasing share of renewable energy. With a strong push towards renewables, the grid faces the challenge of integrating variable energy sources like solar and wind, which brings new complexities related to grid stability, reliability, and efficiency.

The bucket-filling MOD approach, historically used for power dispatch in India, worked reasonably well in a conventional system dominated by conventional dispatchable generators and well understood demand patterns. However, as the grid evolves with the integration of renewables and complex demand, the limitations of this method have become apparent. Through the MOD approach, it is difficult to manage the variability and unpredictability of renewable sources, leading to inefficiencies and higher operational costs. Moreover, it lacks the flexibility to optimize for additional objectives, such as reducing emissions or maximizing the use of renewable energy.

In contrast, LP-based optimization provides a more effective solution for addressing these challenges. LP-based methods can handle large, complex datasets and optimize across multiple objectives simultaneously while handling security constraints effectively. By considering constraints and variables related to generation, transmission, and demand, LP-based optimization delivers more accurate and efficient dispatch decisions.

In light of this, the Maharashtra SLDC is attempting a report analysing the performance of the existing MOD process used by the State Load Dispatch Centre

(MSLDC) compared to the proposed Security Constrained Economic Dispatch (SCED) based on LP optimization. This report will offer a critical evaluation of the current scheduling practices, identify the limitations of the existing methods and propose intra-state SCED-LP optimization as a more efficient and scalable alternative for Maharashtra's evolving power grid.

This report,, aims to scientifically analyse the potential benefits of SCED over MOD based dispatch, and establish a pilot implementation of SCED in Maharashtra to evaluate potential real benefits of SCED over a reasonable period of time.

1.1 Background

The mandate provided under Electricity Act – 2003:

Section 32 of the Electricity Act 2003 mandates that the State Load Dispatch Centre (SLDC) shall be the apex body to ensure integrated operation of the power system in a State. It shall monitor grid operations and exercise supervision and control over the intra-state transmission system. Section 32 (2) of the Electricity Act also entrusts the SLDC with two important responsibilities pertaining to the entities within its jurisdiction. The relevant extracts are quoted below:

Quote The State Load Dispatch Centre shall -

(a) be responsible for optimum scheduling and dispatch of electricity within a State, in accordance with the contracts entered into with the licensees or the generating companies operating in that State; Unquote

Hence, scheduling, dispatching and accounting of electricity transmitted through the state grid have been recognized as an important statutory responsibility of the SLDC.

Sub-section 1 (h) of section 86 of the Electricity Act 2003 provides as follows:

Quote *"Specify State Grid Code consistent with the Grid Code specified under clause (h) of sub-section (1) of section 79;" Unquote*

It is mandated that the State Grid Code is aligned with the grid code specified by the Central Commission as per sub-Section (1) of section 79.

Compliance by MERC: In compliance with the Electricity Act 2003, the Maharashtra Electricity Regulatory Commission notified MERC (State Grid Code) Regulations, 2020 (MEGC, 2020) on 2nd September 2020 and subsequently notified operationalisation of principles for Merit Order Dispatch stack (MOD stack) as specified under Regulations 33.13 of the MEGC 2020.

MSLDC has started the scheduling process based on the MEGC since 1st October 2021 which is predominantly a de-centralised MOD except for some periods during real-time operation when the shift operator initiates centralised MOD due to over-drawl by states of more than 250 MW (DSM Mandate).

The New Indian Electricity Grid Code – 2023:

Sub-section 1 (c) (iv) of section 44 of Indian Electricity Grid Code - 2023 provides for optimisation of scheduling inter-alia through SCED as a function of Load Dispatch Centres and Regional Load Dispatch Centres are mandated to perform these functions. The extract is as below:

Quote *(iv) optimisation of scheduling inter-alia through Security Constrained Economic Dispatch (SCED);* Unquote

Accordingly, SLDCs are also required to start implementing SCED while scheduling to achieve optimization in the process.

National Load Dispatch Centre started running a pilot SCED in 2019 and substantial savings of approx. ₹4000 Cr. could be achieved to date. An amount of ₹165 Cr. was received by Maharashtra against the appropriation of gains from NLDC.

The possibility of intra-state SCED was discussed in detail with MSLDC and MERC on 23rd July 2024. It was suggested that a study could be made on the implemented schedule to find out the possible savings and advantages of the LP-based SCED model.

1.2 Purpose and Scope of the Report

The purpose of this study is to conduct a comprehensive comparison between the traditional MOD model and the LP-based SCED model in the context of power system scheduling and dispatch. The study aims to:

1. **Performance Analysis:** Detailed examination of the efficiency and accuracy of both models in dispatching power, balancing supply and demand, and minimizing operational costs. Evaluation of each model's ability to integrate and optimize future changing scenarios and its flexibility to change. Assessment of the grid stability and reliability outcomes achieved by both models, particularly in handling the variability and intermittency of renewable energy.

2. **Identify Benefits and Limitations:** Highlight the strengths and weaknesses of each model, particularly in handling the integration of renewable energy sources and managing grid stability.
3. **Quantify Improvements:** Provide quantifiable evidence of the improvements achieved through LP-based optimization over the traditional MOD model, using key performance metrics.
4. **Support Decision-Making:** Offer insights and recommendations for grid operators, policymakers, and stakeholders to facilitate informed decision-making regarding the adoption of advanced optimization techniques.

The scope of the report encompasses the following key areas:

1. Review of the present model

Overview of present MOD models and their implementation process in power system scheduling in Maharashtra.

2. Methodology

Description of the study design, including data collection methods, simulation tools, and analytical techniques. Definition of performance metrics to be used for comparison, such as cost efficiency, renewable energy utilization, grid stability, and computational complexity.

3. Data and Case Studies

Details of representative case studies and historical data set for analysis. Comparative analysis of the implemented schedules by MOD and LP-based models under over 96 blocks identifying the centralised and de-centralised run scenarios and contingency events by using one-month historical data.

4. Technological and Operational Considerations

Analysis of the computational requirements and implementation complexity associated with both models. Discussion of the technological infrastructure and operational changes needed to transition from MOD to LP-based optimization.

5. Regulatory and Policy Implications

Examination of the regulatory framework and policy support required to facilitate the adoption of LP-based optimization in the Maharashtra state grid.

Recommendations for policymakers on incentivizing advanced optimization techniques and supporting grid modernization efforts.

1.3 Structure of the Report

The report has been structured as follows:

Section 2: Overview of Merit Order Dispatch

This section shall cover the details logic of Merit Order dispatch models and will include the definition and basic concept of MOD, the historical context and evolution of MOD in power system operations, importance and role of MOD in ensuring efficient and cost-effective power dispatch.

Section 3: Present Approaches to Merit Order Dispatch

This section will cover the algorithms and logic used for the implementation of MEGC Regulations by MSLDC. The strengths and limitations of the present implementation.

Section 4: Strength and Limitations of present approach

This section will cover a various strength of the present MOD system and limitations of the system which necessitates the need for transition to LP method.

Section 5: Transition to Linear Programming (LP) Based Optimization

This section provides the rationale for transition to LP based model for optimization and introduction to LP programming methods. It also covers the specific rationale for MSLDC for transition to LP based SCED model.

Section 6: Development and Implementation of the LP-Based Model

The data requirement, data preparation for the model, development of the model, computational tools and software used for the study and integration with the existing system are covered in this section. This section also covers the various requirement for implementation of LP based optimization model including financial and HR requirements.

Section 7: Comparative Analysis of SCED and MOD

The section will cover the evaluation criteria, a detailed discussion of the study results and key findings and observations.

Section 8: Power of Shadow Price

This section covers the definition of shadow price and how the shadow price could be implemented in decision making process.

Section 9: Challenges and handling infeasibilities

This section deals with the various challenges faced during the study and how it was handled.

Section 10: Value of Stakeholders

This section covers how the proposed implementation helps and benefit all the stakeholders.

Section 11: Way forward and Recommendations

This section highlights the other essential modelling activities to be taken up gradually after initial implementation for further improvement in efficiency and more informed dispatch by the system operators. The section also covers the various pre-requisites which are required for successful implementation of intra-state SCED in states across India.

Section 12: Conclusion

The concluding section re-iterates the requirement of SCED implementations in the State and to start other important activities like hydro optimization, LMP calculations and OPF study.

2. Overview of Merit Order Dispatch

"Efficiency is doing things right; effectiveness is doing the right things"

Definitions and Principles

Merit Order Dispatch (MOD) is a fundamental principle in power system operations that prioritizes the dispatch of electricity generation units based on their Variable costs. The primary objective of MOD is to minimize the overall cost of electricity production while ensuring that the demand for electricity is met in real-time. This method ranks power generation units from the lowest to the highest variable cost and dispatches them in that order, ensuring that the least expensive sources of electricity are utilized first.

2.1 Principles of Merit Order Dispatch

1. **Variable Cost Ranking:** The cornerstone of MOD is the ranking of power generation units according to their variable costs, which are the costs of producing one additional unit of electricity. Variable costs typically include fuel costs, variable operating and maintenance expenses, and any other costs that vary with the level of output. Units with the lowest variable costs are placed at the top of the merit order, while those with higher costs are ranked lower.
2. **Economic Efficiency:** The primary goal of MOD is to achieve economic efficiency in power generation. By dispatching the cheapest available units first, the overall cost of electricity production is minimized. The main objective of this approach is that consumers receive electricity at the lowest possible cost, reflecting the principles of economic dispatch.
3. **Load Matching:** MOD aims to match electricity generation with demand in real-time. Grid operators continuously forecast electricity demand and adjust the dispatch of generation units accordingly. As demand fluctuates throughout the day, the dispatch order may change, but the principle of using the least-cost units first remains constant.
4. **Inclusion of Operational Constraints:** While variable cost is the primary criterion, MOD also considers various operational constraints. These constraints include technical limitations of power plants, such as minimum and maximum generation levels, ramp rates (how quickly a plant can increase or decrease its output), and start-up and shut-down times. Grid stability and

reliability requirements, such as maintaining adequate reserve margins and ensuring voltage and frequency control, are also factored into the dispatch decisions.

5. **Day-Ahead and Real-Time Markets:** MOD operates in both day-ahead and real-time markets. In the day-ahead market, generation schedules are planned based on demand forecasts for the next day, ensuring that the least-cost units are prepared to meet expected demand. In the real-time market, adjustments are made to account for deviations from the forecast, unexpected outages, or sudden changes in demand. Real-time dispatch ensures that the grid always remains balanced and reliable.
6. **Integration of Renewable Energy:** The increasing penetration of renewable energy sources, such as wind and solar power, presents challenges and opportunities for MOD. These sources have near-zero variable costs but are variable, intermittent and weather-dependent. MOD must adapt to integrate these intermittent resources efficiently, often requiring advanced forecasting and flexible grid management strategies to maintain balance and reliability.
7. **Transparency and Simplicity:** One of the strengths of the MOD principle is its transparency and simplicity. The ranking of units based on variable cost is straightforward and easy to understand, providing clear guidelines for dispatch decisions. This transparency fosters trust and accountability among stakeholders, including power producers, grid operators, regulators, and consumers.

In summary, MOD is a well-established methodology that optimizes the economic efficiency of electricity generation by prioritizing units with the lowest variable costs. While its primary focus of MOD is on cost minimization, there is a need to consider operational constraints, environmental impacts, market dynamics, and the integration of renewable energy sources to ensure a reliable and sustainable power supply.

2.2 Historical Perspective and Evolution

During the early years of post-independence, India's power sector was fragmented, with numerous regional grids operating independently. The focus was primarily on expanding generation capacity to meet the rapidly increasing demand. The generation mix was dominated by thermal power plants, particularly coal-fired units, which provided a stable and controllable source of electricity. As the sector grew, the need for a systematic approach to power dispatch became evident.

Formal Introduction of MOD in Indian Grid

The formal introduction of MOD in India occurred in the 1980s and 1990s as part of broader power sector reforms aimed at improving efficiency and reliability. The establishment of the Central Electricity Authority (CEA) and the introduction of Regional Load Dispatch Centers (RLDCs) played a crucial role in this transition. These institutions were tasked with overseeing grid operations, ensuring coordination among different regions, and optimizing power dispatch.

The MOD principle was adopted to prioritize the dispatch of power from generating units based on their variable costs. Thermal power plants with lower fuel costs were dispatched first, followed by those with higher costs. This approach aimed to minimize the overall cost of electricity generation and improve the economic efficiency of the grid.

Power Sector Reforms and the Electricity Act of 2003

The Electricity Act of 2003 marked a significant milestone in the history of India's power sector. The Act aimed to create a more competitive and transparent electricity market, encourage private sector participation, and ensure the efficient utilization of resources. One of the key provisions of the Act was the establishment of the National Load Dispatch Centre (NLDC) and the strengthening of the State Load Dispatch Centres (SLDCs).

Under this framework, MOD became a standardized mandate across the country. The Act emphasized the need for economic dispatch, where power is sourced from the least cost producers to meet demand. This shift was supported by the introduction of Availability Based Tariff (ABT), which incentivized generators to operate efficiently and penalized deviations from scheduled generation.

Integration of Renewable Energy and Modern Challenges

The integration of variable renewable energy sources like wind and solar required more sophisticated dispatch strategies to maintain grid stability and reliability. Despite their near-zero variable costs, variable and intermittent nature of renewables necessitated advanced forecasting and flexible dispatch mechanisms.

The grid modernization efforts included investments in smart grid technologies, real time data analytics, and improved forecasting methods. These advancements allowed grid operators to better manage the variability of renewable energy and optimize the overall dispatch process. MOD need to evolve to accommodate these changes, balancing cost efficiency with the need for grid reliability and sustainability.

Recent Developments and Future Prospects

In recent years, the adoption of SCED (SCED) mechanisms implemented at the central level and the introduction of real-time electricity markets (RTM) have further refined the MOD practice in India. These developments have enhanced the ability to efficiently allocate resources, respond to demand fluctuations, and integrate diverse energy sources.

Looking ahead, the future of MOD in India will need to have greater reliance on advanced optimization techniques, such as LP based models, to address the complexities of a modern, diversified power grid. With the increasing complexities of the grid operations with different constraints of operations, the LP based optimization tool remains a critical tool for achieving economic efficiency and sustainability in India's power sector.

2.3 Historical Reasons for Persistence of Bucket Filling Methods

2.3.1 Historical Precedents and Legacy Systems

The bucket filling method has been in use for several decades. It was established during a time when computational resources were limited, and simpler algorithms were necessary to manage the complexities of power dispatch.

These legacy systems have a significant inertia associated with them. Since they have been in place for so long, there is often resistance to change, both from a technical and operational standpoint.

2.3.2 Lack of Advanced Computational Resources

Earlier, the availability of advanced computational resources and software capable of handling complex LP algorithms was limited. This made bucket filling methods, which are simpler and less resource-intensive, the preferred choice.

2.3.3 Training and Expertise

Many power system operators and engineers were trained on these older methods. Transitioning to LP methods would require extensive retraining and a shift in operational paradigms.

The expertise required to implement and maintain LP-based systems was not widely available, creating a barrier to adoption.

2.3.4 Regulatory and Policy Frameworks

Regulatory frameworks and policies governing the power sector may have been slow to evolve, often lagging behind technological advancements. This has contributed to the continued use of outdated methods.

2.4 MERC order – Implementation of MEGC-2020

The Maharashtra Electricity Regulatory Commission notified MERC (State Grid Code) Regulations, 2020 (MEGC, 2020) on 2nd September 2020 and subsequently notified operationalization of principles for MOD stack (MOD stack) as specified under Regulations 33 of the MEGC 2020.

SLDC prepared the draft Scheduling and Dispatch (S&D) Code considering the Stakeholder's comments and suggestions and submitted it to the Commission for approval. The Commission approved the S&D code on 11 November 2019. The regulation 1.4 of the MEGC 2020 is as below:

Quote *These Regulations shall come into force from the date of its publication in the Official Gazette and remain in force unless amended, varied, altered, or modified by the Commission.*

Provided that, the provisions related to Deviation Settlement Mechanism framework and preparation of de-centralised merit order for buyer-wise scheduling shall come into force from the date to be separately notified by the Commission for implementation of commercial arrangement under MERC DSM Regulations. Unquote

The code clearly indicates a de-centralized mode of Merit Order Scheduling.

The Part E of the MEGC 2020 constitutes the Scheduling and Dispatch Code.

The key point under the MOD Regulations is detailed below:

SLDC is responsible for coordinating the scheduling of buyers and sellers within its control area. SLDC shall also be responsible for the preparation of the MOD (MOD) stack for the day ahead scheduling for each month considering the principles specified in these Regulations and least cost dispatch principles.

For central sector generating stations (CSGS), the variable charge for MOD purposes shall be landed variable charge at the state periphery for the immediately preceding month (N-1), including the injection losses, drawl losses of CTU and other such charges like electricity duty cess of exporting state.

For intra-state open access transactions having single part tariff, total tariff shall be considered as variable charge for MOD purpose.

In case of anticipated generation availability in surplus of anticipated demand, the distribution licensees need to optimise their cost of power procurement considering the contracted sources for the period of anticipated surplus. If the anticipated generation availability is more than the anticipated demand, the distribution licensee in consultation with SLDC may consider giving zero schedule (closing of units) to some of its contracted sources for the period during which the demand is expected to be lower than the total contracted sources availability put together. A reserve margin equivalent to the contracted capacity of the largest unit of the power station, contracted by the Distribution Licensee needs to be maintained.

Key points under Part E of the Code:

All Seller(s) having installed generating capacity of Unit or Combined capacity of all units in the generating station above 25 MW (or such other threshold capacity), including RE generators, open access generators, captive generators having connected to InSTS but excluding wind and solar generating station(s).

Provided that, the provisions of the Scheduling and Dispatch Code shall be also applicable to all RE generating stations (except Wind and Solar Generators) having installed capacity less than 25 MW connected to InSTS for the purpose of scheduling as specified in this Code.

2.4.1 General principles of scheduling and dispatch code (Regulation 52)

The key Regulations with respect to scheduling process are as follows:

52.1.7. SLDC shall prepare buyer wise MOD stack for day ahead scheduling process for each month in Form-5B and Centralised MOD stack for intra-day operation in Form-6B considering the principles specified in the MERC DSM Regulations and MoD principles specified in these Regulations.

52.3.2. Beneficiaries shall submit their requisitions from respective ISGS to SLDC. Considering drawl schedule submitted by the respective Distribution Licensee & availability from all sources & decentralized load generation balance, SLDC shall advise the drawl schedule for each of the ISGS to WRLDC.

52.3.3. SLDC shall consider the schedule received from WRLDC while finalizing the schedule under de-centralized MOD principles.

52.4.1. SLDC shall follow the de-centralized MOD principles as specified by the Commission in these Regulations and MERC DSM Regulations, for respective buyers while preparing Load Generation balance during Day Ahead Scheduling.
52.4.4. SLDC shall prepare the Load Generation balance considering the Ex-Bus generation availability of the Sellers, entitlement of ISGS and load forecast by the Buyers, Buyer-wise MOD principle (de-centralized MOD) and RE Generation forecasted as per the procedure under MERC F&S Regulations.
52.4.5. While giving the Schedule to Generators as per De-Centralised MOD Principles, the SLDC shall maintain the spinning reserve margin in the Generator as specified in these Regulations for the management of the ramp as per the requirement of the Grid.
53.3.4. During real time operation, in case the grid parameters including frequency, voltage, transmission line loading, substation loading conditions or State volume limits (presently +/-250 MW) deviate beyond permissible operating range, SLDC shall take suitable measures in the interest of reliable and safe grid operations and issue necessary dispatch/curtailment instructions in accordance with Centralised MOD principles for the State as a whole.
53.3.5. Accordingly, SLDC shall issue necessary dispatch or curtailment instructions in accordance with Centralised MOD principles for the state as whole, considering the technical constraints such as Ramp rate of generators so as to maintain the Load Generation balance and comply with conditions stipulated under these Regulations and IEGC.
It is observed that de-centralized schedules are prepared by SLDC except during violation of grid parameters including frequency, voltage, transmission line loading, substation loading conditions or State volume limits (presently +/-250 MW) beyond permissible operating range.

3. Present Approaches to Merit Order Dispatch

"Efficiency thrives on tradition, but true innovation begins when we challenge the existing practices."

3.1 Algorithms and Logic Used

The scheduling process is done based on the MOD principle through direct coding based on the following inputs.

1. Demand from DISCOMs
2. No. of generators on-bar - decided by DISCOMs and approved by SLDC
3. Declaration of DC of intrastate generators – Declared by generators
4. Variable cost of generation – Declared by Generators and verified by DISCOMs on a fortnightly basis
5. Intrastate bilateral contracts –Declared by Buyer/Seller
6. Details of Inter-State Open Access transactions incl. PX – not under MOD
7. Renewable Energy Data – not under MOD
8. Details of requisitions from CSGS generation – Decided by DISCOMs
9. Maximum possible Generation and Technical limit– Declared by Generators
10. Ramp rates (Up/Down) – declared by the generators in advance

All the data is collected automatically through APIs. A cloud-based system has been developed to cater to the scheduling requirement. The schematic diagram is shown in Figure 1.

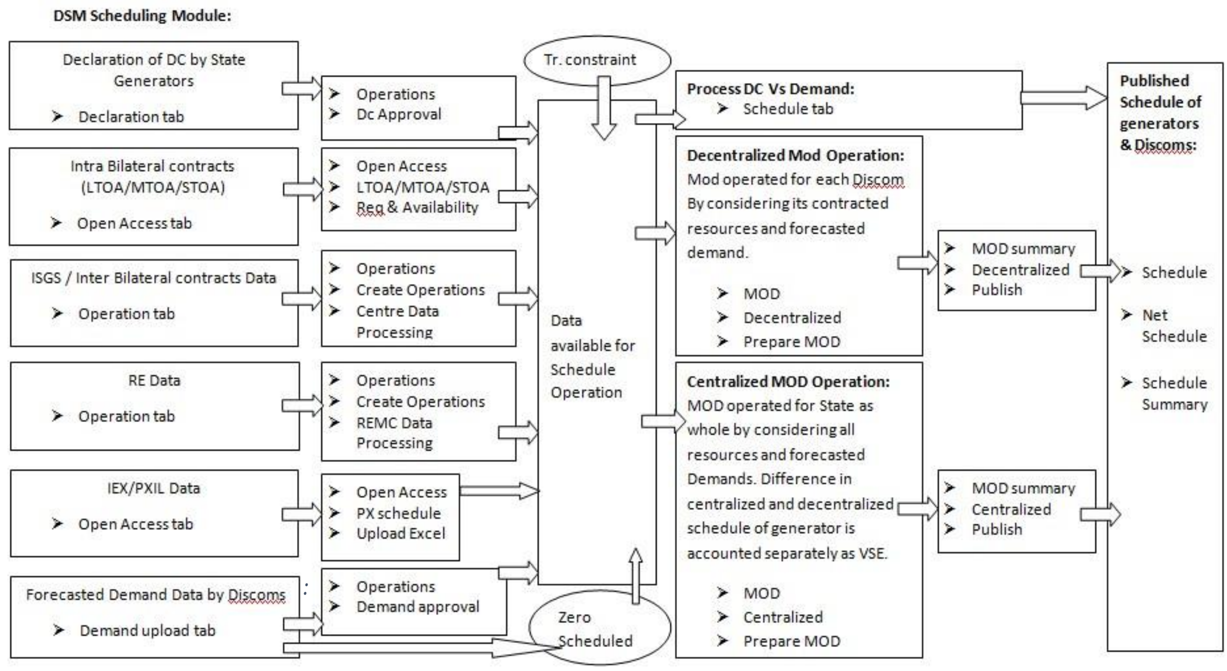

Figure 1. Schematic Diagram of the existing scheduling system

The following basic steps are followed for deciding the schedules:

Step 1: Sort power plants by merit order

Power plants should be sorted in ascending order of their generation costs. This ensures that lower-cost plants are prioritized.

Step 2: Set ramp rate and technical minimum constraints

For each time period (e.g., 15 minutes), ensure that the change in power generation for each plant doesn't exceed the allowed ramp rate. Also, ensure that no plant operates below its technical minimum limit.

Step 3: Allocate demand to power plants

Loop through the sorted list of power plants and allocate power starting from the least costly plant until the demand is met. While doing this, consider each plant's ramp rate and technical minimum limit.

Transmission constraints are not in-built and are considered based on the operator's input. Further, additional generation is scheduled three blocks in advance based on the state deviation observed in real time by the operator.

The special conditions for contracts are also honoured on case-to-case basis.

It may be mentioned here that the scheduling process follows an iterative method to arrive at the schedules and considers the transmission constraints based on the operator's input. The processing time is shown in Figure 2.

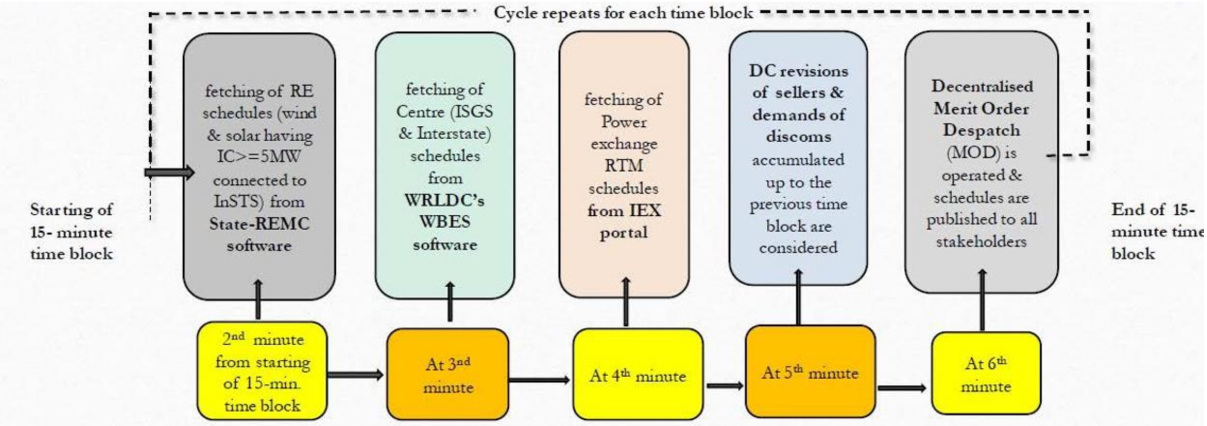

Figure 2. Scheduling Process

3.2 Present scheduling operation – Two modes

Present scheduling operation has two modes:

(i) Decentralized mode

(ii) Centralized mode

Normally decentralized mode is followed to decide schedules of each DISCOMs generators when the DISCOMs place requisitions as per their requirements. The centralized mode is triggered as and when the inter-state deviation is more/less (over-drawl or under-drawl) than a pre-decided value, in case of transmission constraints or in case of system contingencies.

When the centralized mode is invoked and scheduled are prepared, the schedules are modified based on the overall MOD stack of the state. This causes a difference in the generation schedules between the original de-centralised schedules and centralised schedules. This difference is settled through a virtual pool accounts created i.e. "VSE". VSE (Virtual State Entity) is created to balance the deviations of de-centralized and centralized schedules. The difference is settled at the variable charge. The generators getting lesser schedules pay to the VSE at their variable cost and the generator with higher schedules receives the payment at their variable cost. It has been observed that there remains a pool balance after settlement of the generation cost.

4. Strengths and Limitations of Conventional

"To lead in the future, we must optimize for today"

Even though MOD is widely used, it comes with several limitations that can impact its efficiency, scalability, and applicability which are detailed below:

4.1 Complexity and Scalability

MOD is conceptually simple, ranking generators by variable costs and dispatching them, accordingly, making it relatively easy to implement in small or medium-sized systems. Its low complexity reduces the computational overhead, making it an attractive option for simpler grid setups. However, as the system scales, the algorithm faces challenges in handling larger networks with multiple constraints. While it works well in systems with a limited number of power plants, its efficiency diminishes as the number of generators increases, especially when considering modern energy grids with more dynamic factors such as renewable energy integration, transmission congestion, and demand fluctuations. The simplicity of MOD may not be sufficient for handling the complexities and size of modern interconnected power grids, leading to the need for more advanced optimization techniques.

4.2 Specificity and Flexibility

MOD excels in systems where cost minimization is the primary goal, as it is highly specific in its focus on variable costs. This specificity makes it an effective approach in traditional energy markets dominated by thermal generation, where fuel costs drive dispatch decisions however, its flexibility is limited. MOD struggles to incorporate non-cost factors like environmental concerns, emissions, and the integration of variable renewable energy sources. It is not designed to easily adjust to dynamic grid conditions, such as the need to prioritize renewable energy with zero variable costs. This rigidity can lead to inefficiencies in modern grids where flexibility is crucial, particularly with the increasing role of distributed and intermittent energy sources.

4.3 Knowledge and Expertise

MOD's simplicity is one of its key strengths, as it requires relatively low expertise to implement and manage. Operators do not need extensive knowledge of advanced optimization techniques to use MOD effectively in traditional grid systems. This makes it accessible to many power system operators, particularly in markets with predictable and stable energy supply conditions. However, as power systems become more complex—especially with the integration of renewable energy, distributed energy resources, and smart grid technologies—the limitations of MOD become apparent. Operators managing more sophisticated grids may require expertise in more advanced dispatch strategies and optimization methods, as MOD is often insufficient to address the complexities of modern grid operations, such as managing variable generation or real-time market adjustments.

4.4 Convergence and Local Optima

MOD guarantees convergence by providing a straightforward, deterministic solution based on variable cost ranking, making it reliable for ensuring that generators are dispatched in a way that minimizes operational costs. However, its reliance on local cost optimization can result in suboptimal global solutions. For instance, MOD misses to consider network constraints, ramp constraints, transmission losses, or the benefits of non-linear cost structures in certain scenarios, leading to locally optimal but globally suboptimal dispatch decisions. Additionally, MOD does not dynamically adjust to changing grid conditions in real-time, which can prevent it from achieving the most cost-effective or efficient outcome in more complex, modern systems where the energy landscape is continuously shifting.

4.5 Sensitivity to Initial Conditions

MOD is generally robust to initial conditions since it ranks generators based purely on variable costs and dispatches them sequentially. Unlike more complex optimization methods, MOD does not require careful tuning of initial parameters or iterative adjustments. This makes it easier to implement without significant sensitivity to starting points. However, in modern grids where conditions can change rapidly due to demand spikes or renewable energy fluctuations, MOD's inability to adapt dynamically to real-time conditions can result in inefficient dispatch. Although it performs well in more stable environments, its lack of adaptability in volatile or fluctuating scenarios is a significant limitation when dealing with modern power grids that require quick responses to changing energy supply and demand.

4.6 Handling Constraints

While MOD can manage basic constraints such as generator capacity limits and minimum operational levels, it is not well-suited to handle more complex or dynamic constraints. Traditional MOD models do not account for transmission network constraints, grid congestion, ramp rates, or the specific operational characteristics of renewable energy sources. In large and interconnected power systems, these limitations can lead to suboptimal dispatch decisions and reduced overall system efficiency. Moreover, MOD operates on a static basis, lacking the ability to incorporate temporal constraints that change over time, such as demand variability or storage requirements. This results in less effective management of grid resources, particularly as modern grids evolve to integrate more diverse and flexible energy sources.

4.7 Integration with Modern Technologies

MOD is well-suited to traditional power systems where dispatchable thermal generators dominate the energy mix, and its focus on cost minimization is directly applicable. However, as modern grids increasingly incorporate renewable energy sources like wind and solar, MOD's limitations become apparent. Renewables, often characterized by zero or negative variable costs, are not easily integrated into the MOD framework, which focuses on ranking based on cost. Additionally, MOD does not efficiently handle the complexities in modern power systems, which require more dynamic and flexible dispatch algorithms. Without significant modifications, MOD is ill-equipped to manage the intricacies of modern power systems, limiting its usefulness in current energy landscapes.

4.8 Computational Resources

One of the major strengths of MOD is its minimal computational requirements. The algorithm's simple ranking process requires only basic calculations to determine the optimal dispatch order, making it highly efficient in terms of computational resources for small to medium-sized systems. This is advantageous in markets with limited computational infrastructure or in traditional grids where more sophisticated methods are unnecessary. However, as the complexity of the system increases, MOD's lack of computational depth becomes a limitation. It is not well-suited for handling the intricate, multi-variable problems found in large, interconnected grids, where more advanced algorithms with higher computational power are required to handle real-time adjustments and complex constraints.

4.9 Maintenance and Upgrades

MOD is relatively easy to maintain due to its long history of use and its simplicity. It is a well-established method, requiring minimal effort to keep operational in traditional energy systems, where fuel-based generation is predominant. Upgrading or maintaining MOD in such environments is straightforward, as the algorithm is highly stable and has few moving parts. However, adapting MOD to more modern grids present challenges. As the grid incorporates more renewable sources, distributed generation, and advanced market mechanisms, the traditional MOD framework becomes increasingly difficult to upgrade. Significant modifications are required to keep it relevant in these evolving scenarios, often necessitating the use of more advanced dispatch algorithms to maintain grid efficiency and reliability.

4.10 Lack of Parallelization

MOD's algorithm is inherently sequential, based on ranking and dispatching generators one by one according to their variable costs. In smaller and simpler systems, this lack of parallelization is not an issue, as the dispatch process can be performed quickly without requiring concurrent operations. However, in larger, more complex power systems, this limitation becomes more problematic. Modern power systems often require real-time dispatch solutions across a large number of generators and constraints, where the ability to parallelize, computations would significantly enhance performance. MOD's inability to leverage parallel processing slows down its application in large-scale, dynamic systems, limiting its efficiency in environments where rapid dispatch decisions are critical for maintaining grid stability and minimizing costs.

5. Transition to Linear Programming Based Optimization

"Optimization is not the act of perfection, but the pursuit of a better solution"

5.1 Introduction to Linear Programming

Linear programming (LP) is a mathematical method used to determine the best possible outcome or solution from a set of linear equations. It is considered a simple and easy to implement powerful tool in operations research and optimization, widely used in various fields such as economics, engineering, military planning, and management. LP aims to maximize or minimize a linear objective function, subject to a set of linear constraints.

Historical Context

The origins of LP can be traced back to the 1930s and 1940s, when it was developed to address logistical and resource allocation problems during World War II. The seminal work of mathematician George Dantzig in 1947, who introduced the simplex algorithm, marked the formalization of LP as a discipline. This algorithm provided a systematic method for solving LP problems efficiently, revolutionizing the field of optimization.

5.1.1 Fundamental concepts

At its core, LP involves three main components: the objective function, constraints, and decision variables.

1. **Objective Function:** This is the function that needs to be optimized, either maximized or minimized. It represents a quantitative measure of performance, such as profit, cost, or time. The objective function is expressed as a linear combination of decision variables.
2. **Constraints:** These are the limitations or requirements that must be satisfied in the solution. Constraints are also expressed as linear equations or inequalities involving the decision variables. They define the feasible region within which the solution must lie.
3. **Decision Variables:** These variables represent the choices available to the decision-maker. They are the unknowns that need to be determined in the optimization process, however, within bounded constraints. The values of the decision variables that optimize the objective function while satisfying all constraints constitute the optimal solution.

4. **The Karush-Kuhn-Tucker (KKT) criteria:** These are the conditions used to solve constrained optimization problems, particularly when dealing with inequality and equality constraints. In optimization, KKT conditions generalize the method of Lagrange multipliers, applying to both linear and nonlinear programming.

For a given objective function to be optimized (minimized or maximized), the KKT conditions provide necessary conditions that any optimal solution must satisfy if the problem is convex. These include:

1. **Primal Feasibility:** The solution must satisfy all original constraints.
2. **Dual Feasibility:** The associated Lagrange multipliers for inequality constraints must be non-negative.
3. **Stationarity:** The gradient of the objective function, adjusted by the constraints, must be equal to zero.
4. **Complementary Slackness:** If a constraint is inactive (not binding), its corresponding multiplier must be zero.

These conditions are essential in **constrained optimization**, offering a structured approach to finding optimal solutions in complex systems with **multiple** constraints.

5.1.2 Applications

LP has a wide range of applications across various industries and sectors, with a limited list of applications listed below:

1. **Resource Allocation:** LP helps in allocating limited resources such as raw materials, labour, and machinery in the most efficient way to maximize output or minimize costs. For example, it can be used to determine the optimal mix of products to manufacture in a factory.
2. **Transportation and Logistics:** LP is used to optimize routing and scheduling in transportation networks, ensuring that goods are delivered at the lowest cost while meeting demand and capacity constraints. It can also optimize supply chain management by balancing supply and demand across different locations.
3. **Finance and Investment:** In finance, LP can be used for portfolio optimization, where the goal is to maximize returns or minimize risk while adhering to investment constraints. It can also be applied to budgeting and financial planning.

4. **Telecommunications:** LP aids in network design and bandwidth allocation, ensuring efficient utilization of network resources to meet the user demand and service quality requirements.
5. **Energy Management:** LP aids in optimizing energy generation and distribution, balancing supply and demand, reducing operational costs, and integrating renewable energy sources into the grid.

5.2 Solving Linear Programming Problems

The process of solving an LP problem involves several steps:

1. **Problem Formulation:** Define the objective function, constraints, and decision variables based on the problem at hand.
2. **Simplex Algorithm:** For larger problems, the simplex algorithm is a popular and efficient method to find the optimal solution by iteratively moving along the edges of the feasible region to reach the optimal vertex.
3. **Software Tools:** Numerous software tools and solvers, such as Python, CPLEX, Gurobi, and GAMS, are available to handle complex LP problems, providing user-friendly interfaces and powerful computational capabilities.

LP is a versatile and robust optimization technique that plays a crucial role in decision-making across diverse fields. Its ability to model real-world problems and provide optimal solutions efficiently has made it an indispensable tool in the modern era. As computational power and algorithmic techniques continue to advance, the scope and impact of LP are likely to expand, offering even more sophisticated solutions to complex problems.

5.3 Rationale for Transition

The transition from MOD to Security-Constrained Economic Dispatch is essential for modernizing power grid operations, ensuring both economic efficiency and system security. Below is a comparison of key features that highlight the advantages SCED brings over MOD across various operational and strategic dimensions:

Table 3: Rationale for Transition from MoD to SCED

Feature	MOD	SCED
1. Enhanced Efficiency and Scalability	Limited scalability as grid complexity increases.	Optimizes dispatch while considering system constraints, offering better scalability for large, complex grids.
2. Improved Flexibility and Adaptability	Less adaptable to real-time grid conditions.	Provides real-time adaptability to changing grid conditions, integrating dynamic data and handling fluctuations more effectively.
3. Enhanced Solver Integration	Limited solver capabilities, handling basic optimization tasks.	Leverages advanced solvers (e.g., mixed-integer programming) that efficiently handle nonlinear, large-scale optimization tasks.
4. User-Friendly and Accessible	Limited user interaction with dynamic grid data.	Advanced user interfaces with real-time analytics and decision-support tools for more accessible and informed control.
5. Improved Debugging and Maintenance	Debugging and maintenance are harder due to lack of operational transparency.	Enhanced traceability of grid security constraints, making troubleshooting and maintenance more efficient.
6. Integration with Data and Other Systems	Typically operates independently of other grid management systems.	Seamless integration with real-time data streams (e.g., weather, load) and grid systems for holistic dispatch decisions.

7. Enhanced Efficiency and Cost Savings	May lead to higher operational costs in grid-constrained situations.	Optimizes both cost and grid reliability, leading to better overall efficiency and cost savings by preventing costly grid issues.
8. Improved Reliability and Grid Stability	Prone to overlook critical system constraints, affecting reliability.	Integrates security constraints directly into dispatch, ensuring decisions align with system reliability and stability requirements.
9. Integration of Renewable Energy Sources	Struggles with variable generation from renewables.	Adapts to renewable variability, incorporating real-time data to optimize renewable energy utilization while maintaining grid security.
10. Regulatory and Market Compliance	May not align fully with modern regulations emphasizing security and sustainability.	Ensures compliance with regulations by integrating economic, security, and environmental objectives into the dispatch process.
11. Scalability and Futureproofing	Not well-suited for future grid requirements.	Designed for scalability and adaptability, making it future proof for evolving energy systems and new technologies such as smart grids.

The transition from crude bucket filling methods to LP-SCED is crucial for enhancing the efficiency, reliability, and sustainability of power systems in India. While historical precedents and operational inertia have maintained the status quo, the benefits of adopting advanced optimization techniques are clear. Urgent action is needed to retrain personnel, update regulatory frameworks, and invest in the necessary computational infrastructure to facilitate this transition. This will ensure that the power sector can meet the demands of a rapidly evolving energy landscape while optimizing costs and maintaining grid stability.

5.4 Other Justifications for transition for MSLDC

The present scheduling system is in operation since October 2021 and till date has performed satisfactorily. However, with the several complexities envisages in future and the difficulties faced in modifying the present system. Which is being maintained by third party, it is felt necessary to go beyond the present scheduling systems for further optimization and make the system future ready. The envisaged changes in the near futures are as below:

5.4.1 Increase in transmission constraints

Maharashtra transmission system has already started observing transmission constraints in some sections and dispatches are being restricted to honouring these congestions. However, with the increase in demand and integration of renewable sources in a bigger way, the transmission constraints may tend to increase, and it will be difficult to handle more no. of constrained area with the present scheduling system.

5.4.2 Introduction of reserves

With the increase in quantum of the renewables, the real time system should have sufficient reserves to combat the variability of RE. It will be difficult in optimally allocating/provisioning the reserves with the existing system of scheduling system. The SCED has the facility of keeping reserves in the system in an optimal manner. Assessment of reserve price could be done in real time basis and accordingly decisions could be taken for ensuring grid security.

5.4.3 Optimum use of pump storage

Presently, the PSPs are being operated by distribution systems, However, with the increase in RE %age in the demand met, these PSPs are required be optimally used centrally by SLDC. The scheduling of PSPs could be done optimally by SCED model.

5.4.4 Operation of small hydro

Presently, the small Hydel resources are not optimally used. However, it may be required in future looking at the increased variability of generation resources which could be handles by the SCED model.

5.4.5 Requirement of Battery Energy Storage System (BESS)

Installation of BESS are being envisages in near future to take care the envisages high ramping of solar system as well as variability of RE. The requirement of BESS could be assessed with the implementation of SCED looking at the duals of ramping and the limiting constraints of conventional generation resources like technical minimum and Declared Capacity (DC).

5.4.6 Day-ahead Security Constrained Unit Commitment (SCUC)

Currently, unit commitment is not carried out in a scientific way. There is a need for a more systematic approach to unit commitment to ensure grid security and reliability, utilizing LP. Once expertise in LP-based modelling is developed, SCUC can be implemented..

5.4.7 Availability of more system specific information

With the implementation of SCED, more system specific information like System Marginal Price (SMPs), Marginal costs/Duals of different generator constraints e.g. Pmax, Pmin, Ramp-up & Ramp-down which will help SLDCs in operating system more optimally and reliably ensuring security.

5.5 Conventional Approach and LP- Functional Capabilities

MOD and LP offer different approaches to solving optimization problems. Understanding their key differences is crucial for selecting the appropriate method for specific applications. Here are the primary distinctions between the two:

5.5.1 Problem formulation

MOD: In traditional coding, optimization problems are solved by developing custom algorithms tailored to specific problem requirements. This approach involves writing detailed and often complex code to implement algorithms such as brute force search, greedy algorithms, dynamic programming, or custom heuristic methods. Each problem might require a unique algorithm, making the code highly problem-specific and potentially difficult to generalize.

LP: LP uses a mathematical approach to define optimization problems. Problems are formulated using a linear objective function that needs to be maximized or minimized, subject to linear constraints. The formulation is more standardized and abstract, making it easier to apply to a wide range of problems without needing extensive changes to the underlying model.

5.5.2 Complexity and scalability

MOD: The complexity of traditional coding can increase significantly with the problem size and complexity. Custom algorithms might not scale well, as their efficiency often depends on the specific nature of the problem and the skill of the programmer. Scaling up a solution typically requires substantial rewriting and optimization of code.

LP: LP models, once formulated, can be scaled more easily. Advanced solvers designed for LP problems, such as the simplex algorithm or interior point methods, can handle large-scale problems more efficiently than custom-coded algorithms. The mathematical nature of LP allows for more straightforward scaling and application to larger datasets.

5.5.3 Flexibility and adaptability

MOD: While traditional coding offers high flexibility in algorithm design, it can lack adaptability. Modifying a custom algorithm to accommodate new constraints or objectives often requires significant changes to the codebase, which can be time consuming and error prone.

LP: LP models are inherently more adaptable. Adding new constraints or modifying the objective function in an LP model is typically straightforward, involving changes to the mathematical formulation rather than the underlying solution process. This adaptability is beneficial in dynamic environments where problem parameters may change frequently.

5.5.4 Solver efficiency

MOD: The efficiency of custom algorithms in traditional coding depends on the problem and the algorithm design. While custom solutions can be highly efficient for specific problems, developing these algorithms requires significant expertise and effort. There is also a risk of suboptimal performance if the algorithm is not well designed.

LP: LP leverages powerful, well-optimized solvers that can efficiently find optimal solutions. These solvers, such as CPLEX, Gurobi, and Python, are the result of extensive research and development and are capable of handling complex and large-scale problems effectively. Using these solvers can lead to more reliable and efficient solutions than custom-coded algorithms.

5.5.5 Ease of use and maintenance

MOD: Custom-coded optimization solutions can be challenging to maintain, especially as the codebase grows or the original developers are no longer available. Debugging and updating the code require deep understanding and expertise, making maintenance difficult.

LP: LP models, especially when developed using modelling systems like GAMS or A Mathematical Programming Language , are generally easier to maintain. The high-level, declarative nature of LP formulations makes models more readable and easier to modify. Maintenance involves updating the mathematical model rather than rewriting complex code, simplifying the process significantly.

5.5.6 Integration and implementation

MOD: Integrating custom optimization algorithms into larger systems can be complex and time-consuming. The addition of new generators might require additional coding and adjustments to ensure compatibility with existing systems and data sources.

LP: LP models, particularly those implemented in specialized modelling environments, offer better integration capabilities. These systems often provide interfaces for data input and output, making it easier to integrate optimization solutions into broader workflows and systems. Additionally, they support interoperability with other software tools, enhancing their utility in various applications.

The key differences between traditional coding and LP lie in their problem formulation, complexity, scalability, flexibility, solver efficiency, ease of use, maintenance, and integration. While traditional coding offers high flexibility in algorithm design, it can be complex and less scalable. LP, on the other hand, provides a standardized, efficient, and adaptable approach to optimization, more flexible, making it suitable for a wide range of complex applications and easier to maintain and integrate into larger systems.

6. Development and Implementation of the LP-Based Model

"In the complexity of grids, every small efficiency unlocks massive savings."

6.1 Modelling of SCED Framework

The Maharashtra state has currently (as of September 2024) a total of 246 generators, including DISCOMs specific resources, of which 196 generators are responsible for the load balancing across various DISCOMs in the State. The peculiarity of the various intrastate generators along with their share, spread across DISCOMs, have been modelled in GAMS modelling framework for the purpose of the SCED. Although the actual implementation is curated as per current operating practice of MSLDC, the SCED model developed for analysis of MSLDC schedule, highlights various operating constraints while planning system resources.

6.1.1 Objective function

The objective function of SCED is to minimize the total variable cost of generation. It may be noted that the regulated power plants in India have a multi part tariff. The two parts of multi-part tariff are fixed cost and variable cost, with units in ₹/kWh (Rupees per kWh). For ease of refereeing the details of the modelling, referring MOD generators indicates G_{MOD} and $G_{non-MOD}$ generators unless specify otherwise. Based on the understanding from one month data (9th August to 9th September), equation (1) represents the objective function as the minimization of variable costs associated with the generator schedules available for optimization. (hereafter referred as MOD applicable generators) over 96-time blocks of the day. Other than the violation penalties in the objective function, the variable cost of MOD applicable generators have been included. It may be noted that the generators with subcontracts have been modelled as subunits and mapped to the actual unit. The violation penalties have been chosen greater than the highest variable cost generator.

$$\min_{\Xi} = \sum_{t \in T} \left(\sum_{i \in G_{mod}} P_{i,t} \times \gamma_i + \sum_{j \in G_{mod-oa}} \sum_{k \in N} P_{j,t}^{k} \gamma_j + VoLL \sum_{d \in D} P_{d,t}^{LS} \right) \qquad (1)$$

$k \in N_j$	Kth subcontract of the j^{th} Generators
$P_{j,t}^{k,c}$	Optimized schedule power of k^{th} subcontract of j^{th} generator (MW)
$P_{i,t}$	Optimized schedule power of i^{th} generator (MW)
$P_{d,t}^{LS}$	load shedding variable of $d^{th} DISCOM$ due to insufficient generation (MW)

VoLL	Value of lost load for the unserved energy due to insufficient generation (₹/kWh)
γ_i, γ_j	Variable cost of generator (₹/kWh)
$t \in T$	Set of time blocks in a day (|T|=96)
$i \in G_{mod}$	Set of generators that are MOD applicable and do not have the subcontracts
$j \in G_{mod-oa}$	Set of generators that has MOD applicable subcontracts
$d \in D$	Set of DISCOMs

6.1.2 Constraints

Various constraints both at the unit level and at the DISCOM level have been formulated while minimizing the cost of the generation scheduling.

6.1.2.1 Generation-Demand balance at State Level

The state's electricity demand is met by procuring generation from multiple sources, including interstate conventional generators (central share), renewable energy management centre (REMC), real-time market procurement (RTM), power exchanges (PX), standby generators, inter-DISCOM trades, and the remaining from intrastate generators. These responsible components for the state load generation balance are given in equation (2).

$$\sum_{d \in D} P_{d,t} = Centre + REMC + RTM + PX + Standby + InterDISCOM + \sum_{m} P_{m,t} + \sum_{d \in D} P_{d,t}^{LS} \tag{2}$$

$d \in D$	Set of DISCOMs
$m \in \{G_{mod}, G_{MOD-OA}\}$	Set of MOD generators

6.1.2.2 Generation-Demand balance at DISCOM level

In the state of Maharashtra, the share of each generation source listed in equation (2), is further divided among the various DISCOMs. The DISCOM-wise load generation balance is modelled using equation (3). The allocation of intrastate generation to each DISCOM is based on their respective percentage shares.

$$P_{d,t} = Centre + REMC + RTM + PX + Standby + InterDISCOM + \sum_{n \in \Lambda D_m^G} P_{n,t} + P_{d,t}^{LS} \tag{3}$$

$n \in \Lambda D_m^G$ Set of MOD generators that are mapped to the DISCOMs

6.1.2.3 Maximum generation

The maximum generation of MOD generators is constrained by their declared capacity (DC), which serves as the upper bound for generation. Equation (4) models this upper bound for MOD applicable generators. Additionally, during unit trips or when generators are ramping up/down, the upper bound has been relaxed. This adjustment is incorporated through the input parameter $v_{m,t}$ allowing flexibility in generation limits under such conditions.

$$P_{m,t} \leq v_{m,t} \mathrm{P}_{m,\mathrm{t}}^{\max}, \quad \forall \mathrm{m} \in \{\mathrm{G}_{\mathrm{mod}}, \mathrm{G}_{\mathrm{mod-oa}}\}, \mathrm{t} \in \mathrm{T} \tag{4}$$

$$v_m = (1 - Z_m(t))(1 - U_m(t)), \quad \forall \mathrm{m} \in \{\mathrm{G}_{\mathrm{mod}}, \mathrm{G}_{\mathrm{mod-oa}}\}, \mathrm{t} \in \mathrm{T} \tag{5}$$

$P_{m,t}^{max}$	Declared capacity of the m^{th} generator (MW/time block)
$v_{m,t}$	Input parameter to relax the operation limits of the generators
$Z_{m,t}$	Input unit commitment status of the generator
$U_{m,t}$	Input unit trip status of the generator

6.1.2.4 Technical minimum

At generation levels below the technical minimum, the variable charges are insufficient to cover the cost of production. To manage this, a minimum turndown level constraint, as outlined in equation (6), has been modelled for all the generators. Similar to the maximum generation constraint, the technical minimum is adjusted during time blocks when units are ramping up, with these adjustments accounted for by the input parameter $v_{m,t}$.

$$P_{m,t} \geq v_{m,t} \mathrm{P}_{m,\mathrm{t}}^{\min}, \quad \forall \mathrm{m} \in \{\mathrm{G}_{\mathrm{mod}}, \mathrm{G}_{\mathrm{mod-oa}}\}, \mathrm{t} \in \mathrm{T} \tag{6}$$

$P_{m,t}^{min}$ Generator technical minima

6.1.2.4 Ramp up and ramp down rate constraint modelling

The ramping capabilities of generators, in response to load variations, are modeled through equations (7) and (8). Equation (7) imposes the ramp up limit, based on the declared ramp rate for each time block, while equation (8) similarly enforces the ramp down limit. These constraints ensure that generators can adjust their output within the operational limits of ramping flexibility.

$$P_{m,t} - P_{m,t-1} \leq R_{m,t}^{up}, \quad \forall \mathrm{m} \in \{\mathrm{G}_{\mathrm{mod}}, \mathrm{G}_{\mathrm{mod-oa}}\}, \mathrm{t} \in \mathrm{T} \tag{7}$$

$$P_{m,t-1} - P_{m,t} \leq R_{m,t}^{down}, \quad \forall \mathrm{m} \in \{\mathrm{G}_{\mathrm{mod}}, \mathrm{G}_{\mathrm{mod-oa}}\}, \mathrm{t} \in \mathrm{T} \tag{8}$$

$R_{m,t}^{up}$ Declared ramp up limit per time block (MW/block)

$R_{m,t}^{down}$ Declared ramp up limit per time block (MW/block)

6.1.2.5 Transmission constraints

Until the optimal power flow being practiced, the current operational practices of modelling the transmission constraints are to enforce the limit on the generation. This is termed as the transmission constraint and has been modelled using the equation (9).

$$P_{m,t} \leq P_{m,t}^{limit}, \qquad \forall \mathrm{m} \in \{\mathrm{G_{mod}}, \mathrm{G_{mod-oa}}\}, \mathrm{t} \in \mathrm{T} \tag{9}$$

$P_{m,t}^{limit}$ Transmission limit on generators (MW)

6.2 Computational Tools and Software

6.2.1 Availability of GAMS license

It has been decided to use GAMS engine for optimization purposes across India (NLDC has used the same engine for national SCED implementation) to have a uniformity of implementation which will create a very strong group of experts on GAMS language and will facilitate future integration among the states if required for further optimization across region and on a national basis. The issue was taken up with World Bank and a ten-user license of GAMS was arranged for MSLDC for the study.

6.2.2 Capacity building exercise

In a view to have capacity building exercise across States, a no. of IITs were invited to prepare a standardised training module. Accordingly, a meeting was scheduled on 5th August 2024 over video conference when the two-day module was finalised. A signed report is attached as Annexure – I.

Based on the standardised module, Prof. Zakir Hussain Rather, GIL, IITB had given his consent to conduct the two-day capacity building program for SLDC, Maharashtra on development of optimization module using GAMS. The two-day program was convened on 2nd & 3rd September 2024. The sessions were taken by Prof Zakir Hussain Rather and his two research scholars, Sh. Akhilesh Panwar and Sh. Pratosh Patankar. A brief report on the workshop is attached as Annexure – III, A feedback report on the capacity building workshop is placed as Annexure – IV.

6.2.3 Data extraction & preparation

As the study was to be carried out on past data, it was decided to extract the required data from the existing database in a format compatible with GAMS. The "TEST

Server" which is a development server available in the existing scheduling system was earmarked for the optimization study and necessary configuration changes were made to accommodate the additional data within the system.

The excel has been used as the interface for input/output of the GAMS model. The input file was prepared through extracting data from the past database and handed over to IITB team for further processing.

The team from Grid Integration Lab (GIL) IIT Bombay along with MSLDC team led the development of the optimization code and for the study purposes.

It is pertinent to mention here that access to the database of the scheduling system was not available to the SLDC engineers and hence the team had to depend on the engineer of their system integrators for extraction of the data.

As there was no clear understanding of the data with the system integrator, the verification of the extracted data had to be carried out in detail and was a time-consuming activity with lots of effort to have quality data for optimization.

Direct integration of the system was not possible as the integration was to be done by the system integrator of the scheduling system, and they were not ready to integrate the system as the period under the study was small. Accordingly, all the extraction and validation of data was done manually.

6.2.4 Data processing

6.2.4.1 Data pre-processing

The received data (schedules, DC, etc) for using in the Optimisation engine needs to be pre-processed for checking the correctness and to remove inconsistencies. The schedules of generation and drawl of each generator are checked for correctness. Further, the constraints like Pmax. Pmin DC and DC on bar are revised based on the received schedule data in case of mismatch. Sometimes generators, specially must run generators, need to be excluded from the optimization due to various real time constraints based on operator inputs which are also taken care of during the pre-processing of data. All the constraints e.g. Pmax, Pmin, DC & DC on bar are made equal to schedule to ensure that there is no change in generator schedule due to optimization. The pre-processing requirements gradually tunes based on the observation of the performance of the engine and requirement felt during operational phase.

6.2.4.2 Data post-processing

Data post processing is also an important activity in the optimisation cycle. Firstly, in case of infeasibility, the generator constraints are violated which are clamped to its constrained limit during post processing. This has very minor effects on system frequency. Secondly, non-convergence in the engine can occur for various reasons e.g. communication failure to collect input data or sudden errors in some input data. In case of non-convergence, net of the schedules becomes non-zero and SMP values become erratic. In such cases, the output values from the optimisation engine are rejected and again the process is rerun after collecting and checking the data again. In case the non-convergence is observed without any quality issue of the input data, the optimisation engine is re-run after relieving the constraints like ramp rate as this constraint cannot be honoured. Data post processing requirement also needs to be tunes on continuous basis during the observation and analysis.

6.3 Optimization through GAMS

An Excel-based interface was used for the GAMS optimization engine developed. 32 days data was extracted and converted to the GAMS acceptable Excel format and optimization was done on a day basis and the output is stored also in Excel format for further analysis. The GAMS code developed for implementation of SCED framework is added as Annexure – IV.

Penalty functions have been incorporated into the objective function to address constraint violations, providing a structured approach to manage scenarios where constraints cannot be strictly satisfied. These penalties serve as a cost mechanism, discouraging the model from violating constraints by assigning a high "penalty cost" when limits are exceeded, such as in ramp rates, generation capacity, or technical minimums. By increasing the objective function's value when violations occur, the model is incentivized to prioritize feasible solutions that meet all constraints as closely as possible. This approach helps balance the optimization objectives—like cost minimization—while still adhering to operational and security requirements. In power systems, penalties for constraint violations help grid operators make informed trade-offs during real-time dispatch, ensuring stability and reliability even when perfect compliance with constraints is not achievable. The following penalty cost have been considered in the present model:

Ramp (up & down): ₹20 /kWh

Load shed: ₹25 /kWh

Excess generation: ₹30 /kWh

However, further work needs to be carried out on the value of the penalties to be applied for different constraints.

6.4 IT Infrastructure

The present IT infrastructure caters the present requirement of running the present software module for MOD and all the data interfaces are available for collecting the required data for scheduling in real time basis. It is proposed that the developed optimization module will be run on a parallel system on receipt of scheduling data updated in each 15 mins. The schematic diagram is shown in Figure 3.

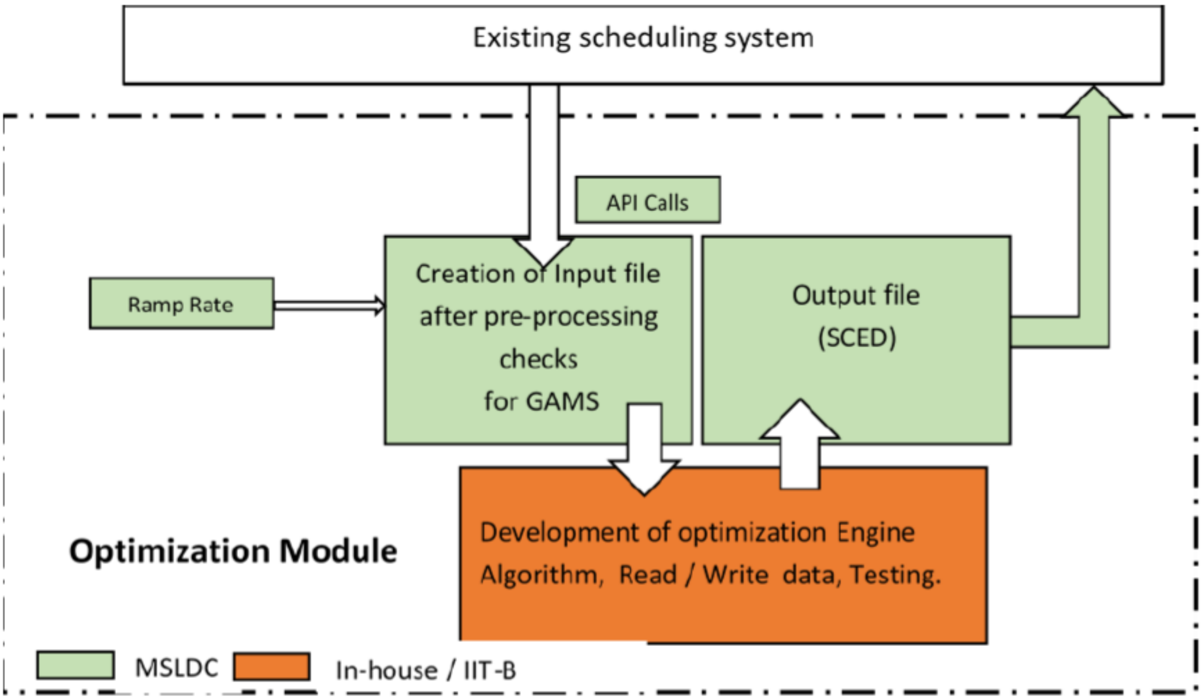

Figure 3. Proposed system implementation

The proposed pilot can be run on the existing IT infrastructure, as it does not require significant processing power for the parallel system. Initially the output may be examined on the a excel based visualisation. However, a visualization platform shall be developed for daily visualization at the time implementations.

It should be noted that fail-safe infrastructure is not planned during the pilot operation, as it will not impact the real-time system. However, a fail-safe infrastructure will be required to run the optimization on real time basis. Through the actual infrastructure could be designed at the time of implementation, it is proposed to have a hybrid system of on-premises and cloud-based system with the back-up system being hosted in the cloud. It will lead to a capital investment for the on-premises infrastructure whereas and recurring annual expenditure for the cloud-based back-up system.

The following additional on-premises infrastructure is envisaged:

1. 32 core high end server incl. OS : 2 nos
2. Database license : 1 no
3. Front end application license : 2 sets
4. Storage system (500GB) : 1 no
5. Cyber security & networking : 1 set
6. Installation cost : Lump Sum

An approximate capital expenditure of **₹ 2 – 3 Cr.**

Further, recurring annual expenditure shall be required to support the cloud-based system.

6.5 Settlement Systems

Presently VSE pool is existing to settle the differential schedules generated due to centralized scheduling as and when invoked. With the implementation of the SCED within the States, there will be change in schedules of the generator on the prepared schedules before optimization (prepared based on contracts), these difference needs to be settled. Further, there will be cost savings generated due to optimization which needs to be settled also through proper appropriation. Further, in case the cost compensation is directed by Hon 'able Commission for the reduced heat rate of the generators, the same also to be compensated from this saving generated. Since the requirement of this settlement is one to many and many to one type, a dedicated pool account needs to be maintained. Energy accounting for SCED optimized schedules needs to be done by the SLDC for participating generators on monthly basis with day wise resolution figure made available in the SCED account based on the available schedule data.

Appropriation of benefit generated due to optimization:

The net benefits as a result of SCED optimization after adjusting heat rate compensation for part load operation of the generator are to be shared as per direction of SERC. The benefits corresponding to the SCED generator out of the total Net SCED benefits can be distributed in the ratio, as decided by the SERC say in the ratio between the SCED generators receiving SCED up and SCED down respectively. This shall be based on the block wise SCED up and SCED down energy aggregated on monthly basis. Similarly, the benefits of the beneficiaries are generally distributed based on the final schedule of import from the participating generators. There are finer methods of distribution which can be as per the dual and values derived from the simulation, and these are future refinements as the maturity is achieved. A detailed procedure needs to be prepared for the benefit sharing for the approval of the respective regulator.

6.6 Formation of Working Sub-groups

The past data was extracted, and study has been carried out which are detailed in the next chapter. Four sub-groups were formed with dedicated responsibility for carrying out the study and analysing the output of the optimization through GAMS.

1st Sub-group: Automatic data retrieval and verification.

2nd Sub-group: GAMS programming

3rd Sub-group: Report and compilation

4th Sub-group: Data integration and storage

The office order in this regard is attached as Annexure – IV.

6.7 Human Resource Requirement

Presently, the sub-groups have been formed for the study and preparation of the reports and planning the future activities for pilot operation. However, it may be submitted that these manpower are shared resources who all have their decicated day to day routine activities allocated and dedicated manpower shall be required for the implementation of this optimization activities and subsequent maintenance requirement as it is proposed to be an in-house development, operation and maintenance. The dedicated resources envisaged for this actiities are as follows:

1.	GAMs coding and maintenance	: 2 nos
2.	IT infrastructure	: 2 nos
3.	Development of visualization	: 2 nos
4.	Data analysis	: 2 nos
5.	Preparation of accounts	: 2 nos
6.	Financial settlements & audit	: 2 nos
	Total	: 12 engineers

7. Comparative Analysis of SCED and MOD

“In the race for efficiency, every megawatt saved is a step toward sustainability.”

The total demand of the state is shared by interstate generators including the RE plants, RTM, power market, inert discom trades and intrastate generators. The remaining demand, after accounting for the contributions from fixed sources, has been allocated among the intrastate generators governed by the MOD. The MOD applicable intrastate generators are categorised based on the MOD applicability and availability of the subcontracts as follows :

1. Generators that do not have subcontracts and MOD applicability. All such generators are scheduled separately, and their schedule is considered as input to the SCED model.
2. Generators that do not have the subcontracts but have MOD applicability. All such generators are part of the optimization.
3. Generators that have subcontracts, but do not have the MOD applicability. All such subcontracts are scheduled separately, and their schedule is considered as input to the SCED model.
4. Generators that have subcontracts with MOD applicability. All such subcontracts are part of the optimization.

Some of the generators have multiple subcontracts with different DISCOMS. Such multiple subcontracts of the generators are mapped to the physical units for maintaining the operational constraints. Based on generator categorization discussed earlier, the linear SCED program has been modelled in the GAMS modelling framework and solved for target injection of the generators for the following operating scenarios:

Case	Case description
Base Case	In this case, constraints used in MOD have been considered including DC, technical limits, Ramp rates etc.

Note: The data has been extracted, thoroughly cleaned, and prepared for compatibility with the SCED module. However, it may be mentioned here that all limits as required in SCED may not be defined in the same manner. The comparison of the results has been done keeping this deviation in to consideration.

7.1 Net Demand

The SCED model has been executed for the one-month data in the base case, where the current operational practices have been modelled. The total demand of Maharashtra fluctuates from around 19 GW to a peak of nearly 29 GW. For this study, we have focused exclusively on the net demand curve to illustrate the optimization from intrastate generators participating in MOD. Specifically, the net demand curve is derived by subtracting from Maharashtra's total demand all must-run generation sources, such as renewable energy, hydro, ISGS allocations, and certain non-MOD contracts. This approach carved out the net demand met by only intra-state generators that are under MOD, facilitating the SCED analysis for those within its scope. In future pilot efforts would be made to bring more generation resources withinwith inwithin the ambit of intrastate SCED. The aggregate scheduled generation is shown in Figure 4 and is compared with the case of the scheduled generation under MOD framework. The overlap between the SCED and MOD scheduled aggregate generation forms the common basis for the comparison of MOD and SCED.

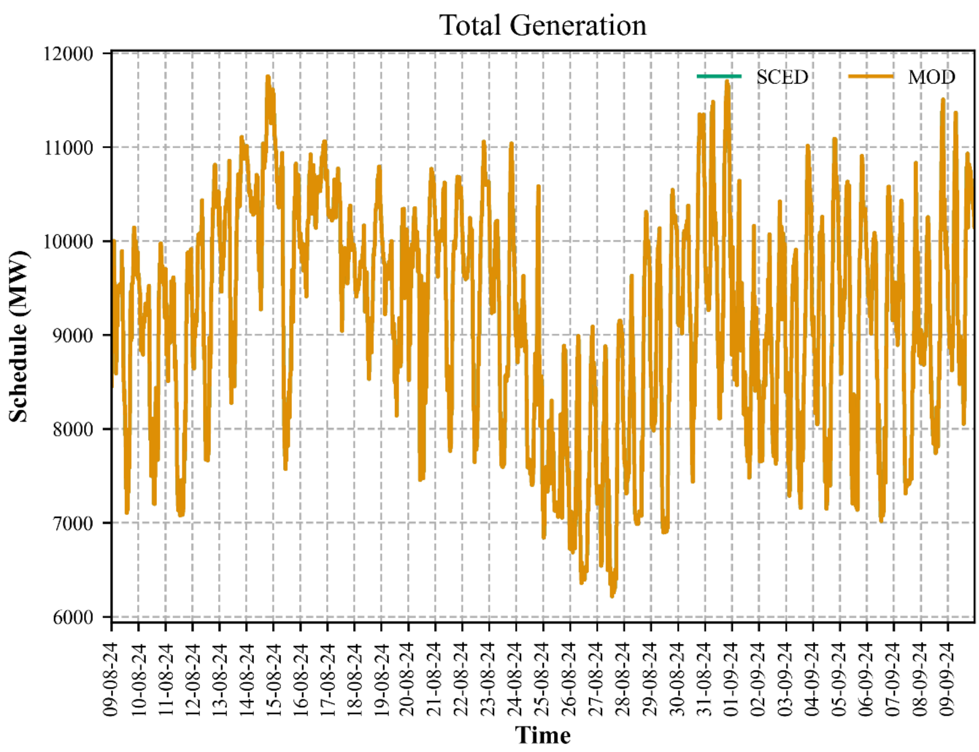

Figure 4. Total Generation of MOD and SCED

The scheduled generation for both MOD and SCED framework for all time blocks (TB) on a sample day (02-09-24) is shown in Figure 5. The corresponding percentage ramp rate observed in the net demand is shown in Figure 6.

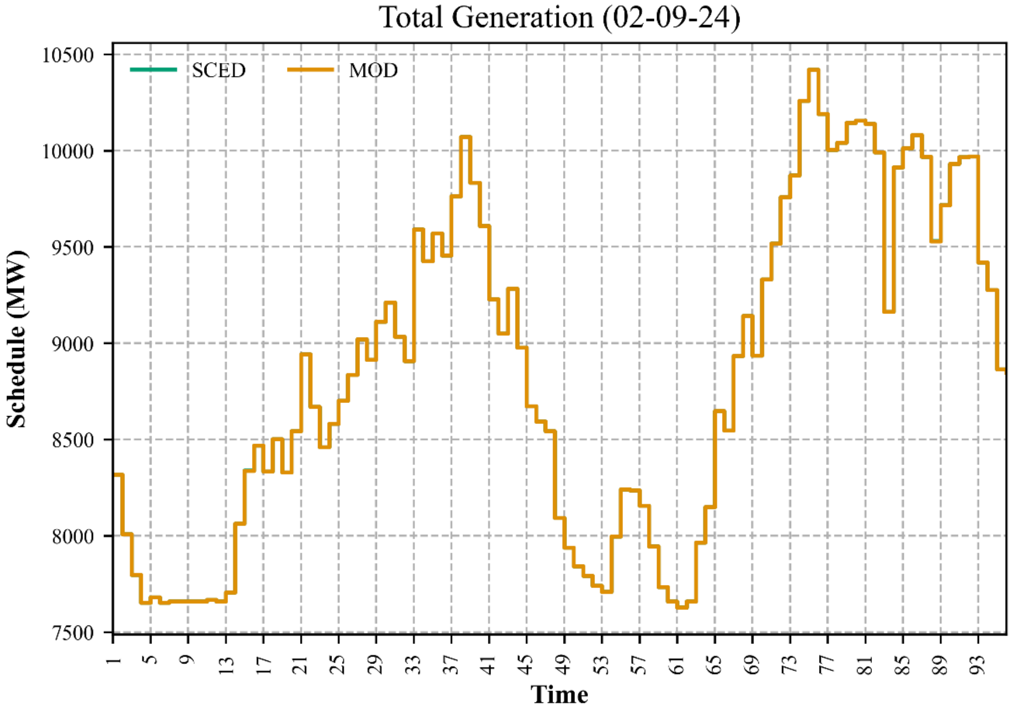

Figure 5. Total Generation of MOD and SCED for a sample day

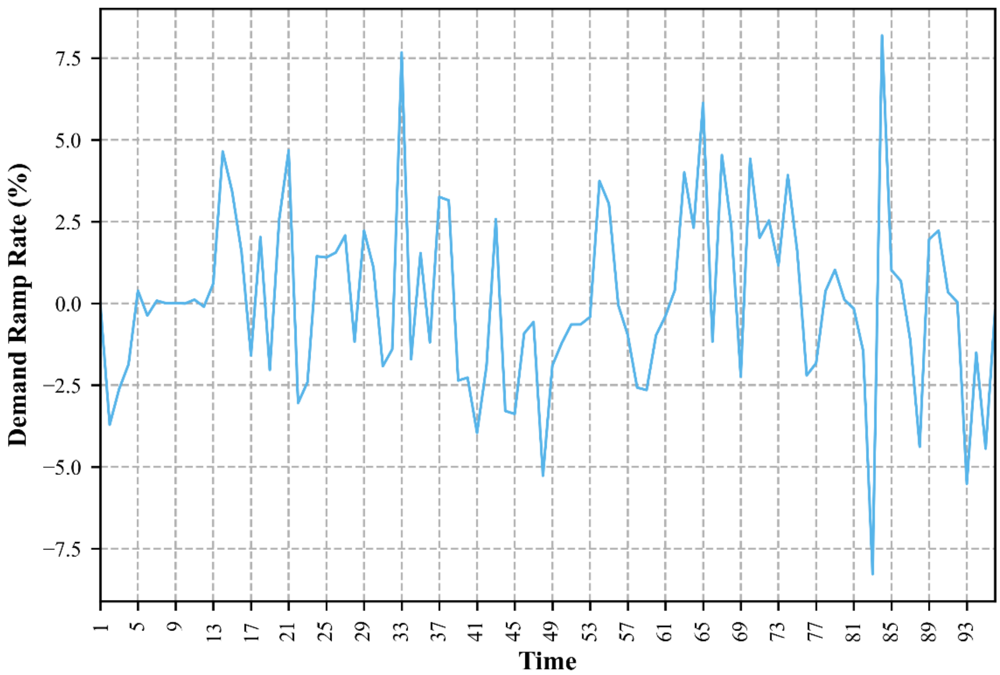

Figure 6. Variation in demand ramp on a sample day (02-09-24)

Based on the net demand shown in Figure 4, the variation of total cost under MOD and SCED for entire duration of study and for a sample day along with the block wise per unit cost difference have been shown in Figure 7, Figure 8 and Figure 9 respectively. Figure 7 shows the block-wise total cost of SCED and MOD for the total duration of study. The variation in block-wise total cost of generation for a typical day (2nd Sep 2024) is shown in Figure 8. It can be observed that there are cost savings in SCED mainly during low demand period. It is clear that optimization is only possible during a period when the demand is low when the low-cost generation is maximized, and high-cost generation is pushed to a technical minimum limit. However, when the demand is high, the possibility of optimization is very low as all the generation is maximized in both MOD and SCED framework.

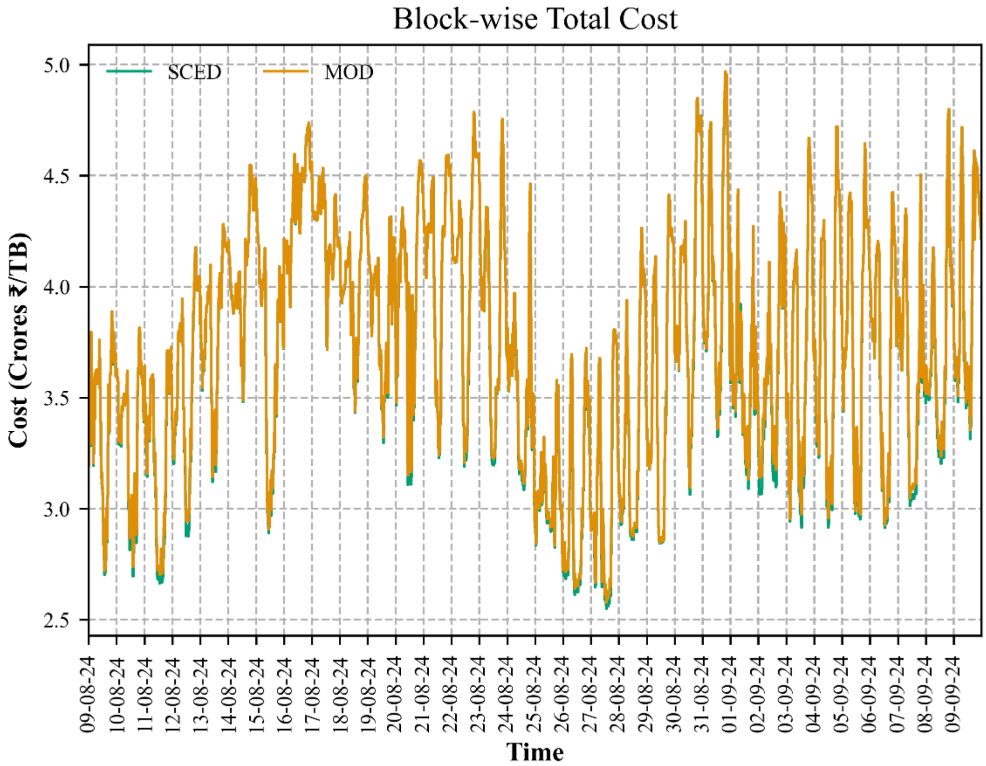

Figure 7. Block wise total cost of MOD and SCED

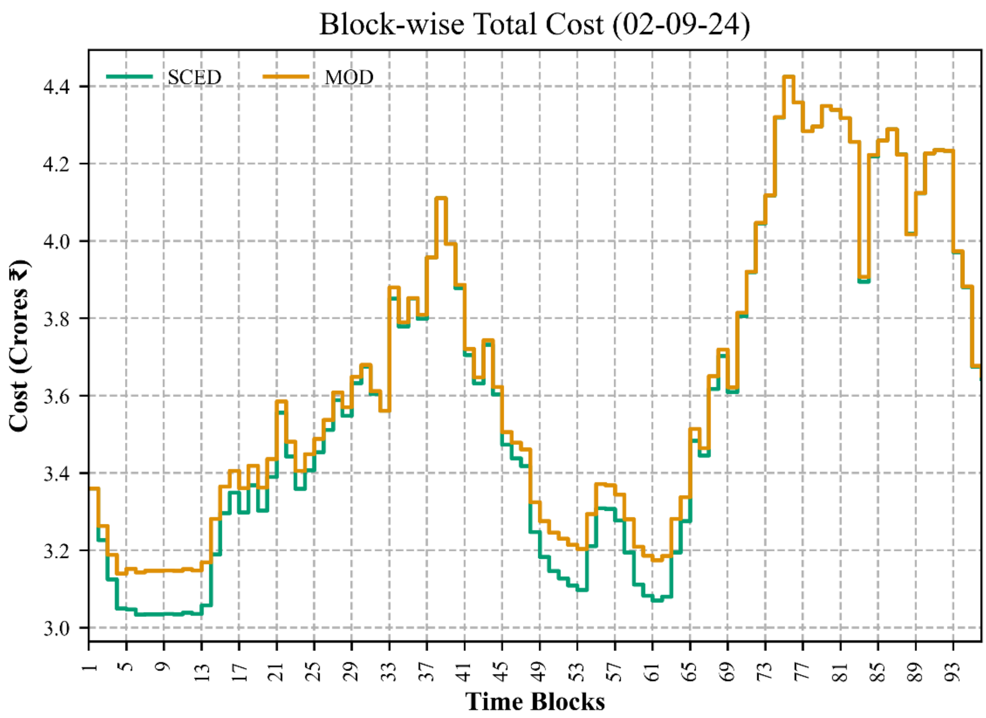

Figure 8. Diurnal plot of block-wise cost for a single day

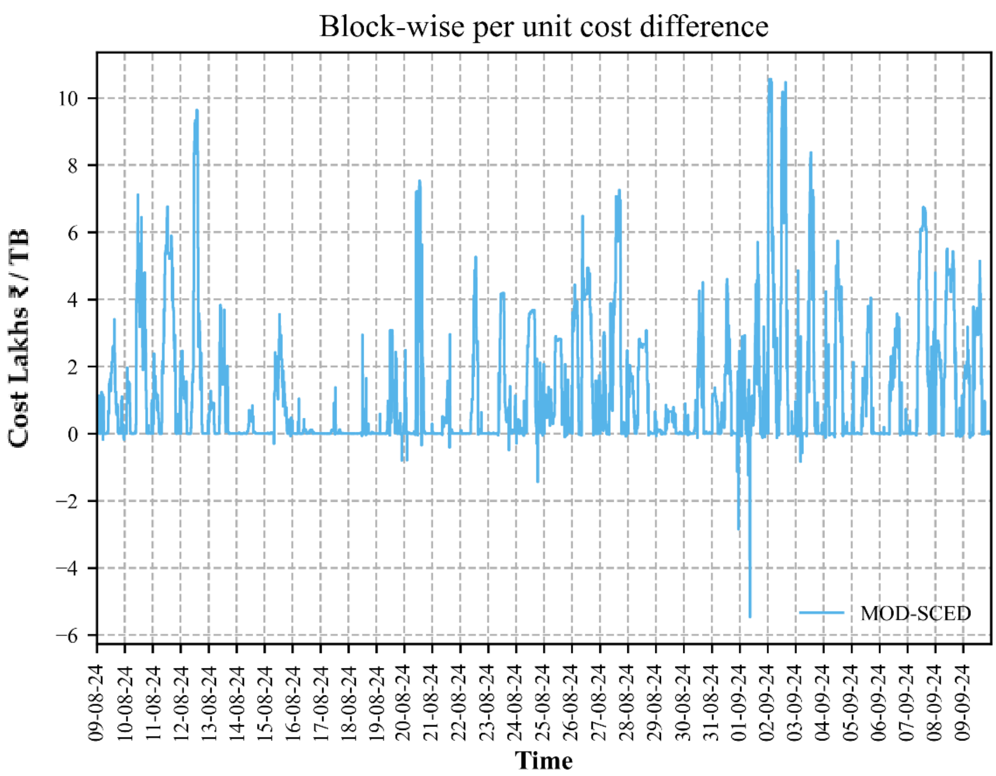

Figure 9. Block-wise per unit cost difference of MOD and SCED

It can be noted that cost savings were achieved in nearly all blocks, with only a few exceptions. In Figure 9, the negative values in few blocks indicate that SCED prioritized system constraints such as ramping capabilities, generator transmission limits, and technical minima. SCED penalizes the objective function with a high variable cost of ₹ 20 in such instances and therefore SCED cost is higher.

A comparison of the total cost, along with the specifics of the days with minimum and maximum savings, has been made in Table 4. The table compares the overall generation costs and savings for MOD and SCED in crores ₹ . SCED analysis suggests potential cost reduction of around 0.25%. Day wise minimum (0.01%) and maximum (0.86%) potential savings in SCED compared to MOD are observed on 16th August and 2nd September 2024 respectively.

Table 4: Total cost and %age savings

	MOD Cost (₹ Cr)	SCED Cost (₹ Cr)	Savings (₹ Cr)	%age Reduction
Total Period of Study (9th Aug-24 to 9th Sep 24)	**11,444.56**	**11,415.75**	**28.81**	**0.25**
Minimum Saving Day (16th Aug-2024)	**422.22**	**422.18**	**0.04**	**0.01**
Maximum Saving Day (2nd Sep- 2024)	**349.28**	**346.29**	**3.00**	**0.86**

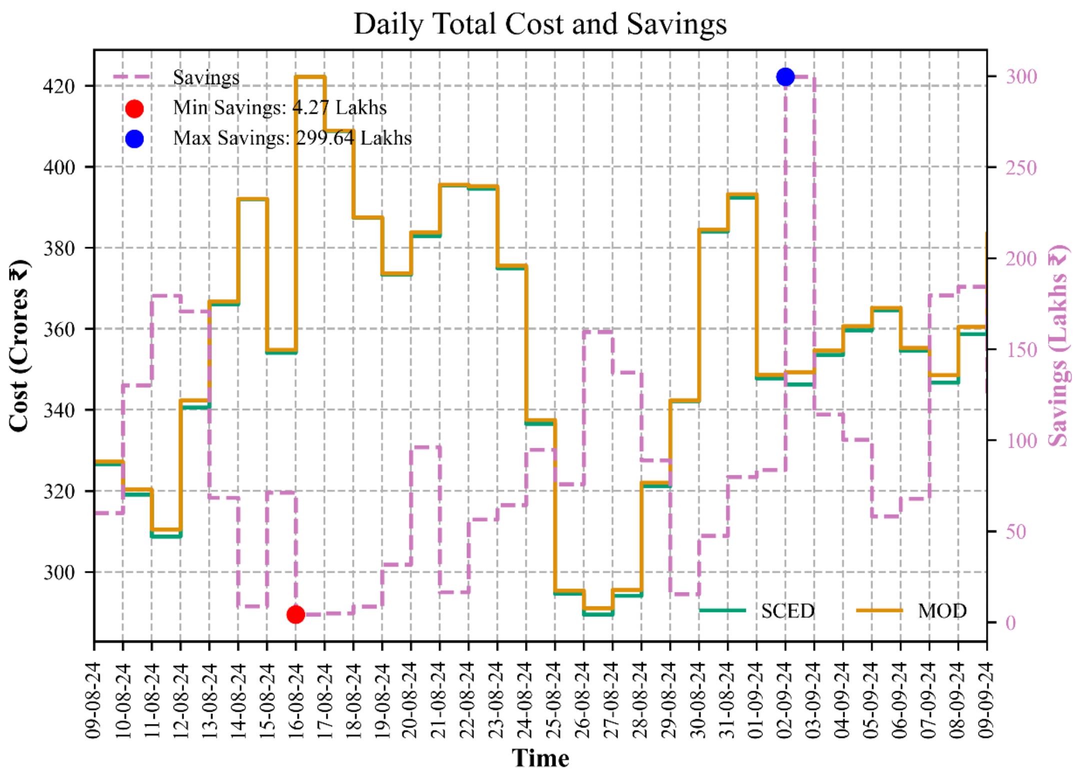

Figure 10. Daily cost savings

It can be observed from Figure 10, that there are positive cost savings in all the days despite negative savings during some blocks in a day due to honoring of security constraints by SCED framework.

Besides the days with minimum and maximum savings, Figure 10 highlights the day-by-day comparison of total costs and savings, highlighting the savings potential for the other days.

Figure 11 shows the block-wise variation of per unit cost during the study period. It is observed that per unit cost is also reduced due to generation optimization by SCED. It can be observed that there is a jump on 16th August 2024 when the variable cost of the generator is revised. Presently, the MOD stack is declared on a fortnight-basis which gets effective on 16th day of the month.

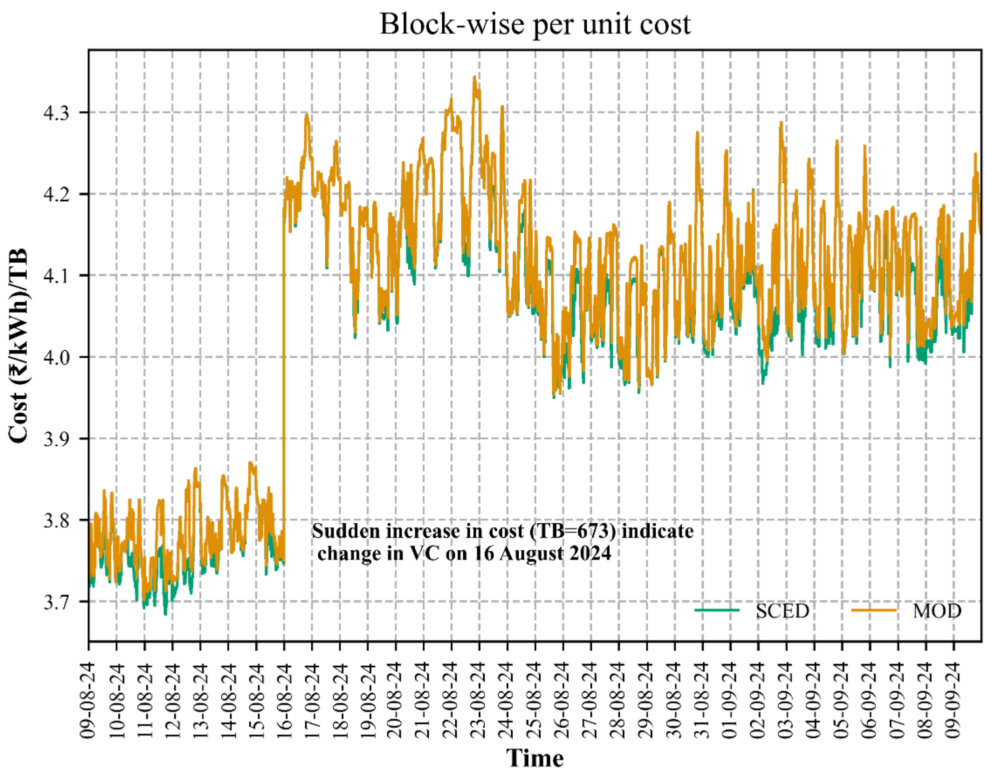

Figure 11. Block-wise per unit total cost.

Figure 12 shows the duration plot of total cost. The plot clearly shows that for around 50% of the time there were positive savings due to optimization through SCED.

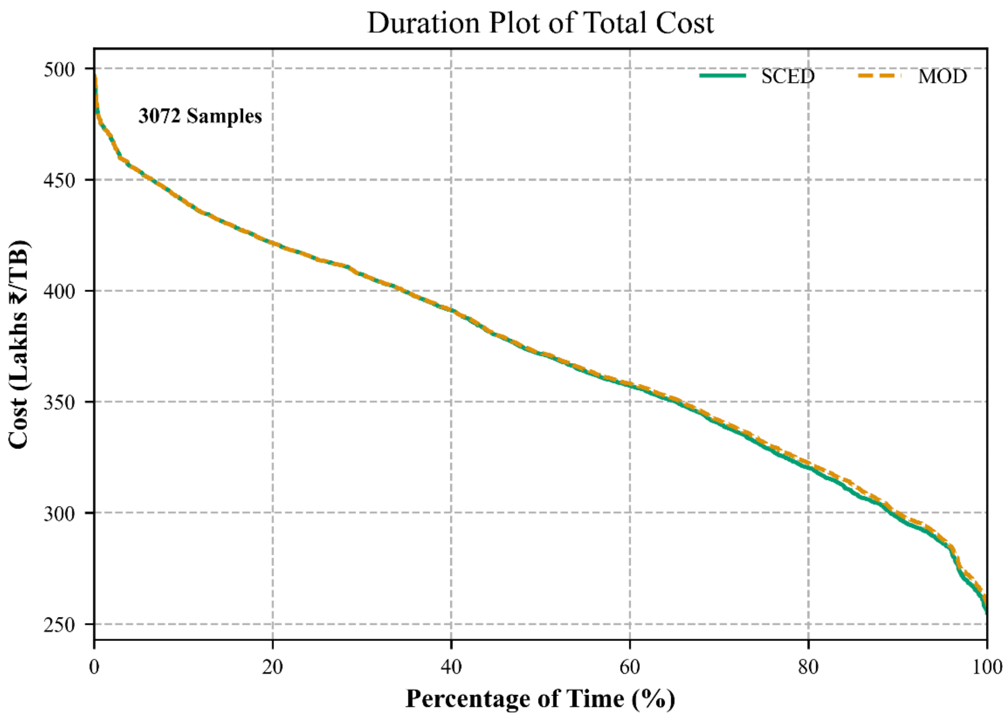

Figure 12. Duration plot of cost difference

The variable cost of each generator which was effective during the period of study has been plotted in ascending order which is shown as Figure 13. It can be observed that the variable cost has been revised on 16th August 2024 , and as a result, a sudden jump in the block-wise aggregate generation cost can be observed as indicated in Figure 11.

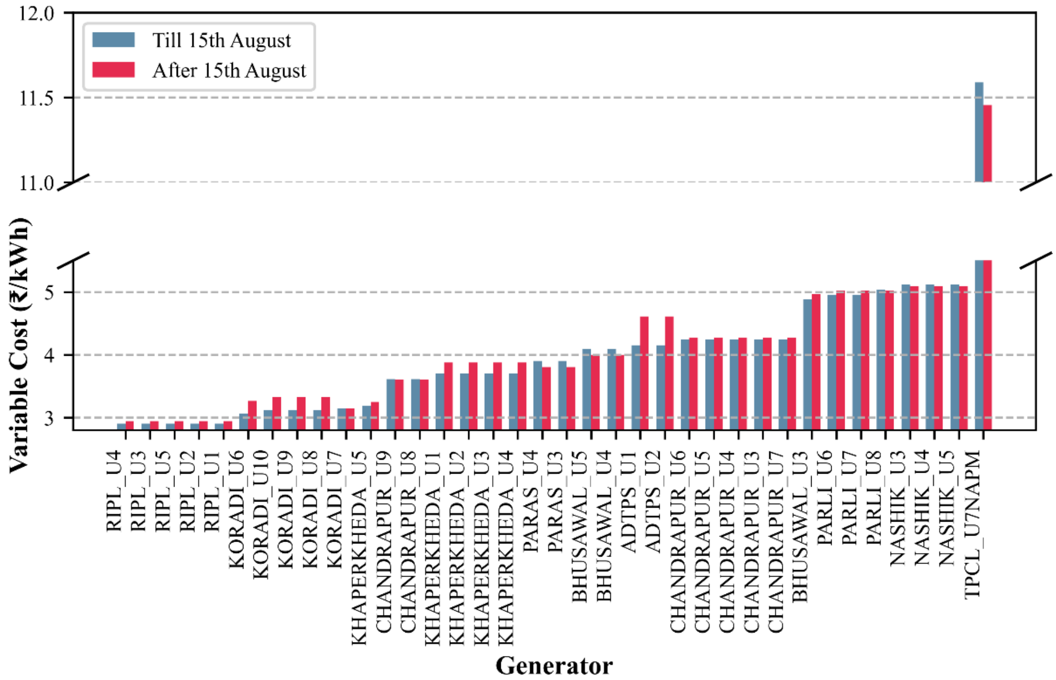

Figure 13. Variable cost in ascending order

Figure 14 shows the duration plot of cost difference between MOD and SCED. The plot clearly shows that for around 45% of the time there are positive savings due to optimization through SCED framework, whereas there are near zero savings for around 44% of the time and there is negative savings with SCED framework for approximately 1% of the total time.

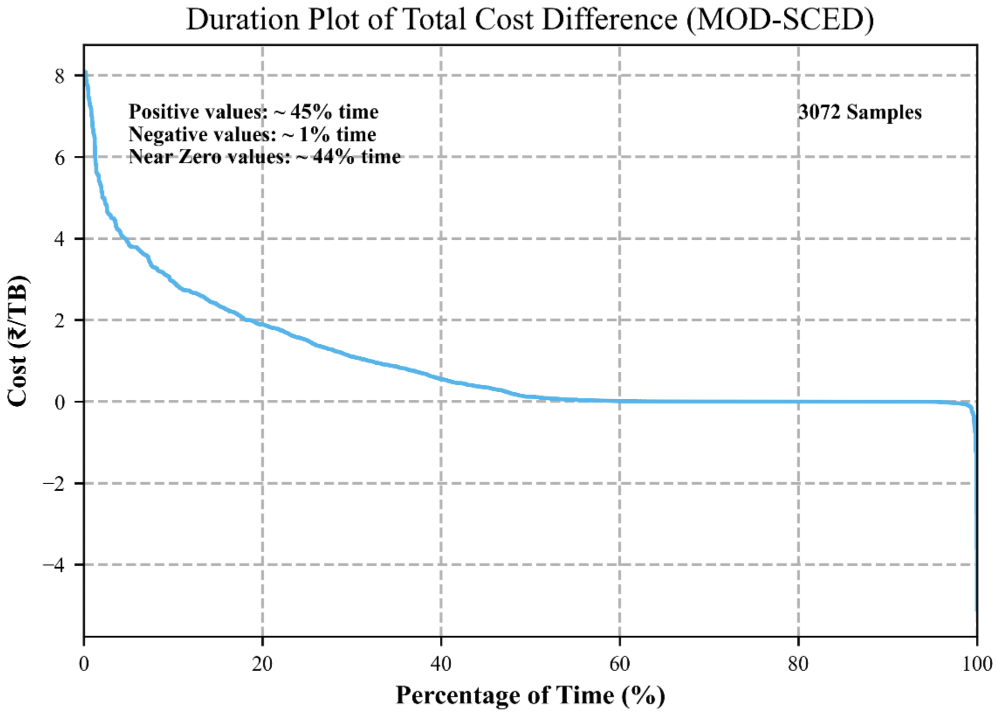

Figure 14. Duration plot of cost difference.

In Figure 15, the scatter plot illustrates the relationship between total cost (in Lakhs ₹/TB) under SCED and total power (in MW). The data shows a strong positive correlation (R^2 = 0.914), with the trendline equation y = 0.04X + 18.39 indicating that for each increase in total production cost with rise in demand met. The increase is ₹ 4000 per MW rise in demand. The dispersion of points around the trendline suggests variability in the SCED process, where costs are influenced by security constraints to ensure system reliability. The two clusters in the plot highlight a shift in the variable costs of generators after August 15. Due to this change in variable costs, the overall generation cost in each block has shifted, resulting in the distinct clustering observed in the data. This reflects the dynamic nature of SCED, where changes in generator costs can significantly impact dispatch outcomes.

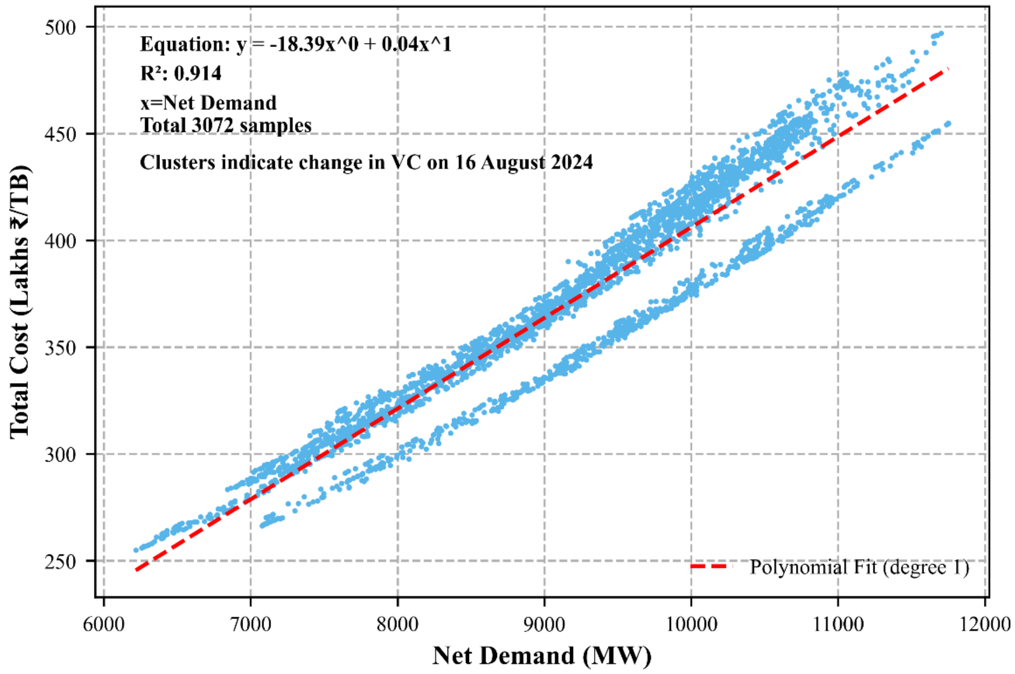

Figure 15. Scatter plot between total cost and demand met.

In Figure 16, the scatter plot shows the relationship between total savings (calculated as MOD cost minus SCED cost, in Lakhs ₹/TB) and total power (in MW). The data appears centred around zero savings, with a dense cluster of points near the origin.

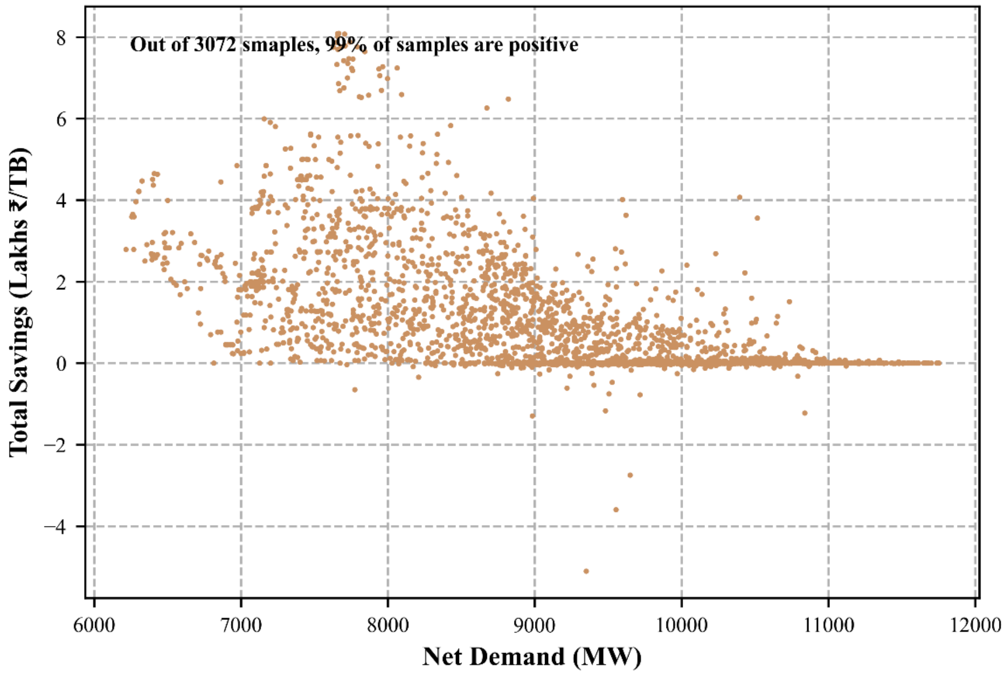

Figure 16. Scatter plot between saving and demand

This suggests that, for most cases, the cost difference between MOD and SCED is minimal when the demand is high. However, there is notable variability and there was saving to the tune of ₹ 2 lakhs to ₹ 4 lakhs when the demand was within 7500 MW to 8500 MW. It is also observed that for 99% of time, there are positive savings, and for balance 1% of time, there are negative savings which indicate that SCED penalises the objective functions due to violation of constraints.

The following sections provide a detailed comparison of the generator scheduling and cost differences between MOD and SCED, focusing on the block-wise and day-wise variations. The analysis highlights periods of significant savings and identifies the factors driving cost increases under SCED, including system constraints and variable charges.

7.1.1 Generator-wise cost comparison:

To summarize the cost differences across the generators, this section begins with spider plots illustrating the total costs and their variations between MOD and SCED, enabling a better understanding of the impact of each generator on overall cost dynamics.

Figure 17 shows total energy generation in both MOD and SCED simultaneously for a direct comparison for each unit. In some cases, like RIPL_U1 and KORADI_U6, SCED generation significantly exceeds MOD generation. Conversely, units like KHAPERKHEDA_U1 and CHANDRAPUR_U9 exhibit much lower SCED generation relative to MOD, the overall pattern suggests that MOD prioritizes some units based on a merit order principle, while SCED adjusts for constraints and optimizes system-wide efficiency, potentially leading to better utilization of certain units

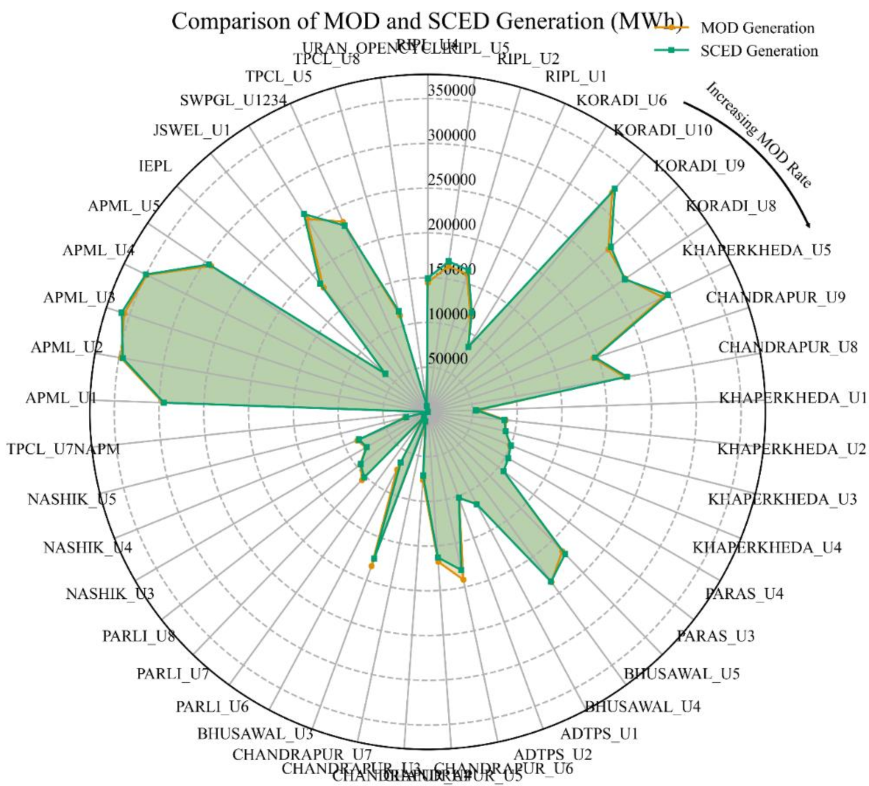

Figure 17. Plant wise total generation comparison

Similarly, Figure 18 shows the total cost difference in MoD and SCED which also clearly shows the SCED cost is higher in cheaper plants than in MoD. Figure 19 shows the difference of MOD and SCED generation for various generating units. The radial axis measures the difference in energy generation between the MOD and SCED schemes, with positive values indicating that MOD dispatch is higher than SCED, while negative values suggest the opposite. There is a clear deviation among different units, with some units showing a significant negative difference (e.g., KORADI_U6, RIPL_U1), indicating that these low-cost units generate less under MOD. In contrast, others, like units from CHANDRAPUR and KHAPERKHEDA, the higher cost units show a positive difference, signifying a higher output under MOD, the mid-range plants. The arrangement of units along the circular axis appears to follow an increasing MOD rate as indicated by the arrow.

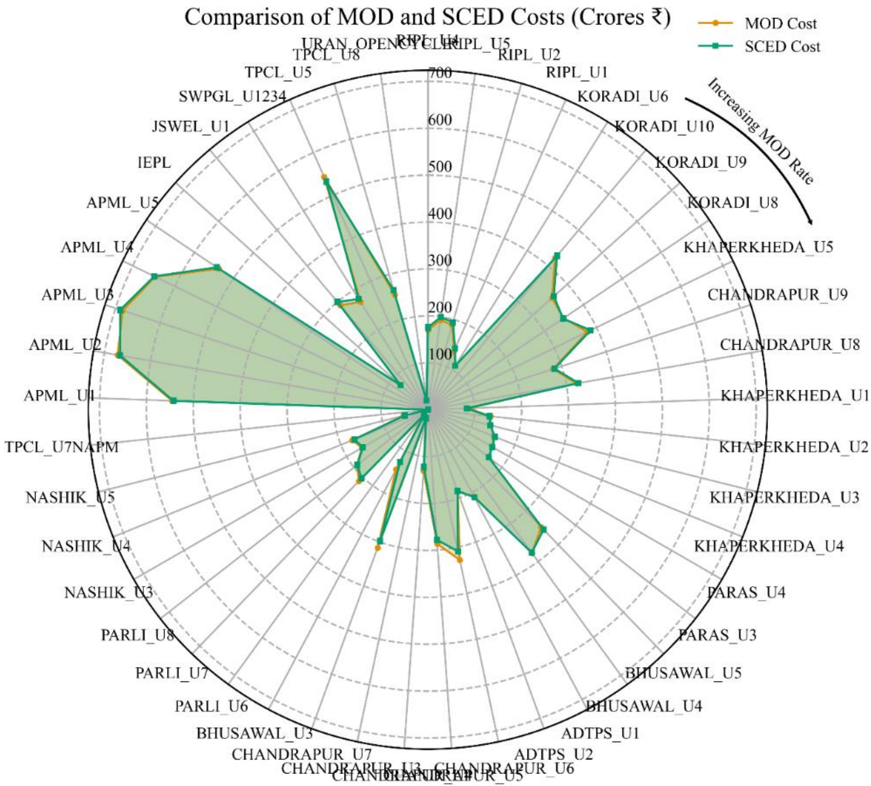

Figure 18. Unit wise total cost comparison

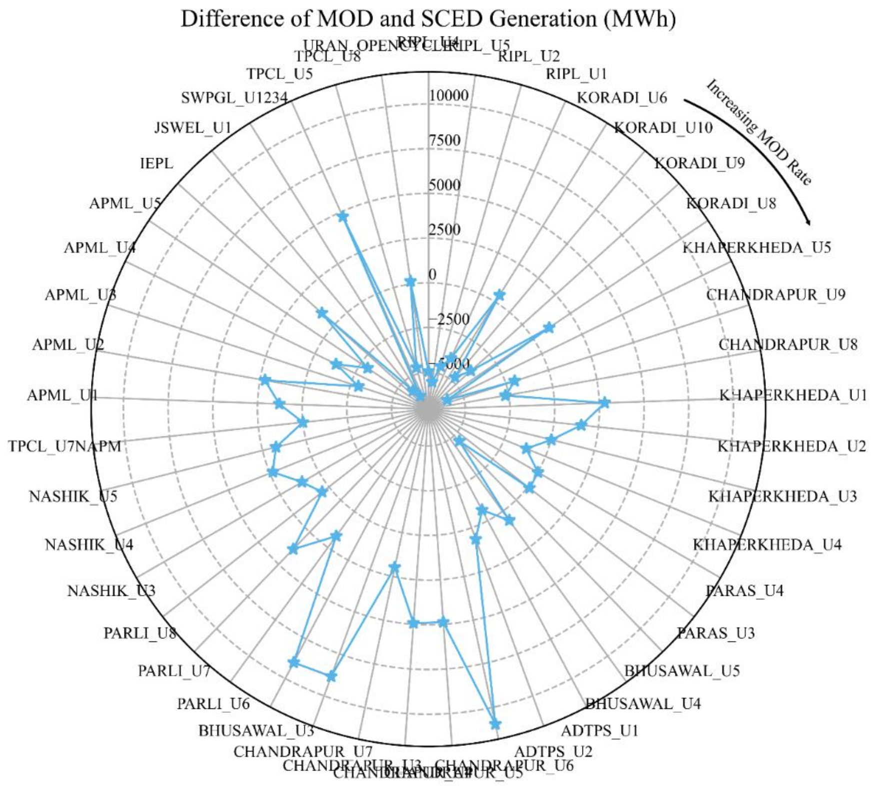

Figure 19. Energy generation difference in MOD and SCED

Figure 20 display the generator-wise cost differences. The potential for cost-saving opportunities primarily lies in the scheduling of generators. It highlights the plant-wise differences, identifying units from KHAPARKHEDA, CHANDRAPUR, BHUSAWAL, and TPCL as candidates for achieving cost savings. Notably, the variable charges for these units are higher compared to the RIPL units, which are predominantly utilized during scheduling in SCED for cost savings.

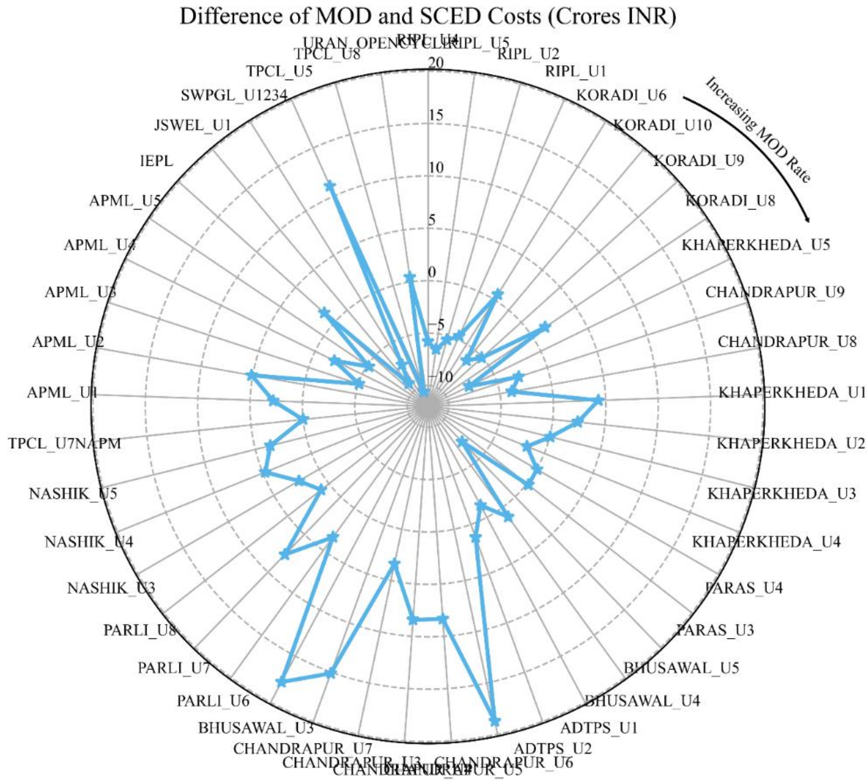

Figure 20. Cost difference in MOD and SCED

7.1.2 Generator-wise scheduling differences

Figure 21 shows a heat map for visualizing the difference between SCED and MOD schedules across time blocks and generators. The plot reveals substantial variability in the difference between SCED and MOD dispatch across time, suggesting that the two strategies are highly dynamic and adjust according to Cost and the constraints. The plot clearly shows that the units like RIPL, Koradi, Khaperkheda generation were increased to the tune of 200 MW whereas the high-cost units like Chandrapur, Bhusawal was reduced. This is the main source of cost savings in the SCED.

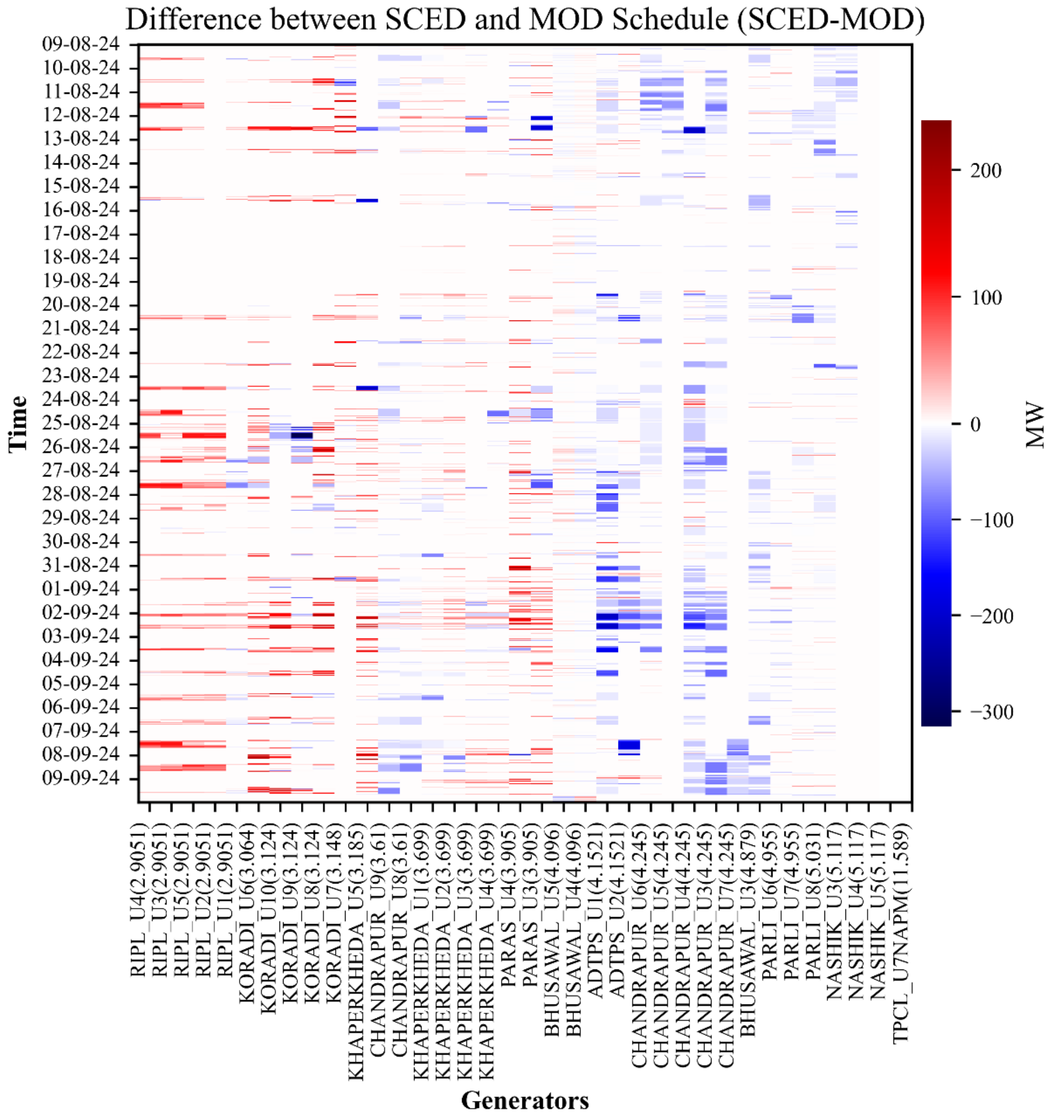

Figure 21. Difference between SCED and MOD schedule.

Figure 22 illustrates the block-wise number of generators with differences in SCED and MOD schedule. There are notable fluctuations, with the number of generators showing differences peaking periodically, reaching up to around 20-25 generators during certain time blocks. It can be observed that the difference between SCED and MOD scheduling is not constant and tends to vary significantly over time. Early time blocks show higher variability, suggesting that SCED makes more adjustments during these periods. The percentage of affected generators often exceeds 30%, with peaks nearing 50%, showing that SCED frequently overrides MOD in real-time. The trend indicates that these scheduling differences are not isolated cases, rather they occur regularly, particularly during specific time blocks where both the absolute number and percentage of impacted generators increase.

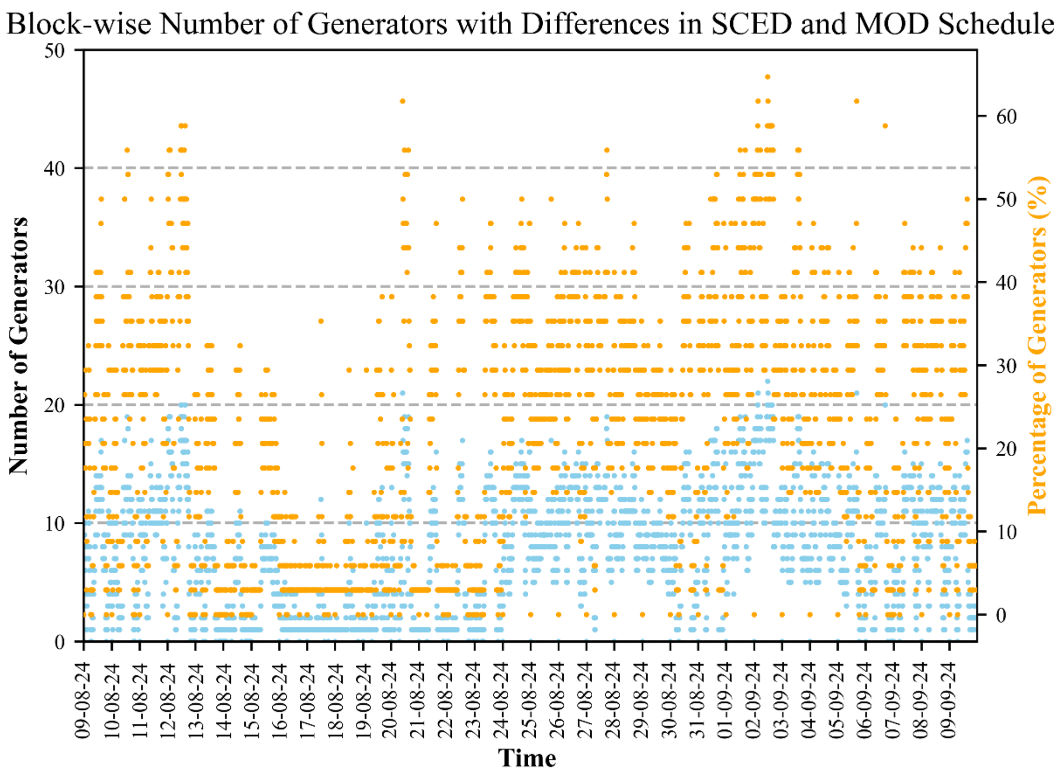

Figure 22. Block-wise difference between SCED and MOD

Figure 23 and Figure 24 show the block-wise number of generators where SCED schedule is greater than MOD schedule and the block-wise number of generators where SCED schedule is lesser than MOD schedule. A consistent trend can be observed in where several generators are frequently dispatched more by SCED, particularly in later days(between 02-09-24 and 06-09-24). This pattern suggests that in SCED, certain units are required to ramp up during this period. It can be observed that, in earlier time blocks, SCED schedule in less compared to MOD schedule. In summary, for the entire month, SCED has 28243 changes over the 27757 changes in the MOD.

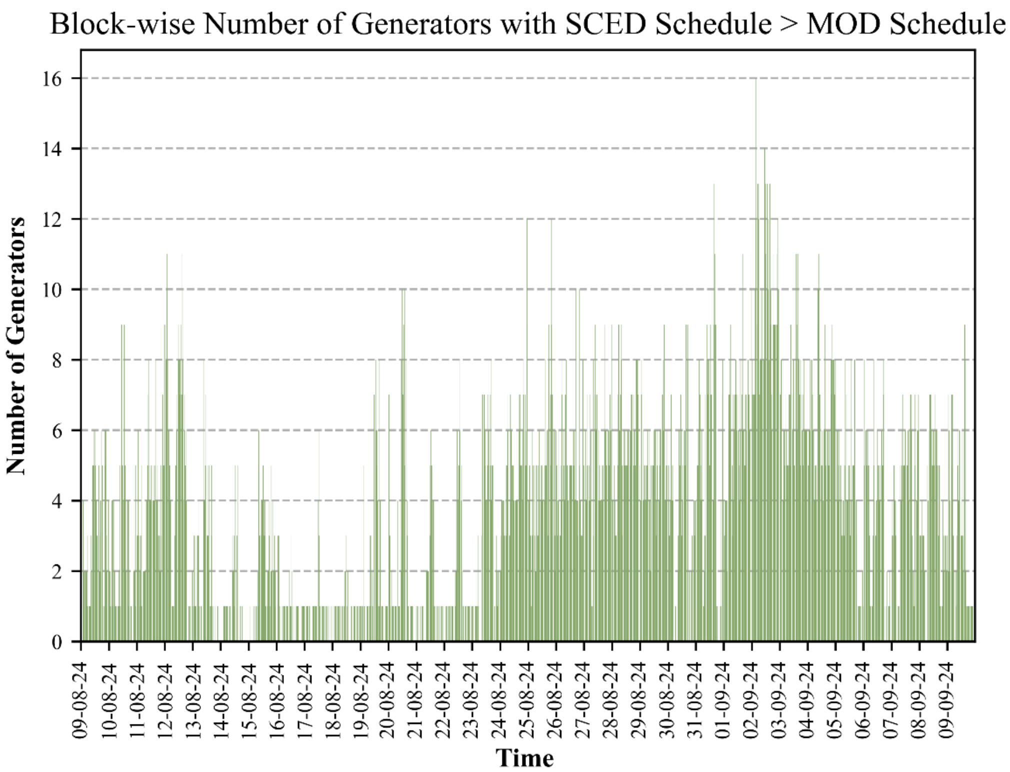

Figure 23. Block-wise no. of generators when SCED schedule > MOD schedule.

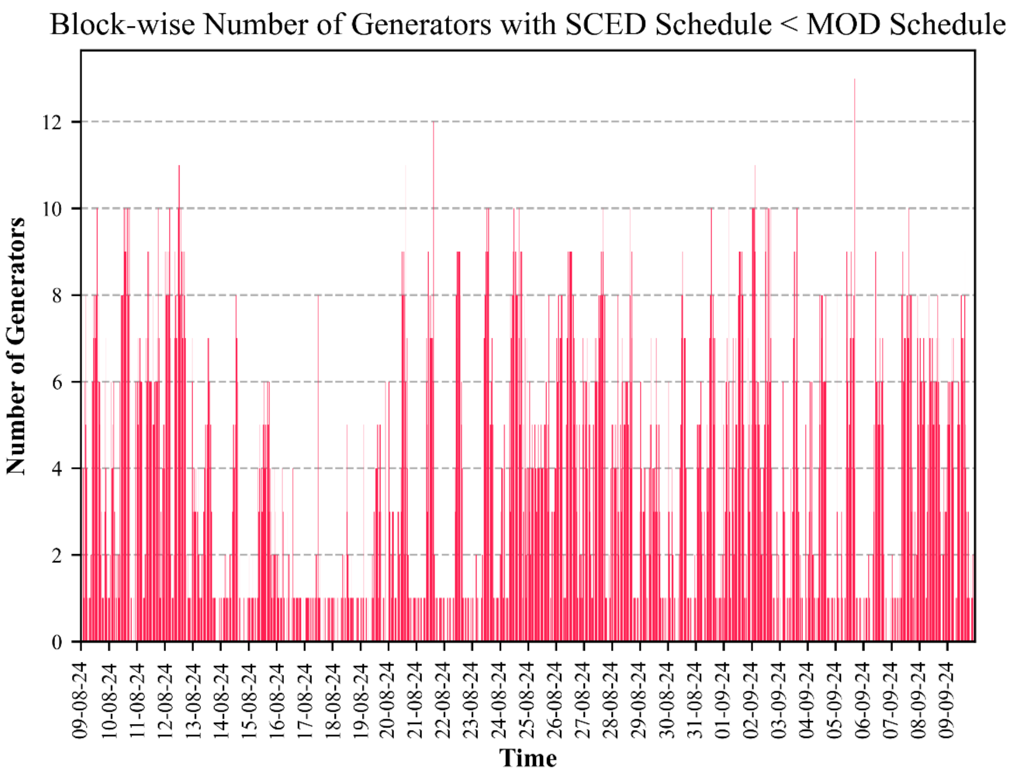

Figure 24. Block-wise no. of generators when SCED schedule < MOD schedule.

7.1.3 Ease of operation of the generators

Figure 25 shows that the SCED has stabilized the generation of the low-cost generation by maximizing their generation. The perturbation of in these units got reduced.

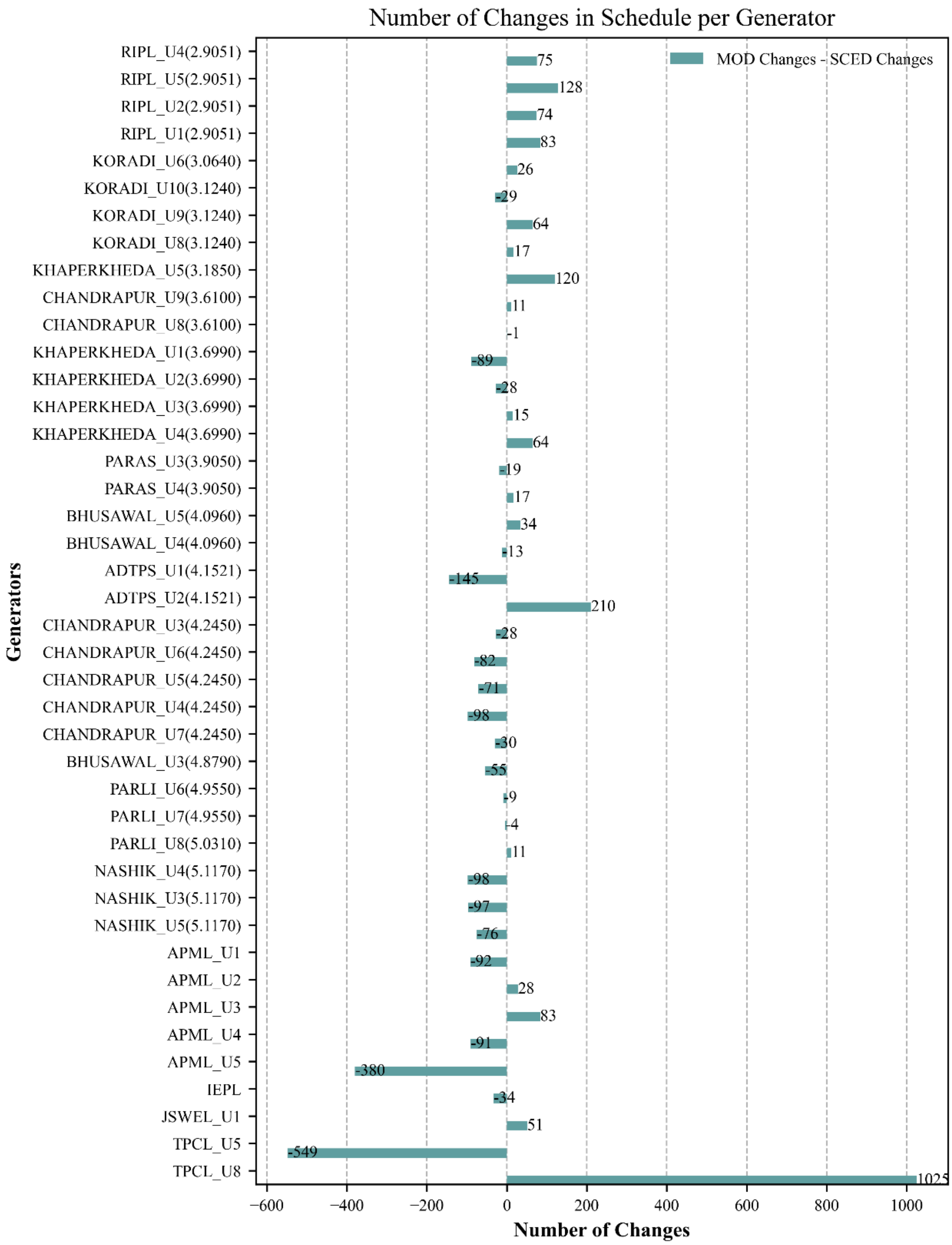

Figure 25. Generator-wise difference in perturbations in MOD and SCED.

7.1.4 Generator operational bounds:

During the analysis, it was observed that ADTPS_U1 and ADTPS_U2, mapped to the AEML DISCOM, have a limited margin between their technical minimum and declared capacity, restricting their scheduling flexibility. Beyond these units, the narrow scope for other plants further underscores the importance of lowering the technical minimum, particularly for units with higher variable costs, to improve scheduling flexibility and cost-efficiency. Additionally, it was noted that a majority of plants were operating below their rated technical minimum, indicating an operational practice where the declared capacity is lower than the rated technical minimum.

Apart from the technical minimum, cost savings under SCED could be significantly enhanced if the declared capacity were increased. Analysis of scheduling data revealed that plants with lower variable costs often have a considerable margin between their declared capacity and ex-bus capacity, indicating untapped potential for optimization. For example, the duration plot for KORADI as shown Figure 26, demonstrates that while the unit's ex-bus capacity is 620 MW, its declared capacity remained below 450 MW for around 70% of the time. This substantial gap suggests that raising the declared

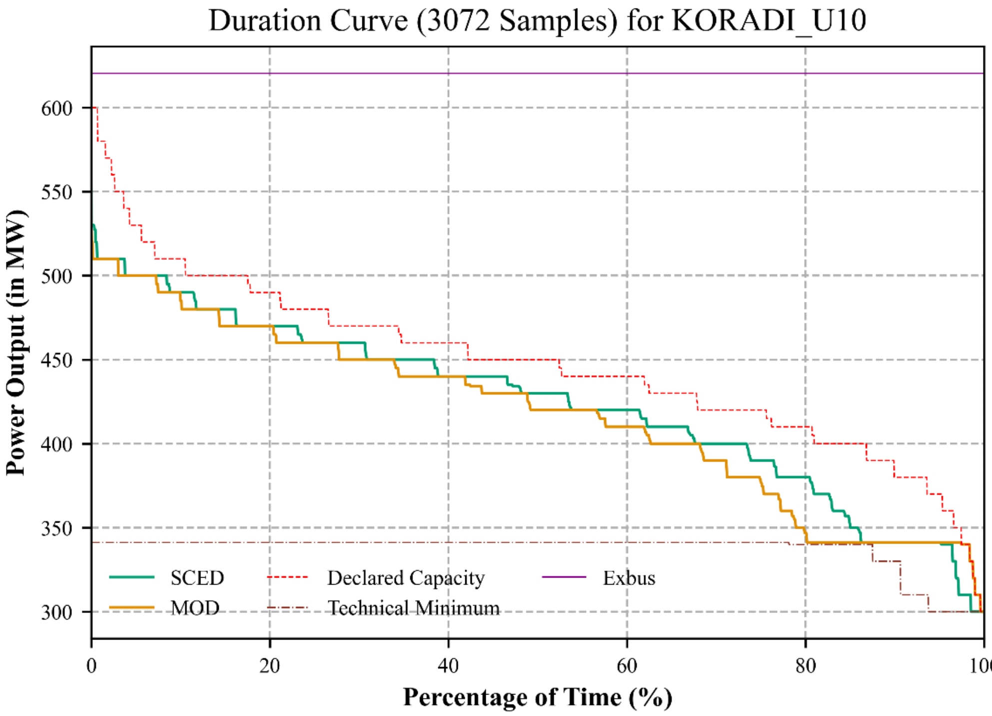

Figure 26. Duration plot of power output for Koradi

capacity of such low-cost units could lead to better utilization, ultimately driving further cost savings and improving overall system efficiency.

Notably, as illustrated in the duration plot of the generator schedule in Figure 27, the primary opportunity for cost savings lies with units like TPCL U5. These units frequently operate at technical minima and declared capacity due to the narrow margin between these bounds. By optimizing the operations of these units, significant improvements in overall cost efficiency could be achieved.

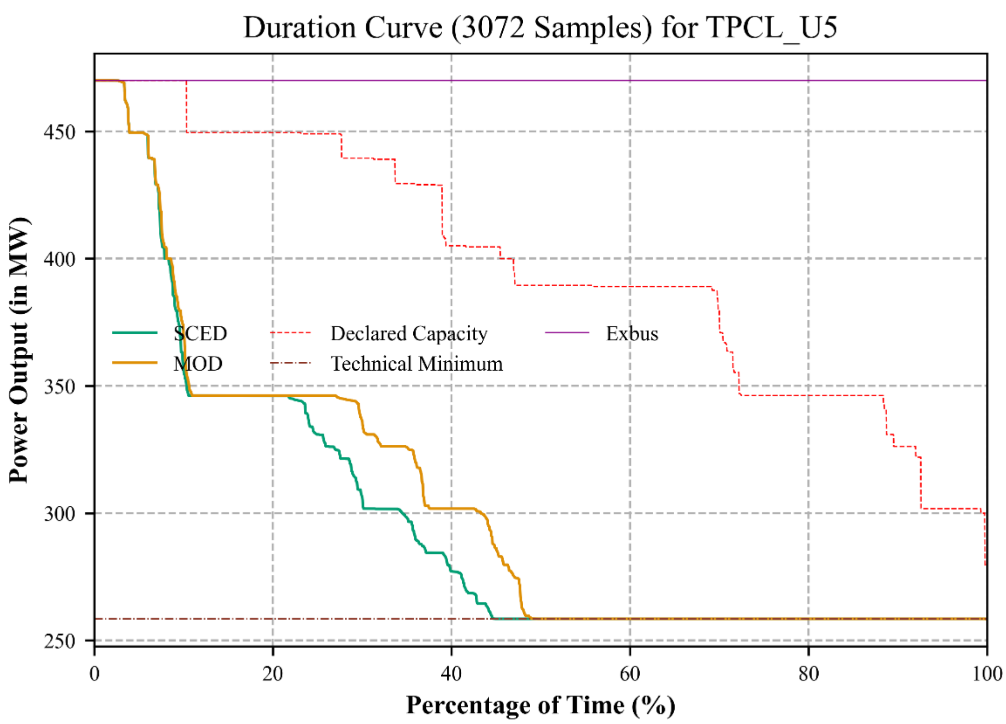

Figure 27. Duration curve of TPCL U5.

8. Power of Shadow Price

"True optimization comes not from doing the obvious but by mastering the constraints."

A shadow price represents the marginal value or opportunity cost associated with a constraint in an optimization problem. In the context of power systems, it indicates the incremental cost of meeting an additional unit of demand or the benefit of relaxing a constraint, such as a generation limit. Shadow prices are essential in understanding the value of scarce resources, providing insights into resource allocation, and identifying potential congestion points within the grid.

8.1 Duals

In optimization, dual variables (or simply "Duals") are associated with each constraint of the primary problem, reflecting the sensitivity of the objective function to changes in constraint values. Duals serve as a bridge between the primal problem (e.g., cost minimization in generation scheduling) and its dual counterpart, highlighting the economic value of resources and constraints.

With SCED, DISCOMs can now engage with the market with a steady hand, relying on the robust decision-making framework that SCED provides. The secure and optimized scheduling reduces the risks traditionally associated with complex trades, enabling DISCOMs to navigate the power market landscape with greater certainty. This shift from a defensive trading posture to an assertive strategy marks a pivotal transformation for the DISCOM, empowering it to fully leverage the benefits of modernized power dispatch. A well-informed decision could be taken once the system Marginal Price of the system is known.

8.1.1 Use of duals by different stakeholders

System Operators (e.g., NLDC, SLDCs): Duals provide insights into constraint valuations, such as transmission limits or generation capacity, helping operators identify high-congestion areas, manage load dispatch, and make real-time adjustments based on system conditions.

By understanding the duals of constraints like Pmax, Pmin, and ramps, operators can optimize plant dispatch strategies and ensure that technology interventions are both economically and operationally sound.

Policy Makers and Regulators: By examining duals, policy makers can better understand the economic impact of constraints, such as emissions limits or renewable integration targets. This information helps in designing policies that balance cost efficiency with regulatory goals, such as emissions reduction or energy diversification. For policymakers, duals of constraints (such as maximum and minimum power limits, ramp rates, and transmission congestion) offer essential insights for crafting effective policies. Regulators can utilize this information to design targeted incentives, such as demand response (DR) schemes or backing down support, which are aligned with real-time grid needs.

Planning Decisions: For planners, shadow prices indicate the value of addressing transmission congestion or increasing capacity in constrained areas. This helps avoid ad-hoc, one-size-fits-all investments by prioritizing areas that maximize system efficiency and resilience.

DISCOMs: Duals help DISCOMs identify the cost implications of various constraints, such as regional supply limitations or peak load requirements, aiding in procurement planning and cost control. For instance, understanding shadow prices of capacity constraints can inform DISCOM's demand response strategies.

Generators: Duals help generators assess the value of their capacity within the market. For example, the shadow price of generation limits informs them of the potential revenue from increasing capacity, indicating profitable opportunities for investment or operational adjustments.

Market Participators: Above all, the SMP derived from SCED is an invaluable output, reflecting the true economic cost of generation and providing the wisdom to guide market transactions, investments, and incentives across the grid.

8.2 Analysis of System Marginal Price

The diurnal pattern, duration curve, and histogram of the system marginal price (SMP) under centralized SCED are shown in Figure 28, Figure 29 and Figure 30 respectively. As depicted in the overall SMP ranges between 340 paise/kWh and 608 paise/kWh. The SMP remains low during the daytime, primarily due to the increased share of generation from interstate sources, renewable energy, RTM, and hydro scheduling. Currently, intrastate hydro plants are not part of the SCED optimization process and are only scheduled when there is a shortfall in generation, which impacts the overall pricing structure.

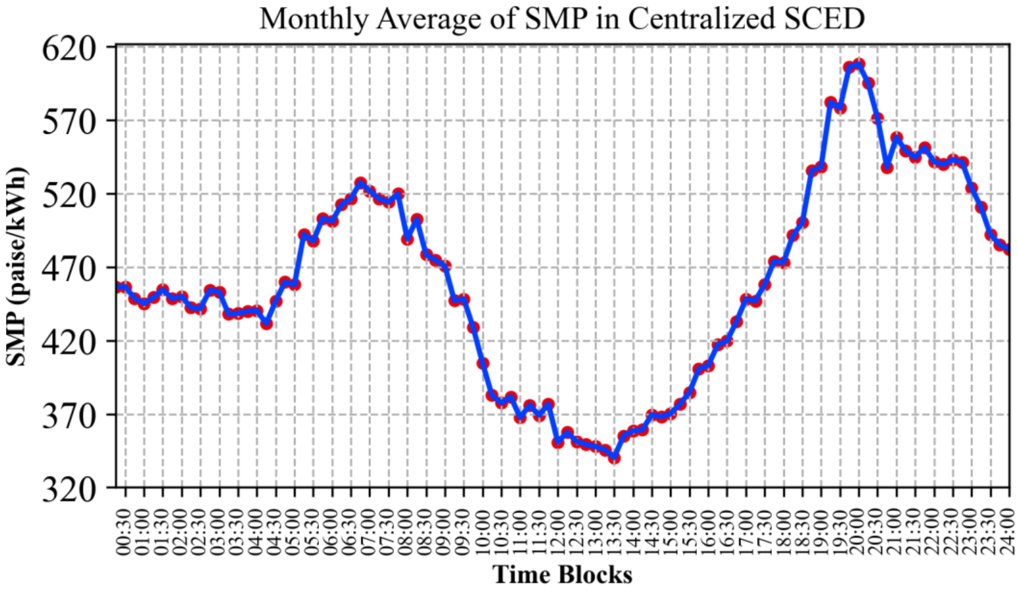

Figure 28. Block-wise monthly average SMP in centralized SCED

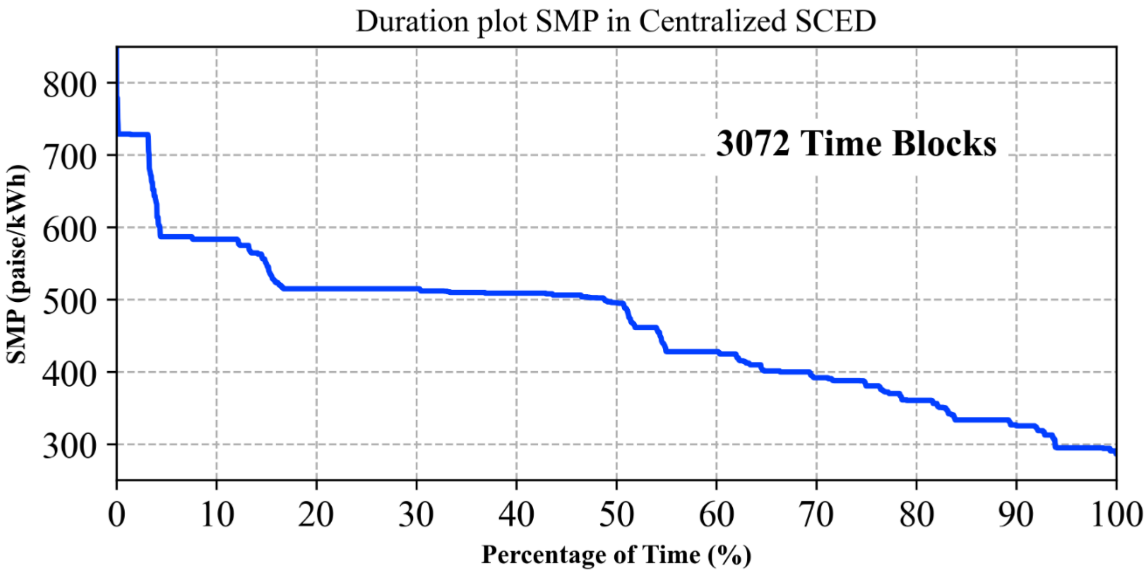

Figure 29. Duration plot of SMP.

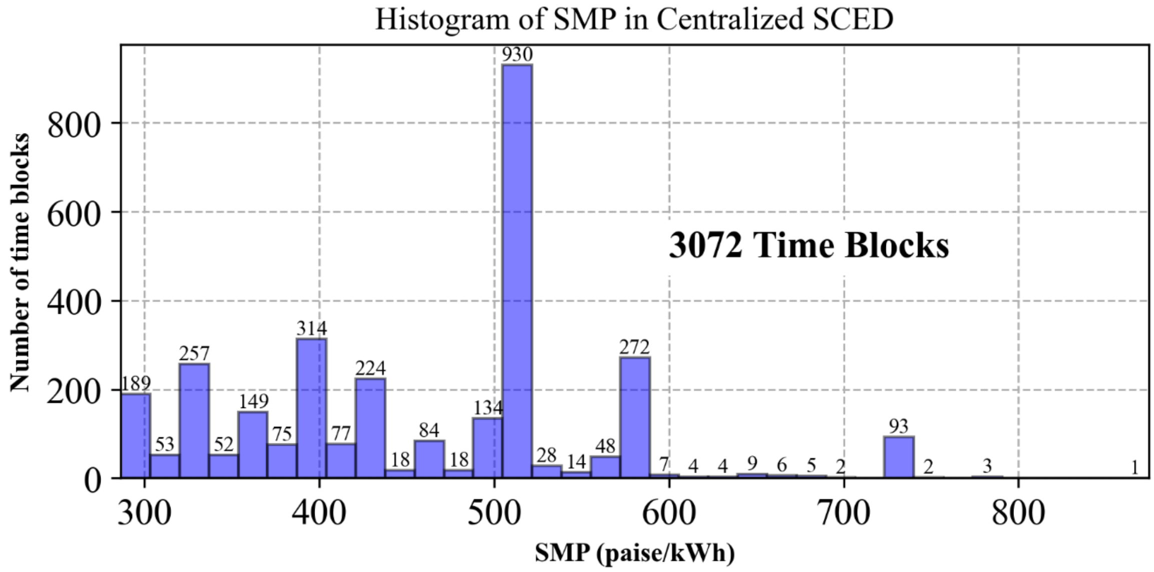

Figure 30. Histogram of block wise SMPs.

Apart from the higher SMPs during ramping periods, the overall SMP fluctuates with load demand. Figure 31 presents a correlation plot indicating the linear relationship between SMP and net demand, where the positive trend shows that SMP increases as load demand rises. This is expected, as higher demand leads to the full utilization of low-cost generators, prompting more expensive generators to be dispatched to meet the additional demand.

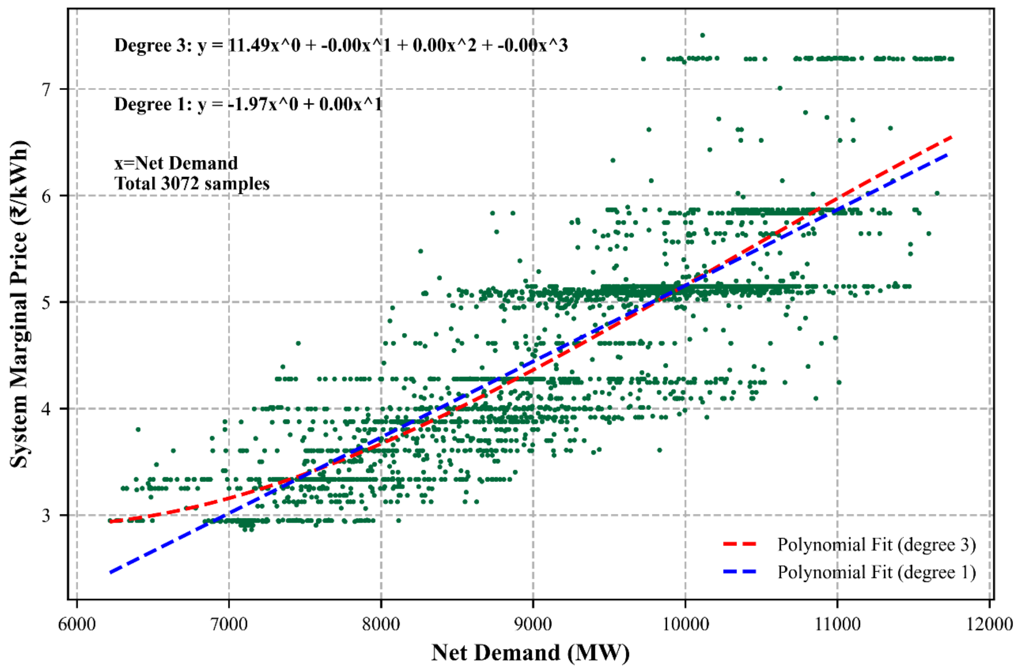

Figure 31. Correlation of SMP with net demand.

Besides the bilinear analysis between SMPs and net load, a scatter plot in Figure 32 highlights the saving opportunities as demand increases, along with the corresponding SMPs. It is apparent that savings potential is higher during periods of low load, where SMPs are also lower. This suggests that during lower demand, more efficient generators are utilized, allowing for greater cost-saving opportunities. It clearly shows that SCED generates the most significant savings during periods of low net load and low SMP. Specifically, when net load is below approximately 8 GW and SMP ranges between 300 and 500 paise/kWh, SCED consistently provides greater savings than MOD, as indicated by the yellow regions representing higher savings (up to 10 lakhs/block). This improvement in savings can be attributed to the system's increased flexibility in dispatching lower-cost generation resources during these lower demand periods. As net load increases beyond 9 GW and SMP exceeds 500 paise/kWh, the savings achieved by SCED begin to decrease, as shown by the transition from higher savings to lower savings. This suggests that advantage of SCED is most pronounced during periods of lower demand, when the system is less constrained and has greater operational flexibility. In contrast, during higher demand and SMP periods, system constraints likely reduce SCED’s ability to optimize costs, causing its performance to converge with that of MOD.

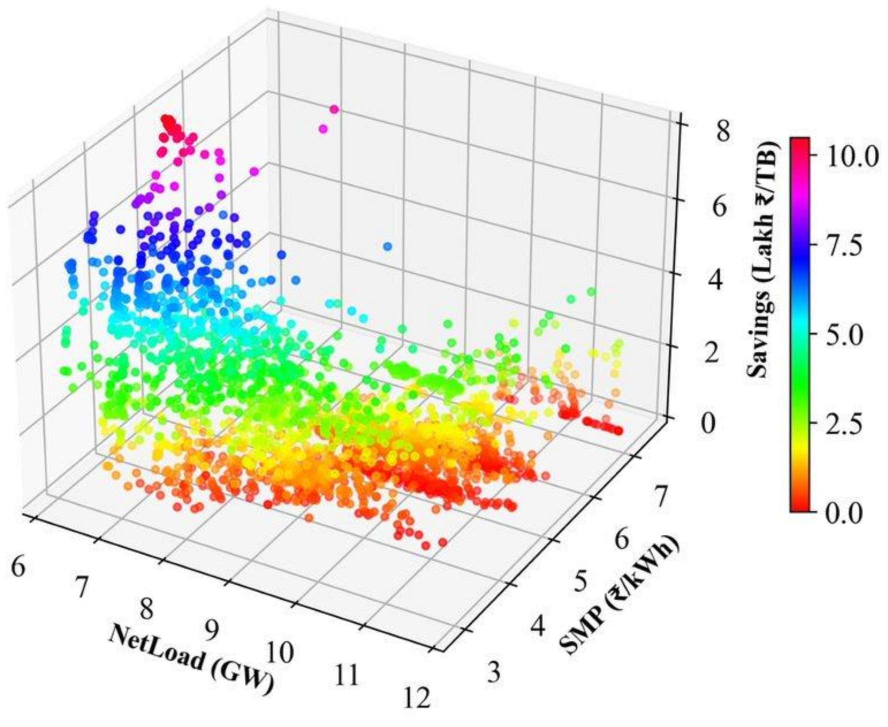

Figure 32. Correlation between savings, netload and SMP

Apart from the state SMP analysis for centralized SCED, the analysis of decentralized SCED, which reflects current operational practices, is summarized in Figure 33 - Figure 42. The diurnal variation of MSEDCL's SMP is shown in Figure 33 and the block-wise monthly average is represented in Figure 34. Unlike centralized SCED, where the URAN-OPENCYCLE plant is primarily used during ramping periods, the decentralized SCED also utilizes the TPCL_U7NAPM gas power plant, which has a higher variable cost of 1158.9 paise/kWh, at certain times. This likely occurs because generation shares are tied to specific DISCOMs, limiting flexibility in dispatch and forcing the use of higher-cost generators when needed. Figure 34 presents the block-wise monthly average of MSEDCL SMPs, where trends mostly align with the state SMPs. This is expected, as MSEDCL accounts for the majority of the state's demand, making its SMP trends closely reflect those of the overall state system.

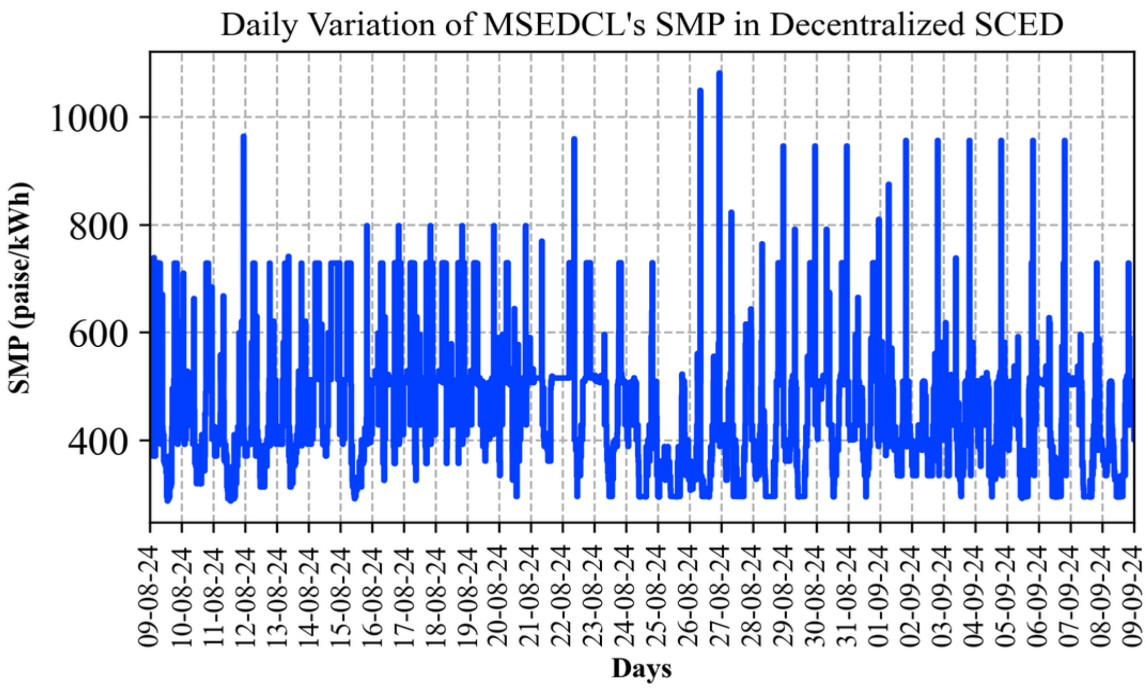

Figure 33. Diurnal variation of MSEDCL SMP

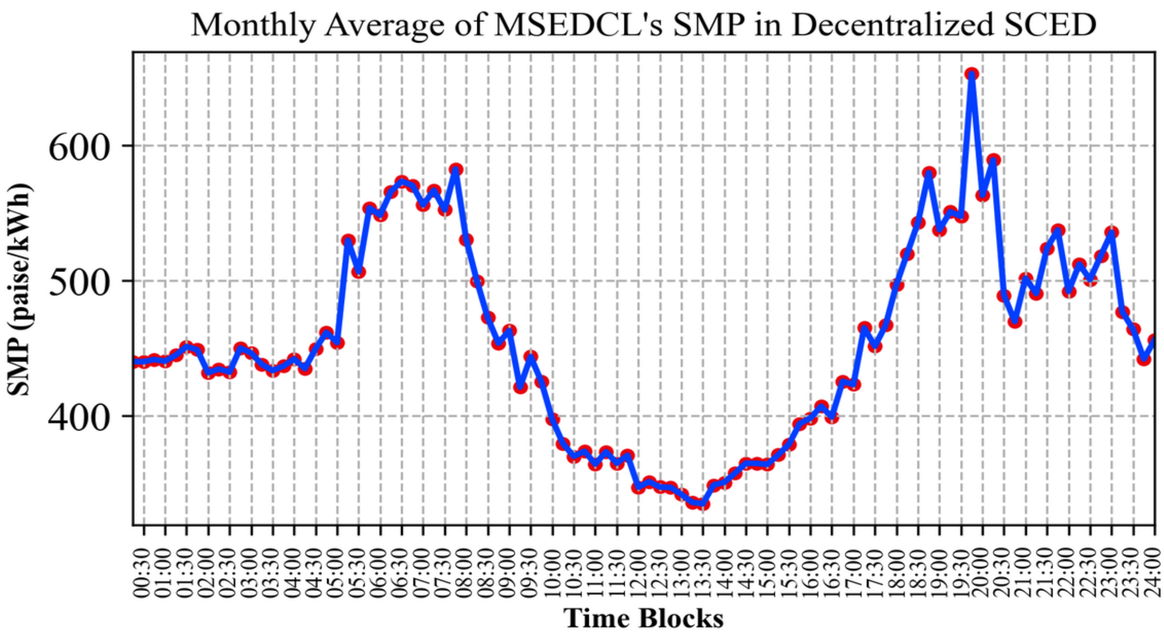

Figure 34. Discom SMP for MSEDCL

Unlike MSEDCL, which sources its demand from a diverse range of generation options, the SMPs for TPCL and BEST are closely aligned because both DISCOMs share generation resources from TPCL and BEST. This shared dependency results in similar pricing trends as shown in Figure 35 to Figure 37 reflecting the limited variability in generation sources available to both DISCOMs.

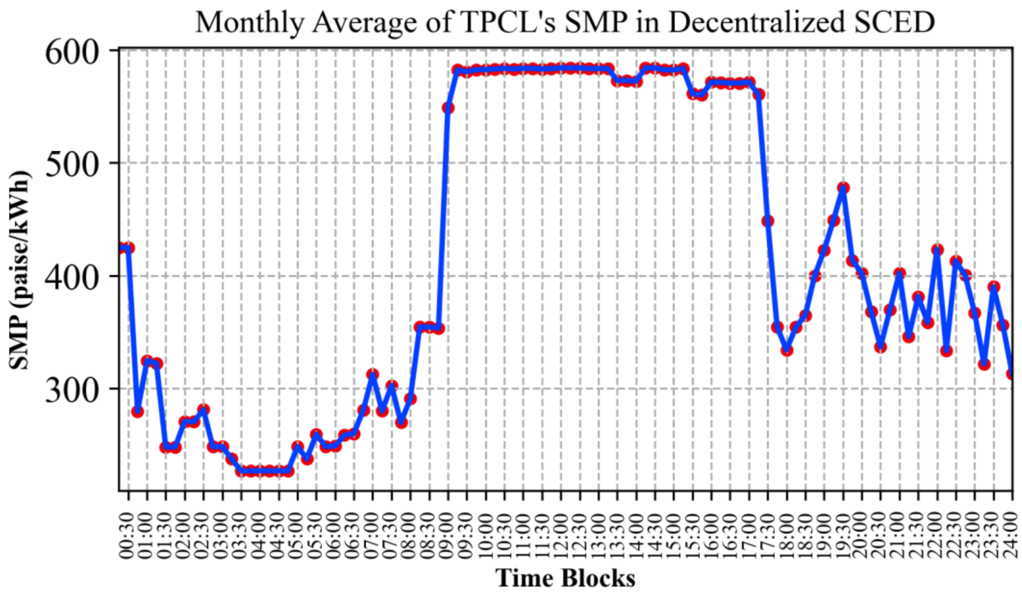

Figure 35. Diurnal variation of the TPCL's SMP

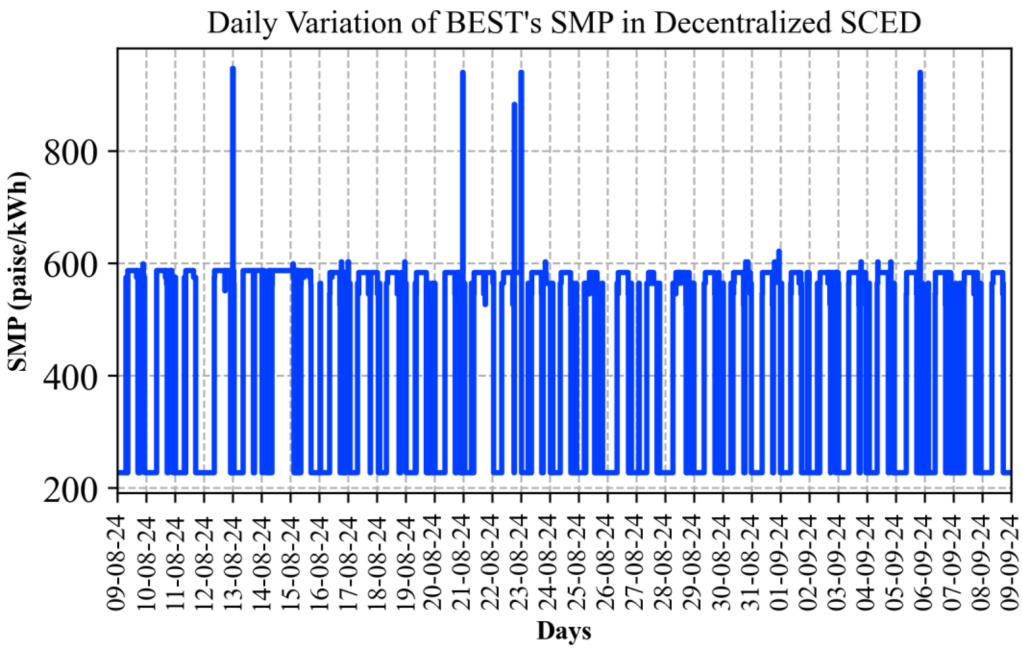

Figure 36. Diurnal variation of the BEST's SMP

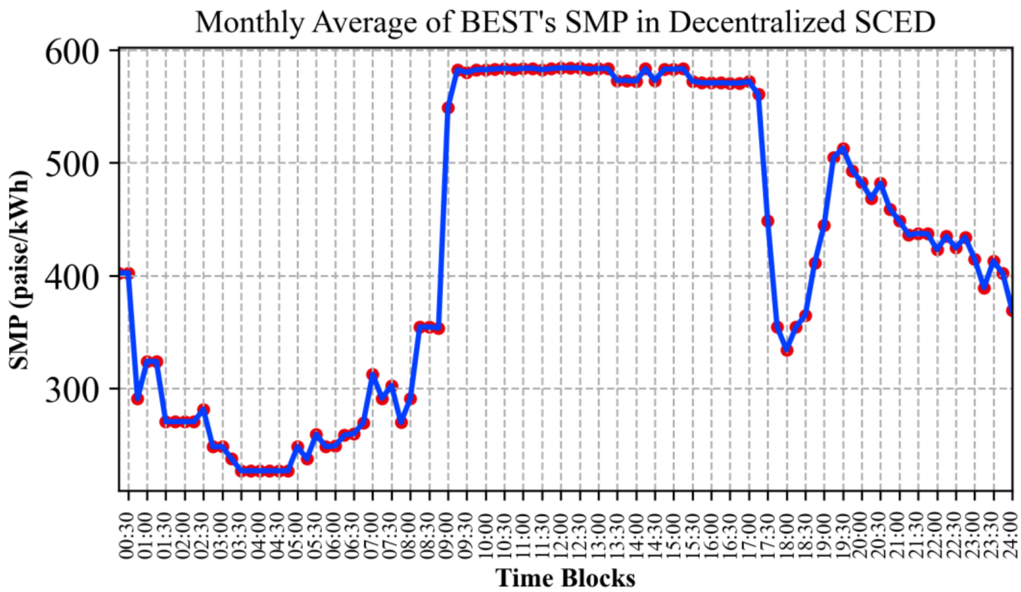

Figure 37. Discom SMP for BEST

A similar trend is observed for AEML as shown in Figure 38, where the ADTPS units are solely responsible for meeting AEML's net demand. As a result, the SMP remains relatively constant, primarily fluctuating between the variable charges of these ADTPS units. This limited generation source contributes to the stability in SMP, reflecting the dependence on a single set of generating units.

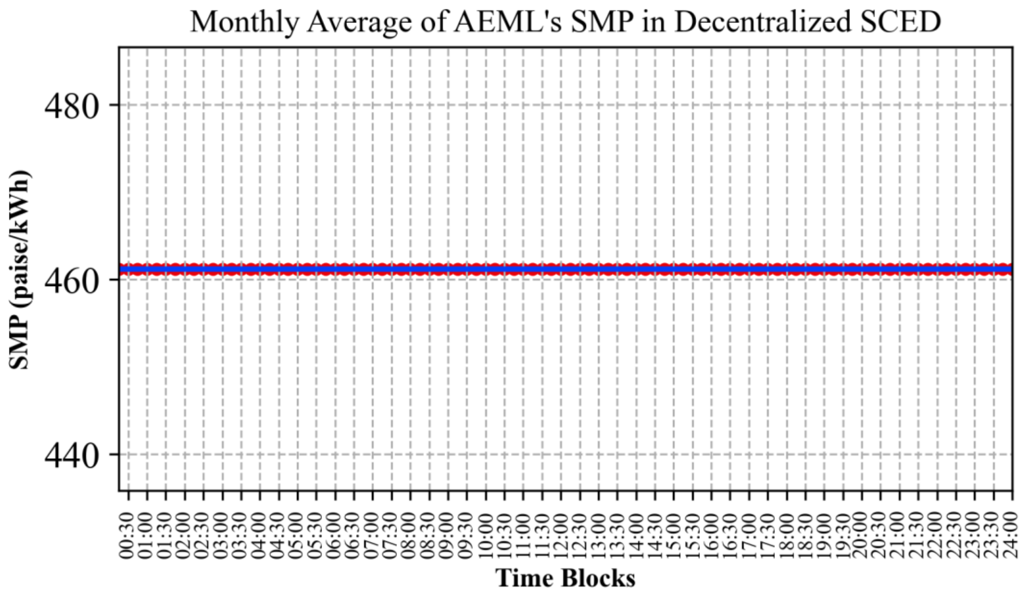

Figure 38. DISCOM SMP for AEML

Lastly, a comparison of the duration of SMPs in centralized and de-centralized SCED has been shown in Figure 39 to Figure 42 Although the trends of MSEDCL SMP is similar to state SMPs, the potential reduction in overall SMP at state level SCED along with reduction in the number of SMP variation (ramping units) in centralized SCED can be observed for around 5% of the time.

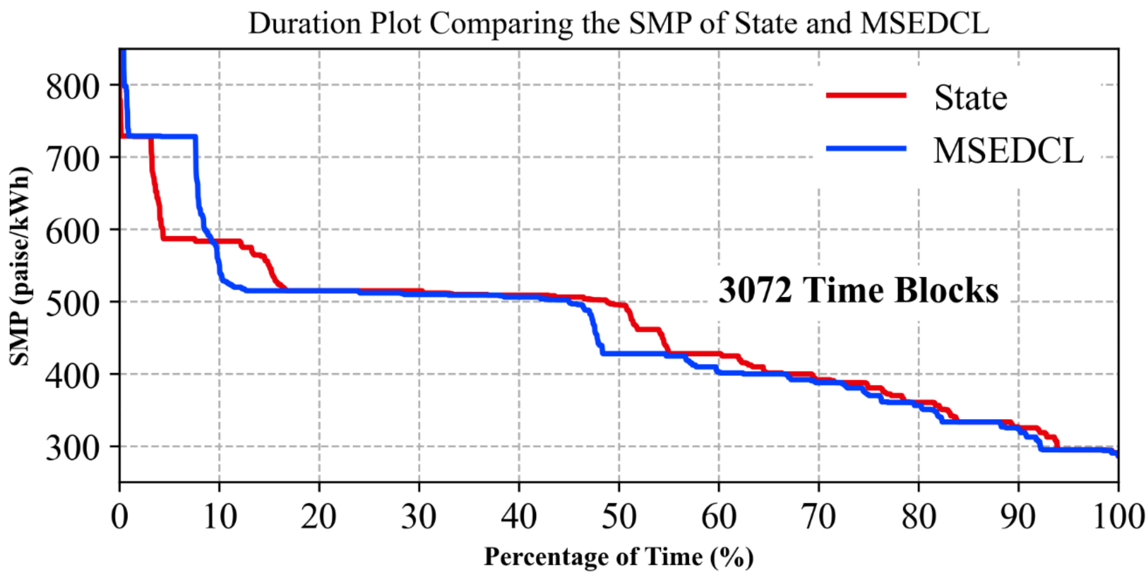

Figure 39. Duration plot of State SMP and MSEDCL

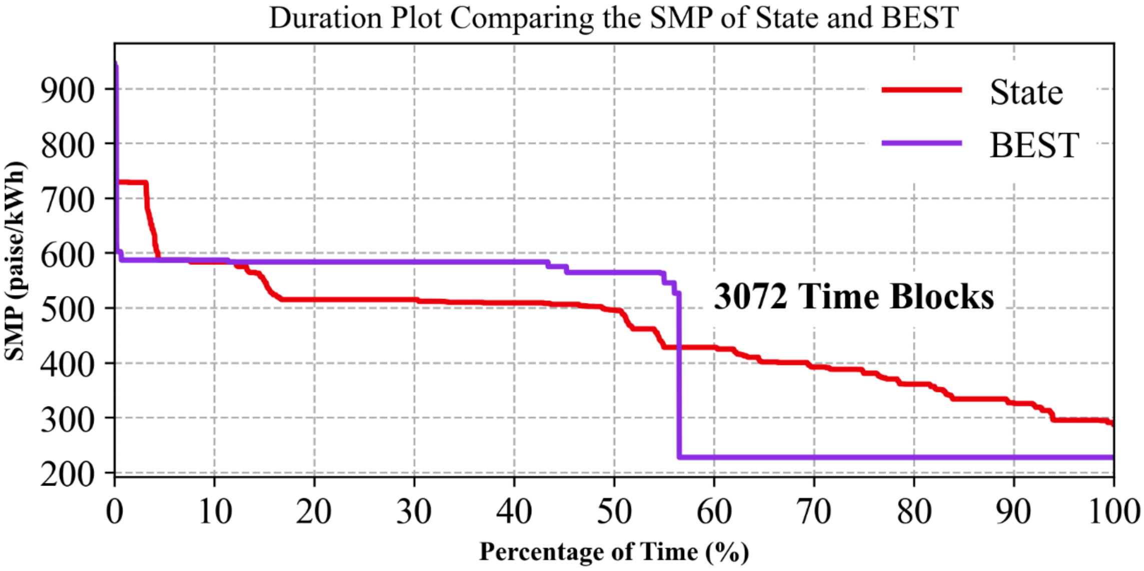

Figure 40. Duration plot of State SMP and BEST

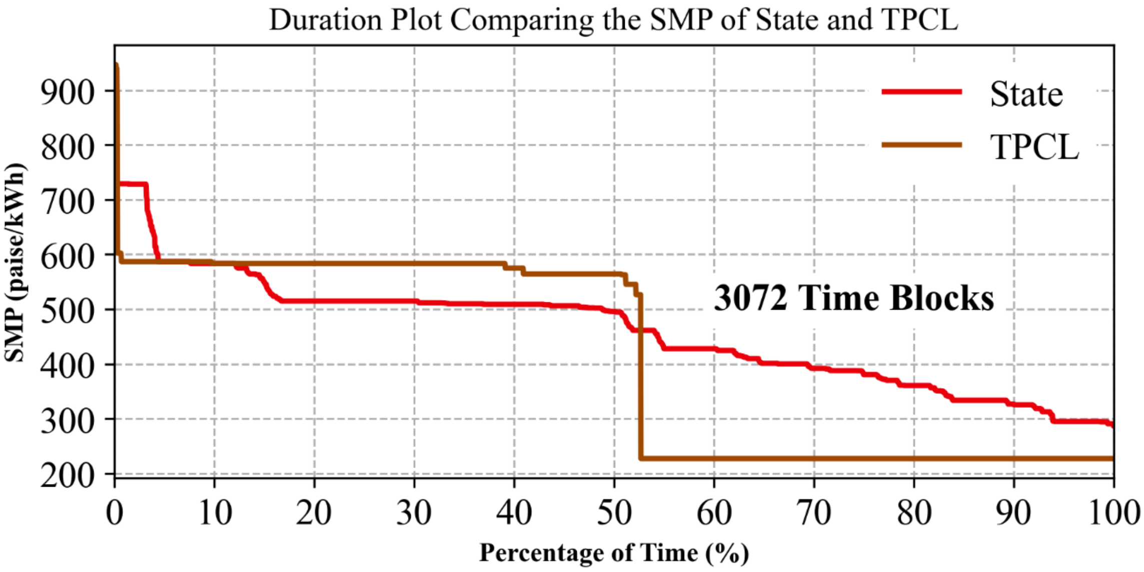

Figure 41. Duration plot of State SMP and TPCL

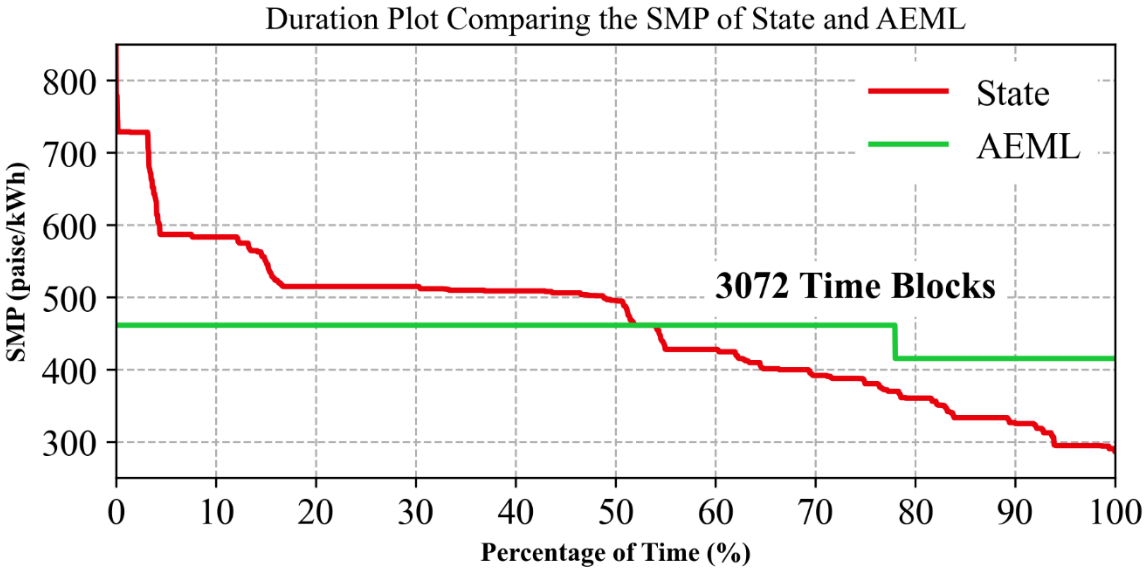

Figure 42. Duration plot of State SMP and AEML

The variation in SMP in case of centralized SCED is shown in Figure 43. It can be observed that the SMP varies from 300 paise/kWh to 800 paise/kWh. It can be noted that SMP is at its minimum value particularly during the periods of high RE penetration during the afternoon hours.

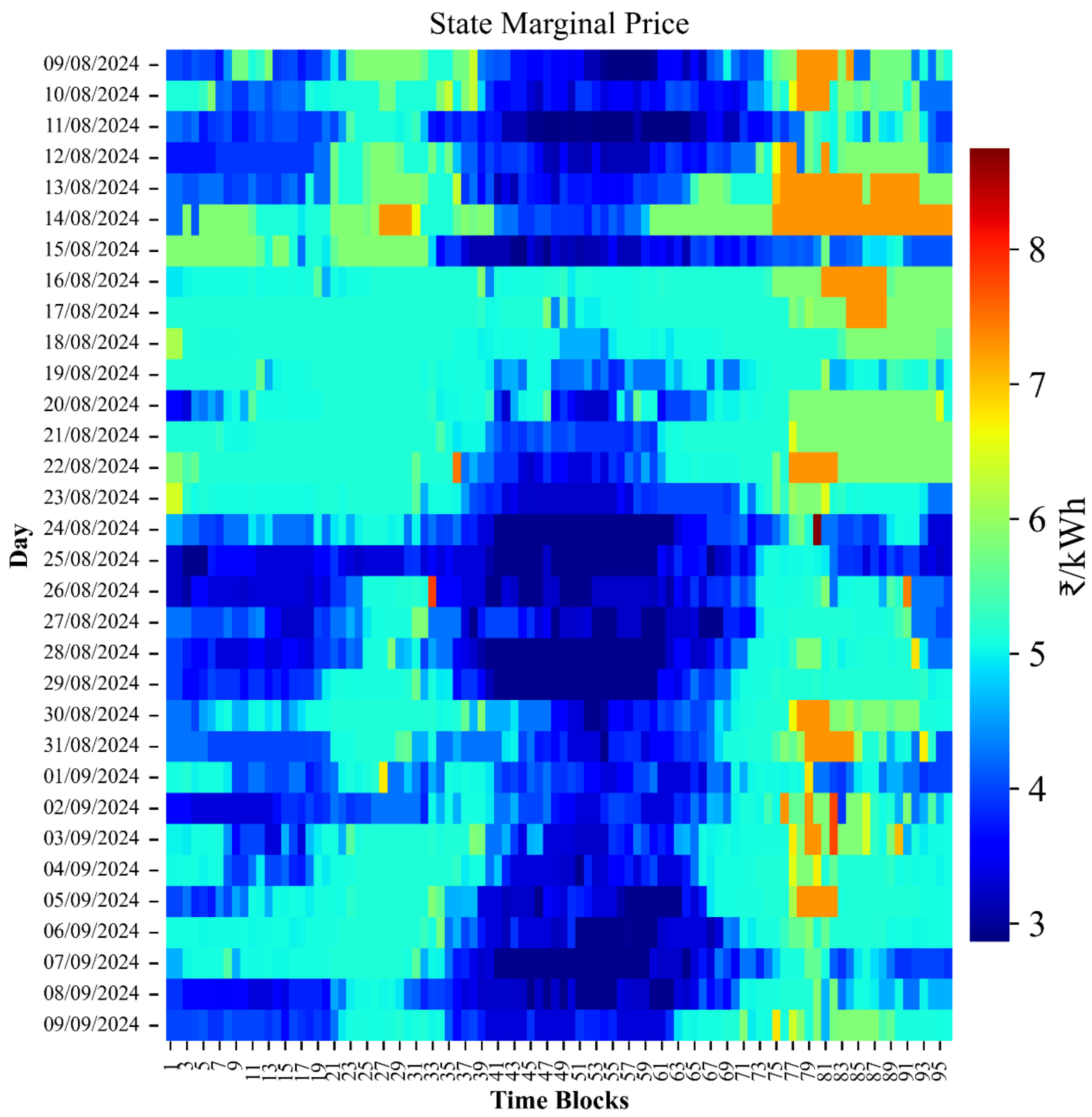

Figure 43. SMP variation in centralized SCED

8.3 Facilitating Procurement Decision

A typical diurnal plot of SMP vs MCP is shown in Figure 44. From Figure 44, it can be clearly observed that while MCP is following the SMP, the value during the day is different. The duration where MCP is less is prompting for procurement from market where MCPs are higher is prompting higher internal generation and reduction in procurement volume which also leads to cost savings.

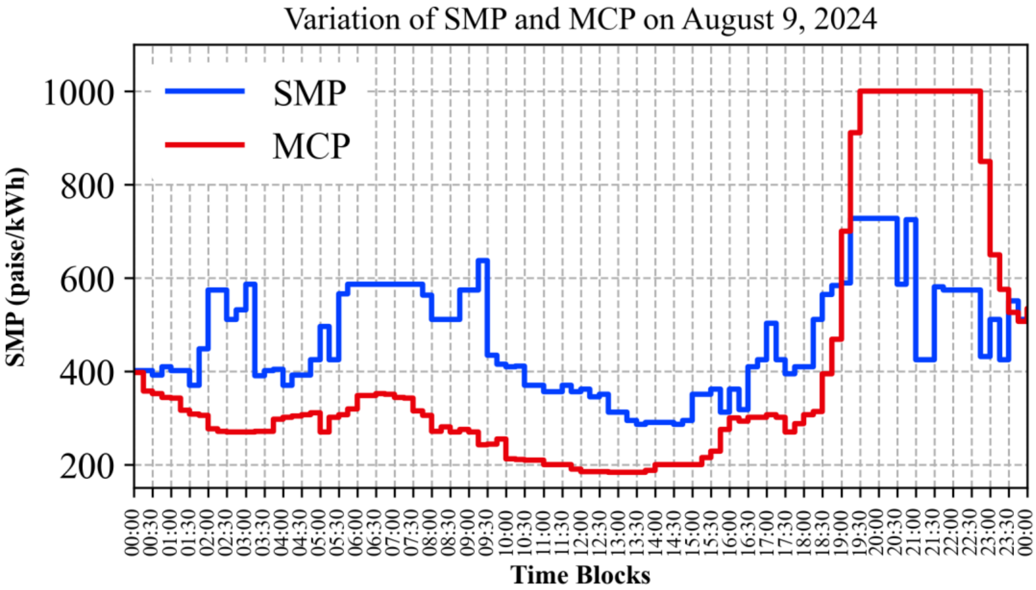

Figure 44. Diurnal variation of SMP and MCP

The duration plot of difference of SMPs and MCP for the period of study is shown Figure 45 and the diurnal variation is shown in Figure 46. It can be seen from Figure 45 that around 80% of the time additional procurement from market would have caused further savings.

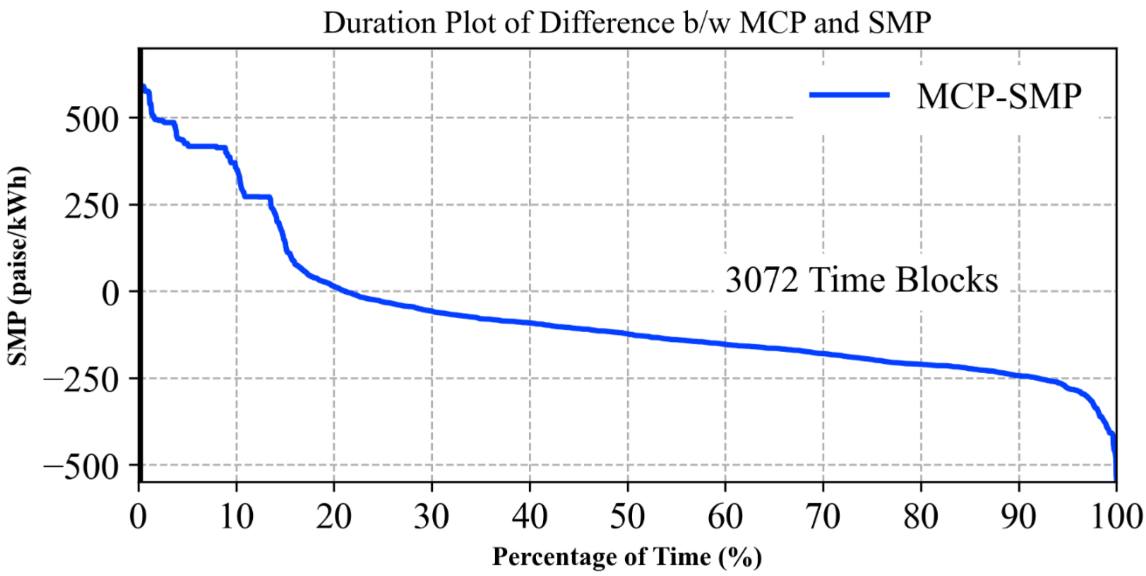

Figure 45. Duration plot of difference of MCP and SMP

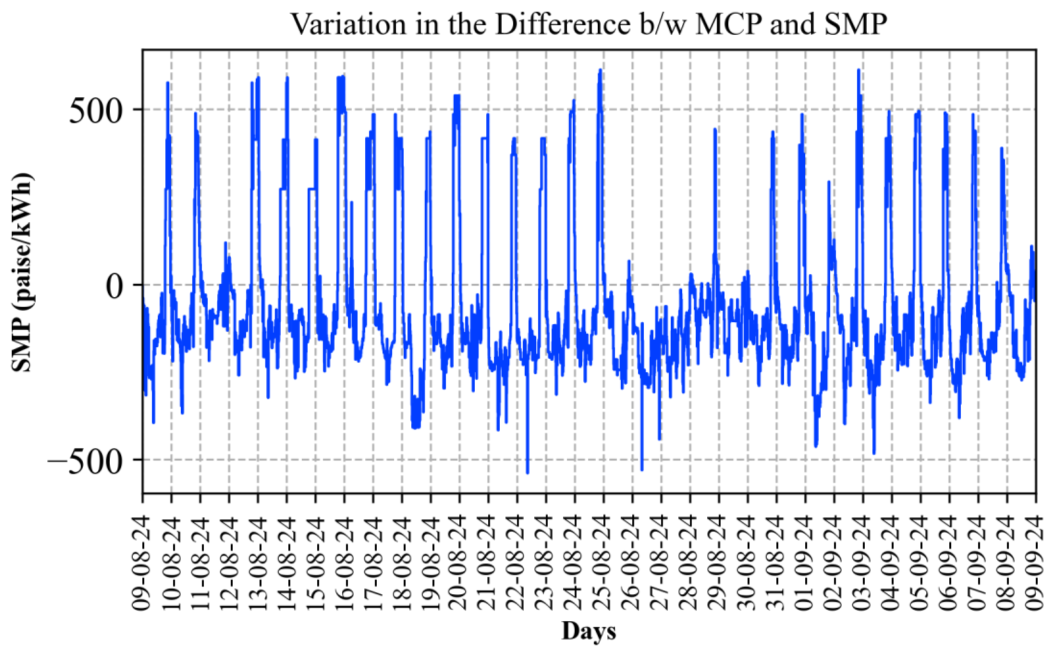

Figure 46: Diurnal plot of variation of Diff between MCP and SMP

By acting as a solid support mechanism, SCED aligns perfectly with DISCOM's objectives—ensuring a reliable, economical, and cleaner power supply. This transition from traditional MOD to an LP-based SCED framework signals a bold new era for power trading in Maharashtra, where stability and confidence drive decision-making. MSEDCL is set to thrive in a more complex market environment, thanks to the clarity, efficiency, and reliability that SCED offers.

8.4 Marginal Cost / Duals of Declared Capability (DC)

Figure 47 shows the marginal cost for declared capacity of all generators i.e. cost saving with 1 MW increase in DC of the respective generator. It shows that in case the DC is increase in the plants with low variable cost (VC) will lead to increase savings. This heat map visualizes shadow prices of maximum power output constraints across generators ordered by cost in a merit-based sequence, over various time blocks. The colour scale transitions from blue, representing low or near-zero shadow prices, to red, indicating high negative shadow prices. Many generators display blue shades, suggesting that their maximum output constraints are not often binding, allowing for operational flexibility most of the time. In contrast, red and orange areas signal negative shadow prices, with values reaching up to –4000 ₹/MWh. These areas indicate times when constraints are binding, implying that increasing the capacity of these generators would reduce system costs significantly.

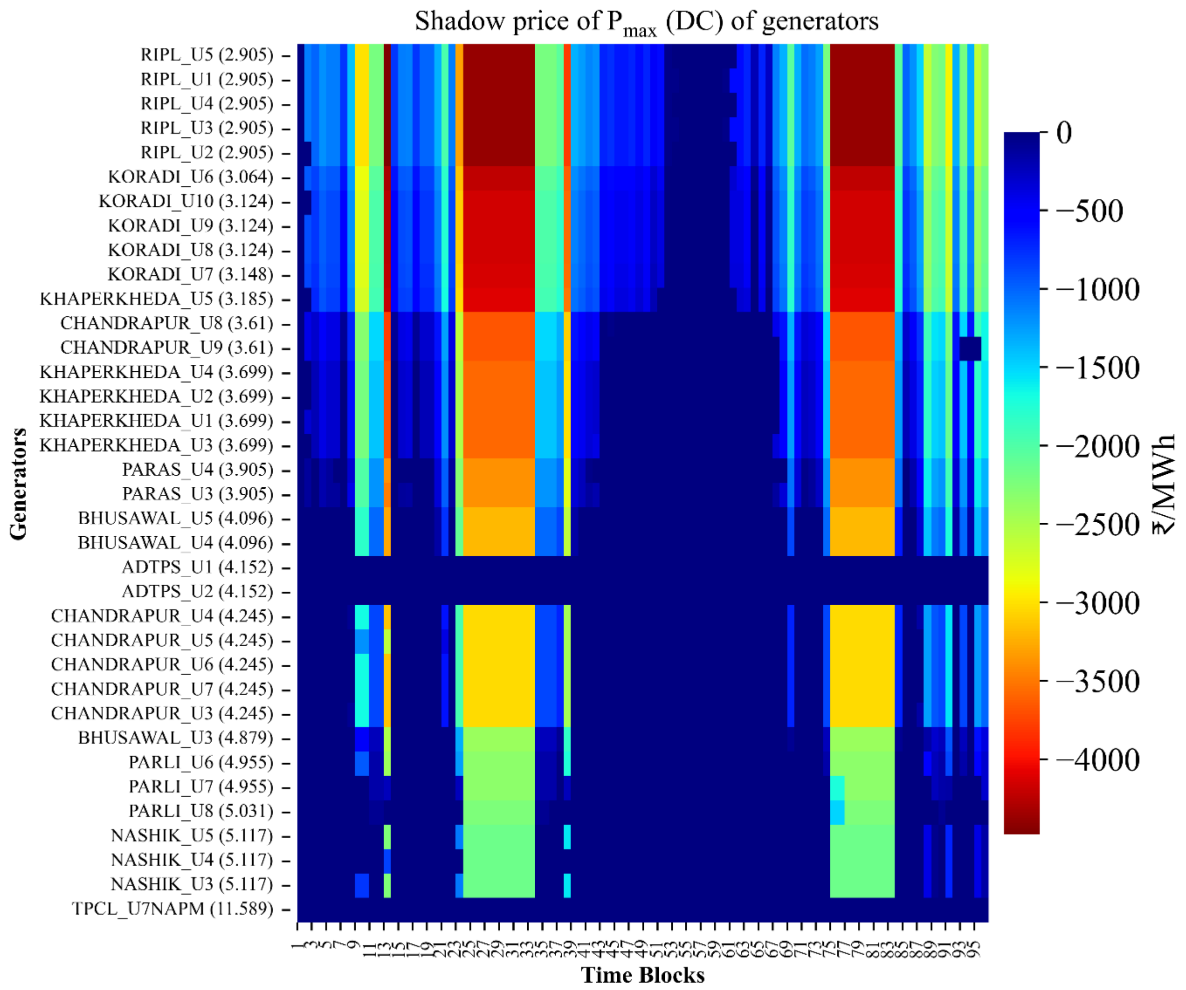

Figure 47. Heat map for marginals of declared capacity.

These binding constraints are not evenly spread but rather concentrated during specific time blocks, pointing to peak or critical hours when certain generators reach maximum output, driving up shadow prices. Lower-cost generators appear more often in these warmer colour zones, indicating they are pushed to their limits more frequently than higher-cost units, which tend to exhibit cooler colours or zero shadow prices. The plots also shows that no saving with increase in DC for ADTPS U1 & U2. This is because the full capacity is never used for these units and hence no possible savings. This is a useful information where in technical intervention is required for possible increase in savings. Insights from this analysis suggest opportunities for enhancing efficiency through capacity expansion, demand management, and strategic load handling, especially during peak hours, to strengthen operational reliability and system resilience.

Figure 48 and Figure 49 illustrate the duration of shadow prices for the Nashik, Parli, Khaperkheda, and Koradi units. Figure 48 reveals a clear disparity in terms of duration of marginal costs. Cheaper units, Khaperkheda and Koradi, exhibit a significantly higher percentage of instances where they hit their DC, while the more expensive Nashik and Parli units experience this condition for a considerably shorter duration. This trend emphasizes the operational efficiency of the lower-cost units during varying demand periods.

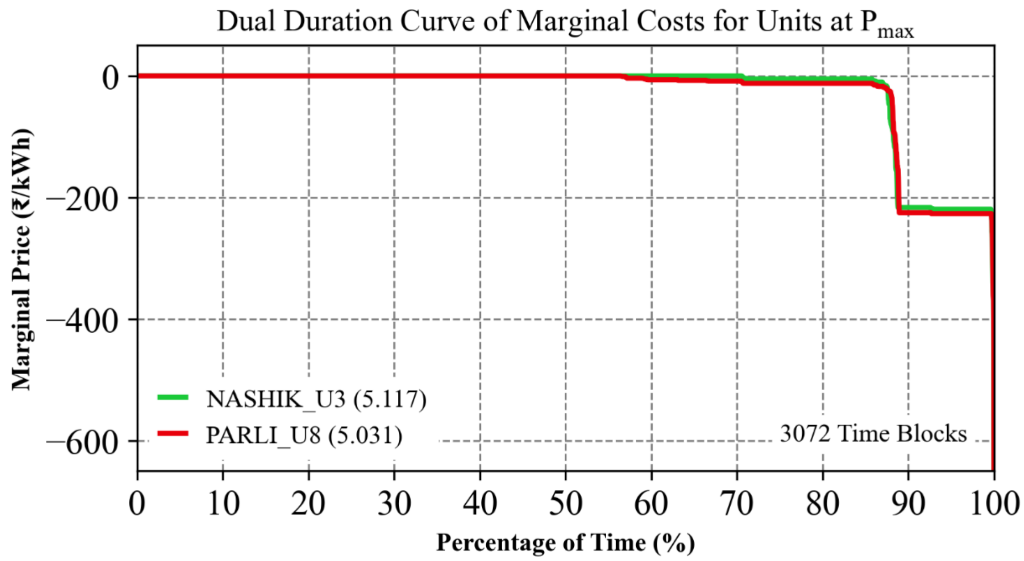

Figure 48. Duration curve of the marginal cost for units, relatively expensive, operating P_{max}

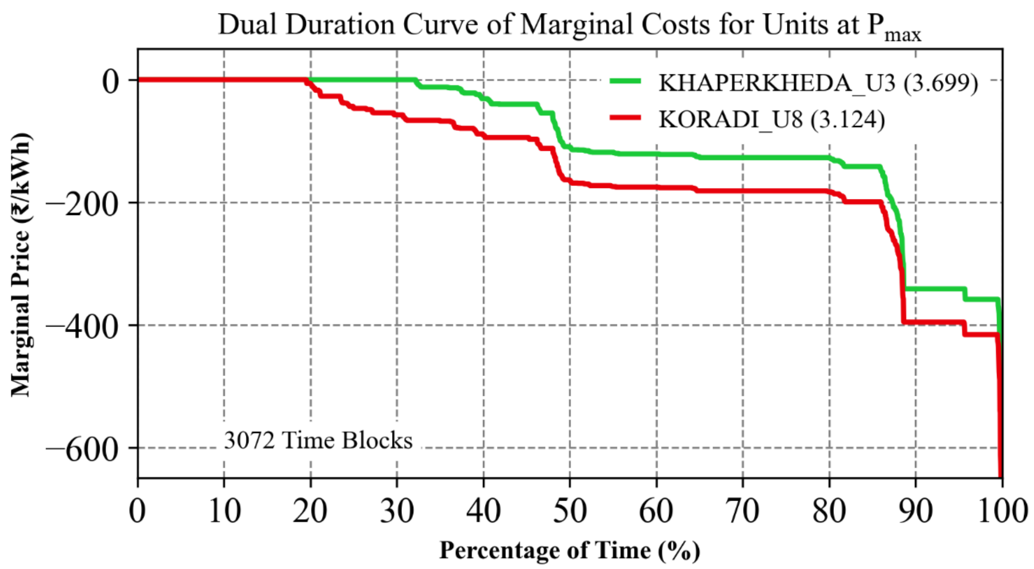

Figure 49. Duration curve of the marginal cost for units, relatively cheaper, operating P_{max}

Figure 50 shows the marginal cost of technical minimum of all the generators, which means the possible additional saving for lowering 1 MW in technical minimum value. The analysis evaluates shadow prices associated with maintaining the minimum technical output (Pmin) for power generators ordered by cost over different time blocks, revealing significant variability and offering strategic insights for policy reform and cost reduction. Quantitative analysis shows that shadow prices vary widely across generators. Lower-cost, base-load units like RIPL and Koradi often exhibit shadow prices near ₹0/MWh, suggesting they can operate close to Pmin without creating economic strain. However, shadow prices reaching up to ₹2500/MWh are observed for higher-cost units like PARLI and NASHIK during peak demand hours. This peak demand correlation with high shadow prices suggests an economic burden when costly units are required to meet minimum generation thresholds.

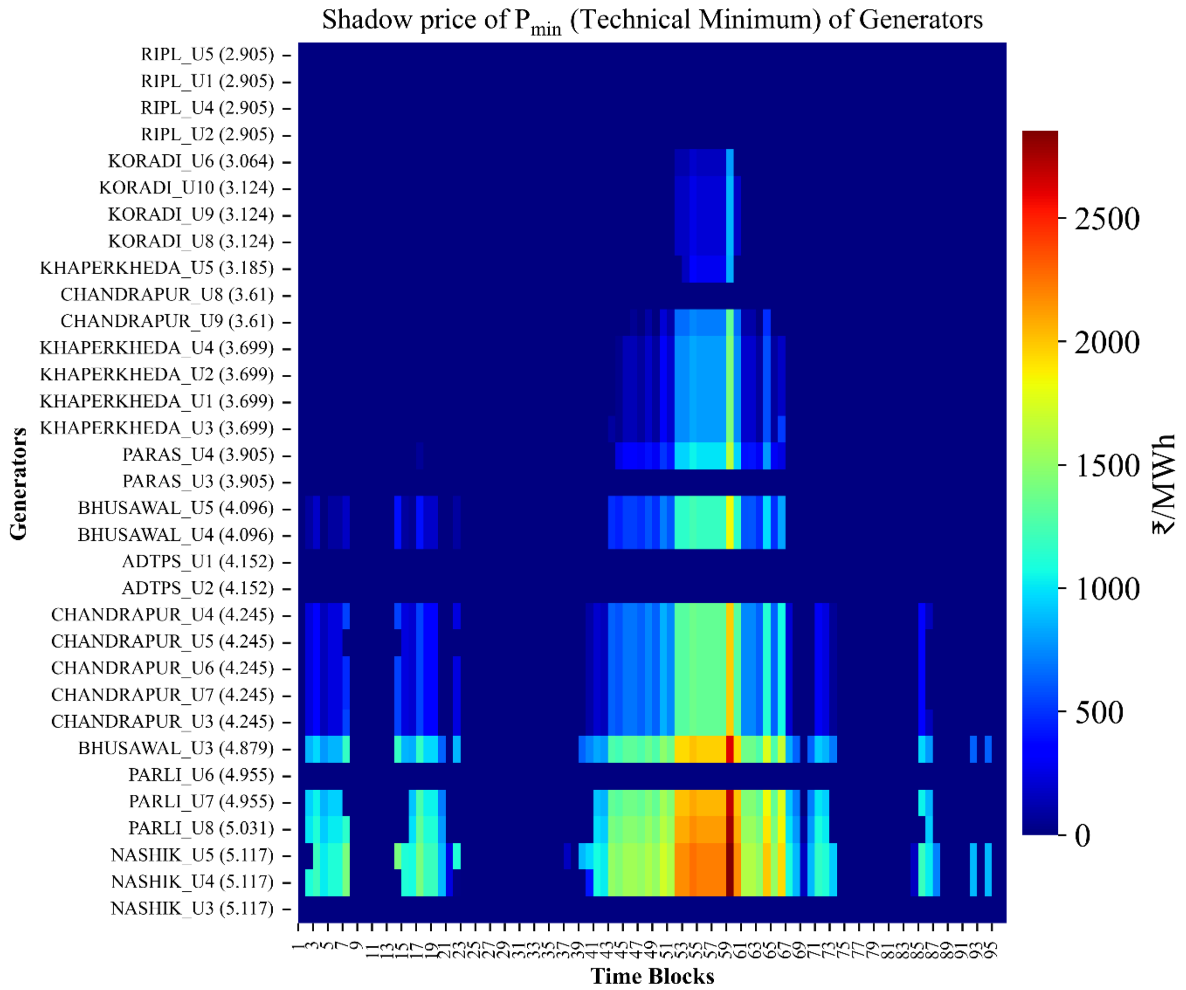

Figure 50: Heat map for marginals of technical minimum

Notably, peak demand blocks (with shadow prices between ₹1000–₹2500/MWh) are concentrated in morning and evening hours, while off-peak blocks generally show lower shadow prices (₹0–₹500/MWh). Generators like PARLI and NASHIK exhibit consistently high shadow prices, pointing to a substantial cost that could be mitigated by implementing demand response programs or investing in flexible generation resources. Summing shadow prices where they exceed ₹1000/MWh could provide a rough estimate of the financial impact due to P_{min} constraints, which likely represents a significant daily expense. Policy implications suggest incentivizing flexibility by lowering P_{min} requirements for high-cost units, integrating storage, and expanding SCED to dynamically optimize dispatch based on real-time costs. Demand-side strategies and flexible generation capacity investments would further reduce the need to operate costly units during peak times, fostering a more economically efficient, resilient system.

The plot in Figure 51 and Figure 52 illustrate the shadow prices for the Nashik, Parli, Khaperkheda, and Koradi units emphasizes the duration of instances related to the minimum technical output (Pmin). The more expensive units, Nashik and Parli, exhibit a significantly higher percentage of instances where they hit their technical minimum, while the cheaper Khaperkheda and Koradi units experience this condition for a notably shorter duration. This trend highlights the operational constraints faced by the higher-cost units compared to their more economical counterparts during varying demand periods.

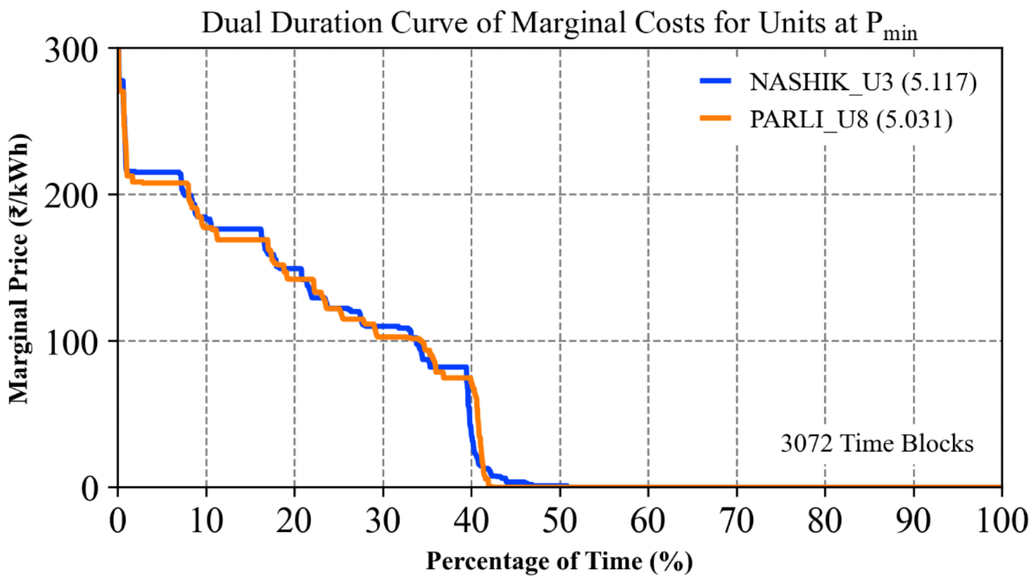

Figure 51. Duration curve of the marginal cost for units, relatively expensive, operating at P_{min}

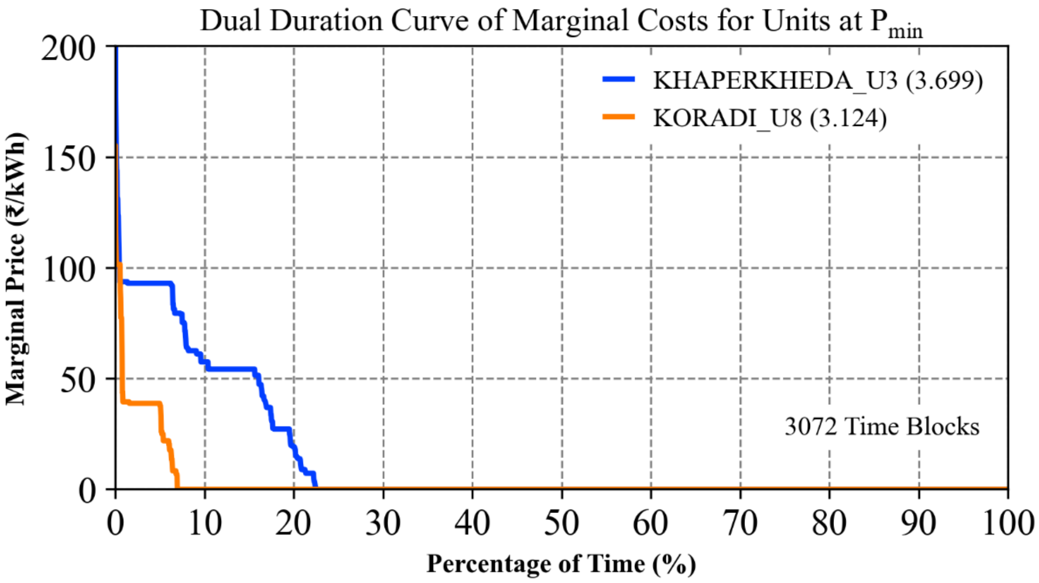

Figure 52. Duration curve of the marginal cost for units, relatively cheaper, operating at P_{min}

8.5 Marginal cost / Duals of Ramping

During the study, it has been observed that the ramping up limit was hit and marginal cost of all these instances have been highlighted in Table 5. In the existing model, ride through for all such violation have been incorporated with penalty cost of 20 Rs/MW/block in the objective function. The marginal cost of the ramp down constraints is shown in the Table 6. It is clear from the plot that savings could be possible in high-cost plants only and no saving is possible in low-cost plants.

Table 5: Generator-wise ramp up dual.

Generator Name	Extreme (₹/MW)	Average (₹/MW)	Variable cost (₹/kWh)
RIPL_U4	-1606.10	-4.82	2.91
RIPL_U5	-1606.10	-4.87	2.91
RIPL_U2	-1606.10	-5.28	2.91
RIPL_U1	-1606.10	-4.37	2.91
KORADI_U6	-1783.20	-2.80	3.06
KORADI_U10	-893.10	-2.22	3.12
KORADI_U9	-542.00	-1.18	3.12
KORADI_U8	-810.00	-2.33	3.12
KHAPERKHEDA_U5	-1798.20	-5.35	3.19
CHANDRAPUR_U9	-2151.20	-4.43	3.61
CHANDRAPUR_U8	-2151.20	-7.40	3.61
KHAPERKHEDA_U1	-911.00	-2.98	3.70
KHAPERKHEDA_U2	-2423.20	-5.03	3.70
KHAPERKHEDA_U3	-1211.60	-3.10	3.70
KHAPERKHEDA_U4	-1211.60	-5.29	3.70
PARAS_U4	-1283.60	-5.12	3.91
PARAS_U3	-767.00	-3.06	3.91
BHUSAWAL_U5	-2179.20	-7.96	4.10
BHUSAWAL_U4	-2179.20	-8.64	4.10
ADTPS_U1	0.00	0.00	4.15
ADTPS_U2	0.00	0.00	4.15
CHANDRAPUR_U6	-673.00	-1.95	4.25
CHANDRAPUR_U5	-1621.20	-3.77	4.25
CHANDRAPUR_U4	-1231.00	-3.20	4.25
CHANDRAPUR_U3	-464.70	-0.30	4.25
CHANDRAPUR_U7	-810.60	-2.33	4.25
BHUSAWAL_U3	-1268.00	-7.78	4.88
PARLI_U6	-857.80	-0.87	4.96
PARLI_U7	-1890.00	-10.59	4.96
PARLI_U8	-1173.00	-10.16	5.03
NASHIK_U3	-1221.00	-6.08	5.12
NASHIK_U4	-1256.40	-5.28	5.12
NASHIK_U5	-872.00	-1.15	5.12
APML_U1	-2022.20	-9.19	OA
APML_U3	-2220.20	-18.84	OA
APML_U4	-2022.20	-12.06	OA
APML_U5	-2022.20	-9.24	OA
IEPL	-675.00	-2.28	OA
JSWEL_U1	-2155.20	-11.06	OA
TPCL_U8	-3373.00	-5.27	OA
APML_U2	-2220.20	-18.19	OA
TPCL_U5	-2993.00	-1.35	OA

Table 6: Generator-wise ramp down dual

Generator Name	Extreme (₹/MW)	Average (₹/MW)	Variable cost (₹/kWh)
RIPL_U4	-839.70	-2.13	2.91
RIPL_U5	-639.40	-1.30	2.91
RIPL_U2	-526.40	-0.59	2.91
RIPL_U1	-639.40	-1.32	2.91
KORADI_U6	-3243.00	-3.30	3.06
KORADI_U10	-387.70	-0.56	3.12
KORADI_U9	-3530.40	-3.61	3.12
KORADI_U8	-6365.60	-5.75	3.12
KHAPERKHEDA_U5	-316.40	-1.67	3.19
CHANDRAPUR_U9	-1507.00	-3.37	3.61
CHANDRAPUR_U8	-620.00	-4.03	3.61
KHAPERKHEDA_U1	-625.00	-1.65	3.70
KHAPERKHEDA_U2	-1167.00	-3.55	3.70
KHAPERKHEDA_U3	-625.00	-2.75	3.70
KHAPERKHEDA_U4	-1167.00	-3.87	3.70
PARAS_U4	-470.00	-2.22	3.91
PARAS_U3	-614.00	-2.41	3.91
BHUSAWAL_U5	-941.00	-5.64	4.10
BHUSAWAL_U4	-970.00	-7.42	4.10
ADTPS_U1	0.00	0.00	4.15
ADTPS_U2	0.00	0.00	4.15
CHANDRAPUR_U6	-2656.00	-3.22	4.25
CHANDRAPUR_U5	-1076.00	-4.97	4.25
CHANDRAPUR_U4	-1713.00	-4.11	4.25
CHANDRAPUR_U3	-546.00	-0.60	4.25
CHANDRAPUR_U7	-1026.00	-2.95	4.25
BHUSAWAL_U3	-4985.00	-20.27	4.88
PARLI_U6	-2240.00	-2.61	4.96
PARLI_U7	-2201.00	-14.87	4.96
PARLI_U8	-2353.00	-22.78	5.03
NASHIK_U3	-4521.10	-17.58	5.12
NASHIK_U4	-3609.00	-12.63	5.12
NASHIK_U5	-5794.40	-8.29	5.12
APML_U1	-7300.30	-45.60	OA
APML_U3	-5562.00	-72.57	OA
APML_U4	-5812.00	-62.91	OA
APML_U5	-9084.40	-46.74	OA
IEPL	-346.00	-1.49	OA
JSWEL_U1	-1435.00	-8.78	OA
TPCL_U5	-3598.00	-5.22	OA
APML_U2	-5562.00	-72.56	OA
TPCL_U8	-3753.00	-8.99	OA

9. Challenges and Handling Infeasibilities

"Every challenge is an opportunity to innovate."

During the implementation of SCED, several challenges were encountered, requiring appropriate measures, such as modelling scheduling ride-through capabilities. Ensuring consistent and accurate data is crucial for the effective execution and success of SCED. In numerous instances, data inconsistencies resulted in the model becoming infeasible or reduced the potential benefits of SCED compared to MOD-based generation scheduling. A summary of these issues and their impacts are provided below:

9.1 Inconsistent declared capacity with zero schedule

One key issue encountered was the inconsistency between the declared capacity and a zero-generation schedule (unit commitment status). In several cases, generators reported a declared capacity but were assigned a zero schedule, leading to operational inefficiencies and rendering the SCED model infeasible. A sample case for APML_U4 on 24th August 2024 has been shown in Figure 53. This mismatch between available capacity and actual scheduling hinders the optimization process and reduces the potential cost-saving benefits of SCED. Another issue observed was during unit decommitment, where the declared capacity (DC) should typically decrease to reflect the reduced operational status. However, the data often did not capture this adjustment, leaving the declared capacity unchanged despite the unit decommitting. This inconsistency not only affects the accuracy of the SCED model but also leads to infeasibility.

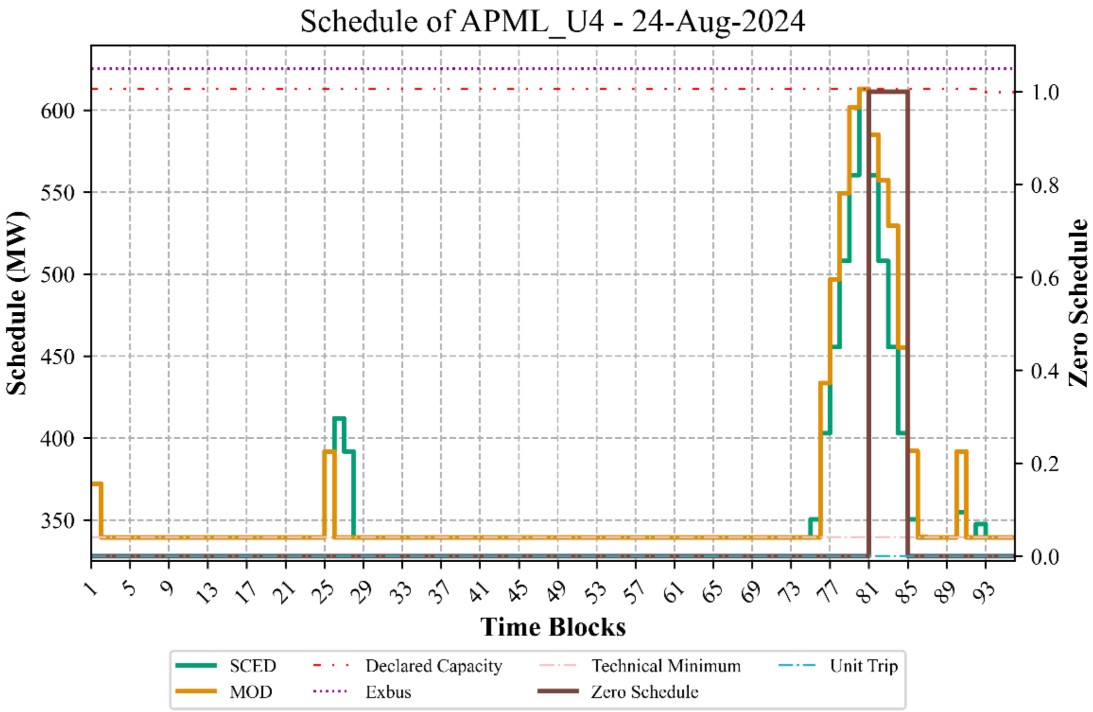

Figure 53. Inconsistent declared capacity with zero schedule

9.2 Inconsistent declared capacity with technical minima

A further inconsistency identified was the mismatch between the declared capacity and the technical minimum of certain units. In several instances, the declared capacity was set below the technical minimum, which contradicts operational norms and leads to inefficiencies in the scheduling process. A sample schedule of the BHUSAWAL_U3 on 1st September is mentioned in Figure 54. This misalignment causes complications in ensuring that generators are operated within feasible limits and need a special treatment in SCED modelling. To address this inconsistency, a workaround has been done by adjusting the technical minimum within the model to ensure operational feasibility. However, it would be more effective and efficient if the adjusted technical minima were accurately reflected in the original data itself. This would enhance the consistency of the input data, streamline the SCED process, and improve the overall optimization of generation schedules.

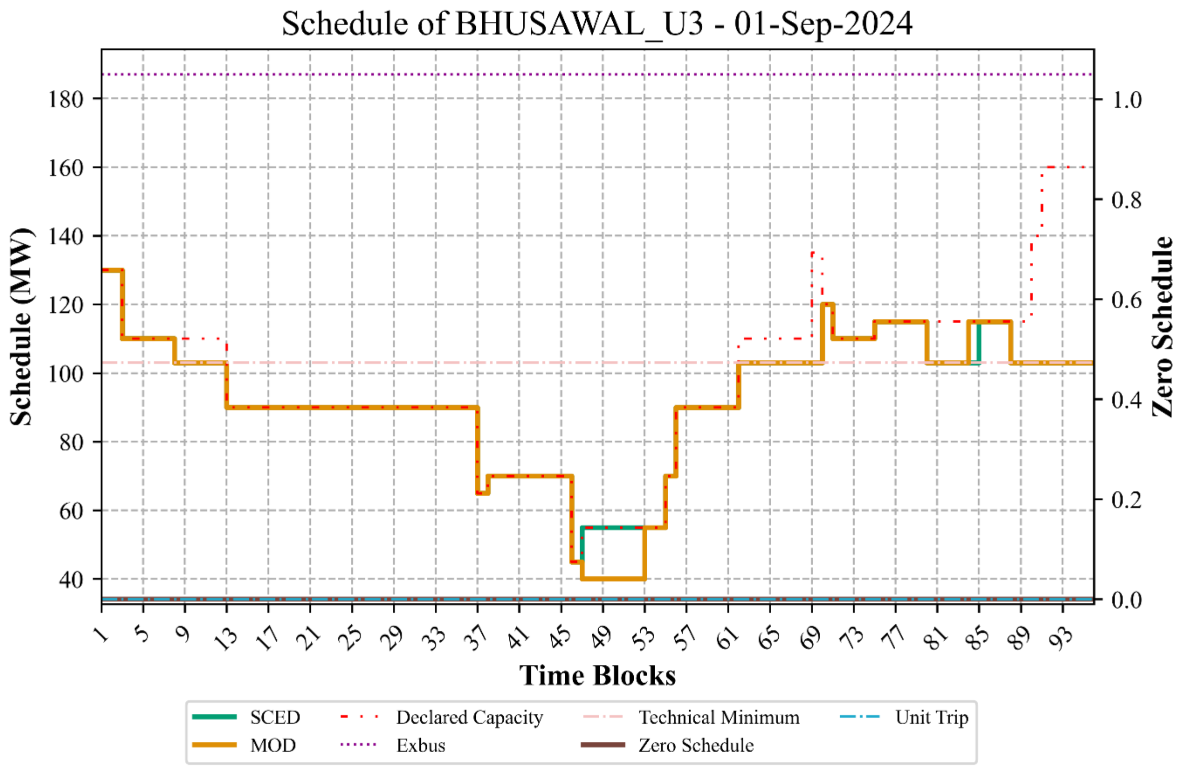

Figure 54. Schedule of BHUSAWAL_U3 operating below adjusted Tech. minimum.

9.3 Inappropriate scheduling of unit being tripped

Another issue encountered was the inappropriate scheduling of units that had tripped. Despite a unit being offline due to a trip, it was still scheduled under MOD in certain instances, leading to operational inefficiencies. A sample case for NASHIK_U4 on 22nd August has been shown in Figure 55. This leads to scheduling inconsistencies, as under SCED, the unit is not assigned, while MOD continues to schedule the unit. This discrepancy creates confusion in the generation schedule and undermines the optimization process, as SCED may be based on outdated or incorrect data from MOD. Ensuring alignment between SCED and MOD scheduling practices is crucial for maintaining operational coherence and maximizing the effectiveness of the optimization efforts.

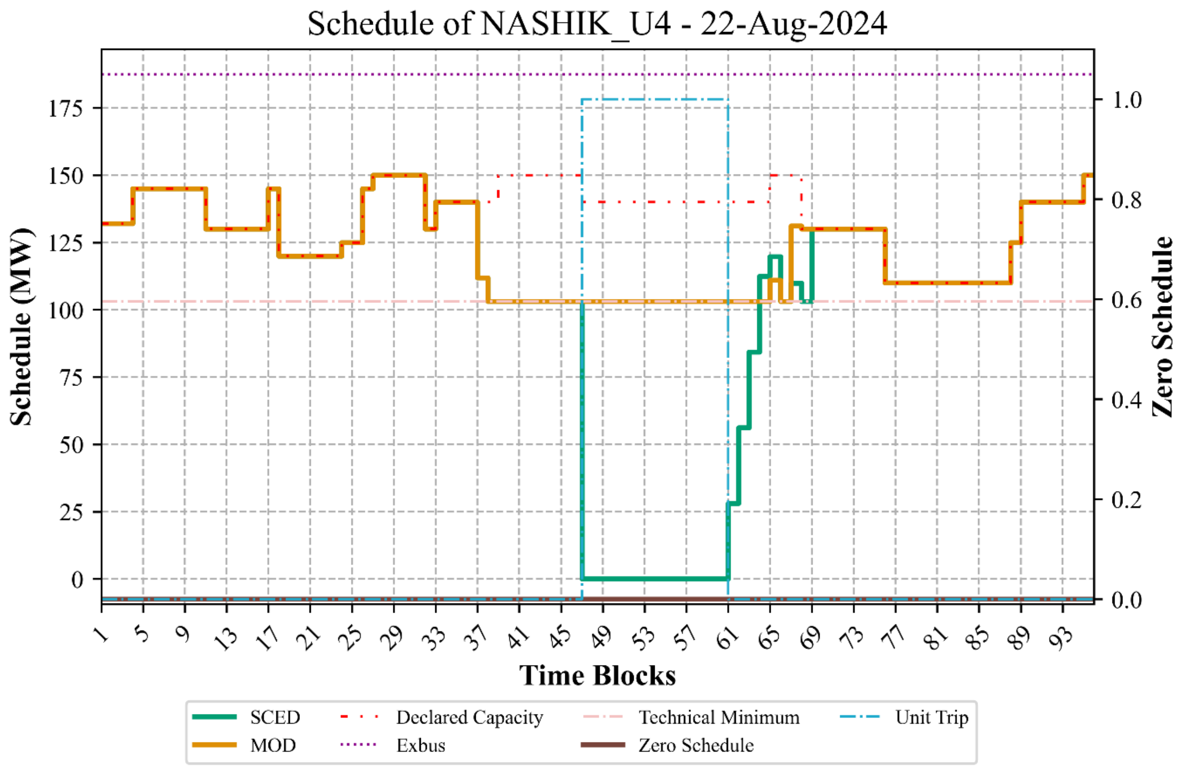

Figure 55. Schedule of the NASHIK_U4 unit experiencing trip.

9.4 Discrepancy in scheduling of the subcontracts

Discrepancies in the scheduling of subcontracts were observed, particularly when comparing the MOD and SCED approaches. In certain instances, the MOD did not schedule specific subcontracts; however, these same subcontracts were treated as fixed commitments in the SCED model. As a result, the SCED schedule exceeds the MOD schedule, leading to potential overestimations of available generation capacity. This inconsistency not only affects the accuracy of the scheduling process but also complicates the assessment of overall system performance. Aligning the scheduling practices for subcontracts between MOD and SCED is essential for ensuring coherence and optimizing resource allocation.

Addressing these inconsistencies in SCED model is crucial for enhancing the effectiveness of the SCED process and ensuring operational coherence in the scheduling framework.

9.5 Computational Resources

LP-based optimization requires significant computational power, especially for large-scale problems. Ensuring that all states have access to the necessary computational resources can be a challenge. The present system is fully capable of running both the existing and the proposed new system as these two systems can run parallelly for 2 – 3 months to check and verify the results and to check the reliability of the new model. Additional resources need to be arranged for the new module which could be either on premise or cloud-computing resources.

"History of Optimal Power Flow and Formulations • December 2012

TABLE 1: POTENTIAL COST SAVINGS OF INCREASED EFFICIENCY OF DISPATCH (EIA 2012)

An ultimate goal of ISO market software, and a topic of future research, is the security-constrained, self-healing (corrective switching) AC optimal power flow with unit commitment over the optimal network.

Today, the computational challenge is to consistently find a global optimal solution with speeds up to three to five orders of magnitude faster than existing solvers. There is some promising recent evidence that this could be a reality in five to ten years. For example, in the last two decades mixed-integer programming (MIP) has achieved speed improvements of 107; that is, problems that would have taken 10 years in 1990 can be solved in one minute today. As a consequence, MIP is replacing other approaches in ISO markets. Implementation of MIP into the day ahead and real-time markets, with the Commission's encouragement, has saved American electricity market participants over one-half billion dollars per year (FERC 2011). More will be saved as all ISOs implement MIP and the new formulations it permits in the next several years."

10. Value for Stakeholders

"Optimization driving efficiency, cost savings, and grid reliability for all."

It is observed in the above study that the transition from MOD (MOD) to SCED (SCED) in power systems is a significant evolution, which introduces greater efficiency and flexibility. SCED incorporates system constraints like grid reliability, and security, offering a more dynamic and real-time approach to dispatch. The benefits of this transition extend to multiple stakeholder groups, as outlined below:

10.1 Distribution Companies (DISCOMs)

- **Cost Optimization:** SCED allows the dispatch of power from the most efficient generators while accounting for system security constraints. DISCOMs can benefit from more cost-effective power procurement compared to the rigid structure of MOD, which may not always select the least-cost generation option.
- **Improved Reliability:** With SCED considering grid constraints, the likelihood of grid disturbances or outages is minimized, leading to more reliable power for consumers.
- **Enhanced Market Participation:** DISCOMs can participate more flexibly in real-time energy markets, where SCED promotes competitive pricing, reducing the need for long-term, high-cost Power Purchase Agreements (PPAs).

10.2 Generators

- **Optimal Utilization of Generation Assets:** SCED ensures that the generation is dispatched based on both cost and system requirements, potentially leading to better utilization of generators that may have been underused in MOD.
- **Revenue Stability through Efficiency:** Generators, especially efficient ones, can expect a more stable revenue stream since SCED promotes dispatch based on least-cost generation, security considerations, and real-time market dynamics.
- **Increased Grid Access for Renewables:** SCED enhances grid flexibility, which is particularly beneficial for renewable energy generators (solar, wind, etc.). The system's ability to handle fluctuating generation allows better integration

of renewable sources, leading to higher output and better market opportunities.

10.3 System Operators (SLDC)

- **Enhanced Grid Security:** SCED optimizes power dispatch while factoring in system security and transmission constraints, helping operators maintain grid security. By moving away from MOD's static nature, SCED enables better management of real-time contingencies.
- **Improved Operational Efficiency:** System operators can make decisions that balance economic efficiency with operational security, ensuring that the most cost-effective and reliable generators are dispatched within system limits.
- **Support for Renewable Integration:** SCED provides operators with the tools to integrate more renewable energy sources while maintaining system reliability. This supports India's renewable energy targets, as variable generation can be better managed.

10.4 Regulators

- **Efficiency and Transparency in Dispatch:** SCED provides a framework where the cost-benefit of dispatch decisions is more transparent, making it easier for regulators to ensure that the system operates efficiently. This also helps in monitoring market dynamics and setting fair tariff structures.
- **Facilitating Market Reforms:** SCED aligns with regulatory objectives of creating a more competitive, transparent, and economically efficient power market. It fosters competition among generators, ensuring that consumers benefit from lower prices without compromising on grid reliability.
- **Support for Long-Term Policy Objectives:** The move to SCED aligns with India's goal of reducing the emissions. The emission parameter may be included in SCED as one of the objective functions to minimise it while deciding the final dispatch. Regulators can enforce policies that promote clean energy dispatch, while maintaining a balance between economic and environmental considerations.

10.5 Policy Makers

- **Support for National Energy Goals:** SCED is aligned with India's policy goals of promoting renewable energy, improving grid efficiency, and reducing greenhouse gas emissions. It creates a flexible platform for integrating policy-driven initiatives such as increased renewable capacity.
- **Market Flexibility and Innovation:** SCED encourages the development of ancillary markets and demand-side management initiatives. Policy makers can leverage SCED's dynamic nature to introduce policies that promote innovation in energy storage, flexible demand response, and grid modernization.
- **Long-term Planning:** SCED allows for a more future-proof grid, enabling policy makers to design energy systems that are resilient and adaptable to evolving technologies, such as electric vehicles, energy storage, and distributed generation.

10.6 Consumers

- **Lower Electricity Cost:** As SCED prioritizes the dispatch of the most economically viable generation options while maintaining system security, it leads to lower costs for electricity. These savings are ultimately passed on to consumers in the form of reduced tariffs.
- **Improved Reliability:** Consumers benefit from a more reliable grid, as SCED ensures that the system operates securely even under peak demand or during contingencies. This reduces the risk of outages and service disruptions.
- **Sustainability Benefits:** Consumers are increasingly conscious of the environmental impact of their energy consumption. SCED supports the integration of renewable energy sources, allowing consumers to enjoy cleaner energy while supporting the country’s climate goals.

10.7 Planners

- **Enhanced Grid Efficiency:** SCED optimizes power dispatch by considering both cost and security constraints, ensuring that the most economical and reliable generation units are prioritized. This leads to a more balanced and efficient grid.

- **Improved Forecasting and Resource Allocation:** Planners gain better insights into generation needs and can allocate resources more accurately, supporting long-term planning for capacity additions and infrastructure investment.
- **Renewable Integration Support:** SCED's flexibility allows for smoother integration of renewable energy sources, which is critical for meeting sustainability targets and grid decarbonization goals.
- **Cost Optimization:** By reducing reliance on high-cost generation and improving resource use, SCED helps manage overall system costs.
- **Informed Policy and Market Decisions**: Data and insights from SCED can guide planners in developing policies and market structures that foster competition, transparency, and grid resilience.

11. Way Forward

"To lead in the future, we must optimize for today."

As India continues to evolve its energy landscape, the implementation of State SCED represents a significant step towards achieving greater efficiency and sustainability in electricity generation. To maximize the benefits of SCED and ensure its successful integration into the existing framework, several key actions are necessary.

11.1 Future Modeling Activities

As the power system landscape evolves, modeling efforts must keep pace with the increasing complexity of integrating renewable energy, optimizing hydro resources, and managing day-to-day system dynamics. Future modeling activities will require a sophisticated approach that includes multiple facets, such as hydro resource optimization with water valuation, consideration of transmission constraints, and the incorporation of real-time system dynamics. These developments will be critical in ensuring a reliable, cost-effective, and sustainable power system.

11.1.1 Hydro resource optimization with valuation of water

Hydropower plays a crucial role in the energy mix of the State, as it provides flexibility, peak load management, and grid stability. However, optimizing hydro resources involves much more than merely scheduling generation. It requires balancing energy production with competing demands on water resources, such as irrigation, flood control, and environmental preservation.

a) Valuation of Water in Hydro Models

Incorporating the valuation of water in hydro resource optimization is an emerging trend. Water, being a limited resource, has different economic and social values based on its use. The following attributes need to be considered:

Economic Valuation: Models need to assign an economic value to water used for energy generation versus other applications. During periods of water scarcity, models will need to optimize the generation of electricity while balancing the needs of agriculture and human consumption.

Dynamic Water Availability: Seasonal fluctuations, reservoir inflows, and monsoon patterns affect water availability, influencing hydropower generation.

Future models will account for these variables dynamically, integrating real-time hydrological data and forecasts to adjust generation schedules accordingly.

Multipurpose Reservoir Management: Reservoirs serve multiple purposes, including irrigation, flood control, and energy generation. Models should consider the trade-offs between these uses, ensuring that the allocation of water resources aligns with social, economic, and environmental priorities.

b) Hydro's Role in Renewable Integration

As countries increase their reliance on intermittent renewable energy sources like wind and solar, hydropower's ability to provide quick ramp-up and ramp-down capacity becomes invaluable. Models will need to incorporate hydro's role in stabilizing the grid, acting as a backup for renewables, and providing ancillary services such as frequency and voltage regulation.

11.1.2 Treatment of ISGS share in intra-state SCED

Presently, the central sector allocations are not considered under MOD and hence, initially not proposed to be included in the SCED optimization. The inclusion of the central sector allocation within the ambit of SCED optimization will cause further cost savings. Once the SCED pilot is implemented, the central sector allocations also shall be included in the optimization.

Currently, ISGS allocations to Maharashtra are treated as fixed must run within the state's optimization framework. Intra-state SCED focuses on optimizing state-level schedules, supporting unit commitment, decommitment, and flexibility for state plants. Aligning ISGS requisition timelines could enhance schedule viability. and likely to cause further economy. For a future nested SCED model, states would first optimize dispatch, including ISGS shares, within their own jurisdictions, factoring ramp and technical minimum,etc., followed by an inter-state SCED adjustment. This tiered approach would improve resource use and grid stability at both state and national levels. This being an important but complex topic requires interactions with NLDC RLDC and amongst other SLDCs .

11.1.3 Inclusion of transmission constraints

Transmission constraints are one of the most critical factors in the successful operation of a modern power grid, particularly as renewable energy capacity expands. The inclusion of transmission constraints in future modeling activities is essential to ensure that the generation from diverse resources can be reliably delivered to the load centers. Neglecting these constraints can lead to inaccurate predictions of system behavior, causing inefficiencies and even operational risks.

It is proposed to include the transmission constraints for the selected section/flow gates taking the real time input from the data acquisition system and feeding the same to the optimization engine as the real time status for deciding the optimum dispatch with constraints honored. The optimization model will develop accordingly to take the real time input.

11.1.4 Inclusion of day-to-day system dynamics

Day-to-day operations of the power system are subject to a wide range of dynamic factors that can impact both short-term decision-making and long-term planning. Incorporating these dynamics into future models will make them more robust and reflective of real-world scenarios.

a) Variable Renewable Energy (VRE) Forecasting and Uncertainty

Wind and solar power are subject to variability and forecasting errors, introducing uncertainty into the system. Future models will need to include stochastic elements that account for the unpredictability of renewable generation. This involves:

Probabilistic Forecasting: Integrating real-time forecasting data with probabilistic models to manage the inherent uncertainty of VRE sources. This will help in optimizing dispatch schedules and reserve requirements to maintain grid reliability.

Impact on Reserve Requirements: Day-to-day models must consider the need for additional spinning reserves to compensate for the variability of VREs. These models will optimize the amount of reserve capacity needed, minimizing costs while maintaining system security.

b) Load Forecasting and Demand Response

Accurate load forecasting is essential for efficient system operation. Models will include more granular demand forecasting, taking into account factors such as weather, economic activity, and emerging trends like electric vehicle (EV) charging. In addition, demand response (DR) programs will play a significant role in balancing supply and demand.

11.1.5 Extraction of important system information

a) Price of Reserves

In a power system increasingly reliant on intermittent renewable energy sources, the role of reserves—whether spinning, non-spinning, or quick-start reserves—is crucial for maintaining grid stability. SCED provides valuable insights into the optimal allocation and pricing of reserves, which is essential for maintaining system reliability during both normal operations and unexpected contingencies.

b) Cost of Congestion

Transmission congestion is a critical issue in power systems, especially in grids with increasing renewable energy penetration and complex power flows. SCED provides detailed insights into the cost of congestion, as it dynamically accounts for transmission constraints in dispatch decisions. This information is invaluable for grid operators, regulators, and market participants, as it helps in optimizing grid usage, planning infrastructure investments, and reducing overall system costs.

c) Prices of Demand Response

Demand response (DR) has emerged as a critical tool for grid flexibility, allowing system operators to balance supply and demand dynamically. SCED, with its real-time optimization capabilities, provides a comprehensive view of how DR can be priced and deployed effectively in response to grid needs. This creates a more efficient market for demand-side participation.

d) Resource Adequacy

Resource Adequacy and its allocation to different areas is also an important issue in day-to-day real-time operation, which could be handled optimally by SCED. Resource Adequacy is an important issue especially with increasing renewable energy penetration. By prioritizing the dispatch of low-cost, reliable generation and considering transmission constraints, SCED helps to ensure that adequate resources are allocated to meet real-time demand, even during peak periods or unexpected contingencies. This optimization reduces the need for reserve capacity, supports renewable integration, and enhances the reliability of the power supply.

11.1.6 Security Constrained Unit Commitment

SCUC plays a critical role in ensuring resource adequacy by optimizing the commitment and scheduling of generation units while respecting operational constraints. Through SCUC, MSLDC can commit sufficient generation to meet forecasted demand reliably, even under unexpected contingencies. By accounting for transmission limits, ramp rates, and unit constraints, SCUC ensures that available resources are utilized efficiently to maintain grid stability. This approach enhances the system's capacity to manage peak loads, integrate renewables, and respond flexibly to demand variations, thereby strengthening resource adequacy and grid resilience in an economically efficient manner. It is proposed to start SCUC on a day-ahead basis to ensure optimal unit commitment ensuring mandated reserves in the system.

11.1.7 Centralized Dispatch

Presently, MSLDC is following a decentralized dispatch as the direction of Hon 'able Commission. However, with the implementation SCED modeling, it will be possible to have a thin layer of centralized dispatch above the present decentralized dispatch. It is proposed to have such a centralized dispatch to have further optimization in day-to-day scheduling.

11.1.8 Constrained Emission Dispatch

Constrained Emission Dispatch (CED) represents a forward-looking enhancement to SCED, aiming to optimize power generation while minimizing the emission of thermal generation. By integrating emission constraints into dispatch decisions, CED prioritizes low-emission and renewable generation sources, and minimizing the high emission thermal resources, balancing economic efficiency with environmental responsibility. This approach supports the reduction of reliance on high-emission plants, especially during periods of lower demand or favorable renewable generation. Future implementation of CED under SCED could pave the way for a cleaner energy mix, facilitating a gradual shift toward sustainable power systems without compromising grid reliability or cost-effectiveness.

11.2 Future Actions

Actions are being taken for the implementation of SCED at State level which are as below:

11.2.1 Capacity building

The standard modules for two-day workshops have been developed in consultation with IITs as mentioned under 6.2.2. It is proposed to use this standard module for the capacity building activities in all the States who are coming forward to implement Intra-state SCED.

USAID also agreed to extend their assistance in carrying out capacity building programs in the states and accordingly they have reached out to a few States and FOLD Secretariat. Various other organizations working in Indian power sector are also likely to extend support in capacity building for SCED implementation.

11.2.2 Development of optimization engine

It has been decided to use GAMS for the development of the optimization module as a standardized platform across the State Load Dispatch Centre. A ten-user GAMS license has already been arranged by the World Bank free of cost and handed over to Maharashtra and Gujarat. Once the states are in the process of implementing the intra-State SCED, GAMS license could be arranged by the World bank.

11.2.3 Coordination among states for SCED implementation

Forum of Load dispatch in its 48th meeting discussed the implementation of intra-state SCED and requested the interested states to come forward so that assistance could be provided. The following activities are envisaged:

1. Technical support through online workshops
2. Interactions with national and international experts
3. Shared resources, publications folders, and sample code directories would be made available
4. Short deputations of resource personnel for training/brainstorming
5. 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 and experience could be shared.

The FOLD also stressed on the in-house development and implementation of the Intra-State SCED at the states and urged the fold members to create the following groups:

- Scheduling and Dispatch – 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

11.2.4 Coordination among SERCs

Implementation of intra-State SCED would only be possible after appropriate direction from respective SERCs. It is utmost important that the direction be uniform across the States so that uniform implementation is affected which in turn will pave the way for integration of SCED initially at regional level and then to national level. The coordination activities need to be done at the level of Forum of Regulators (FOR).

11.2.5 Recommendations

The following recommendations outline a comprehensive approach to enhance the effectiveness of State SCED in India.

1. **Data Standardization and Integrity:** Establishing a standardized framework for data collection and reporting is essential to ensure accuracy and consistency. This includes harmonizing parameters such as declared capacity, technical minima, and variable costs across all generators. Implementing robust data validation mechanisms will minimize inconsistencies and enhance the reliability of SCED outputs.
2. **Integration of Hydro-Resources**: The optimization of hydro resources under SCED is a crucial area for future development, requiring deeper exploration of key factors such as the cost of water, its availability, and the role of water as a limited resource. Unlike thermal plants, where fuel costs dominate, the valuation of hydro resources involves the opportunity cost of water—a complex variable tied to multiple competing uses, such as irrigation, municipal supply, and ecological needs. Further studies are needed to quantify this cost-effectively, considering seasonal variations in water availability, reservoir levels, and environmental regulations. Additionally, the source of water, such as river flows, snowmelt, or rainfall, introduces variability that can significantly affect the reliability of hydroelectric generation. Integrating these dynamics into SCED will allow for more efficient dispatch of hydro resources, balancing economic, environmental, and social priorities while enhancing grid stability and ensuring sustainable use of water. This optimization can help maximize the economic and strategic value of hydropower in an energy mix increasingly dependent on renewable sources.
3. **Integration of Renewables:** As renewable energy sources become a larger part of the energy mix, the SCED should be adapted to incorporate variable generation profiles. This includes developing advanced forecasting tools and scheduling algorithms that can effectively balance intermittent renewable generation with conventional power sources and overall broaden the scope of the optimization.

4. **Integration of SCED:** The study was made with a model that honored DISCOM-wise percentage generation share of different generators in line with existing contractual obligations. The SMPs of all the DISCOMs have been determined and have been included in the report. The study also provides opportunities in the present system of arbitrage in inter-DISCOM and market transaction**s.** This implies that gradual integration of the DISCOMs has the opportunities for higher savings. With gradual integration, DISCOMs would enhance grid efficiency and reliability as it offers greater flexibility in dispatch, minimizes transmission congestion, and ensures more effective handling of system-wide constraints. This approach would potentially lead to further cost savings, and enhanced real-time decision-making, ultimately benefiting all the stakeholders including utilities and consumers.
5. **Utilizing Marginal Values:** Leverage marginal pricing mechanisms to incentivize generators for adjusting their declared capacities, technical minima, and providing necessary ramping services. Regulatory intervention is needed to improve the harmonic adaptation of marginal values, ensuring that incentives align effectively with operational realities and market dynamics. This will not only enhance flexibility in generation but also encourage optimal dispatch of resources based on real-time demand and supply conditions.
6. **Enhanced Modelling of Technical Parameters:** Future SCED frameworks should incorporate more detailed modelling of technical parameters, including line flow limits, reserve, and inertia. This will improve scheduling flexibility and operational efficiency, particularly during periods of fluctuating demand. The implementation of Optimal Power Flow (OPF) integrated with SCED represents a key future strategy for enhancing grid security and improving market efficiency. OPF ensures optimal power generation and distribution by minimizing generation costs while adhering to system constraints such as transmission limits, voltage stability, and generation capacities. When combined with SCED, this approach not only ensures cost-efficient dispatch but also incorporates real-time security considerations, such as N-1 contingency analysis, which ensures the system can withstand component failures. A very important outcome of implementing OPF with SCED is the calculation of Locational Marginal Prices (LMPs)— the true cost of delivering electricity to different points in the grid. LMPs provide transparent price signals that reflect congestion and losses in

the system, enabling more efficient and competitive markets. By using this integrated framework, system operators can optimize resource allocation, improve grid resilience, and foster the development of energy markets that are better equipped to handle dynamic conditions, such as increased renewable penetration and demand variability. This future plan will enhance both grid reliability and market transparency, paving the way for a more secure and economically efficient power system.

7. **Performance Monitoring and Reporting**: Establishing key performance indicators to monitor the effectiveness of SCED implementation will help identify areas for enhancement. Regular reporting on SCED outcomes can foster accountability and drive continuous improvement.
8. **Capacity Building and Training:** Investment in training programs for personnel involved in SCED operations is vital. This will enhance their understanding of complex scheduling algorithms, operational constraints, and market dynamics, ultimately leading to more informed decision-making.
9. **Feedback Mechanisms:** Implementing robust feedback mechanisms to continuously assess and refine the SCED process is crucial. Regular reviews and stakeholder consultations can provide valuable insights into operational challenges and areas for improvement.

It is **recommended to implement a six-month pilot of SCED** to observe its benefits and gain crucial insights for long-term adoption. The result of the study on SCED has demonstrated its potential to improve grid reliability, optimize resource allocation, and enhance market efficiency by incorporating transmission constraints and real-time security considerations into economic dispatch. The pilot period will provide an opportunity to observe its performance across different seasons, capturing how SCED responds to varying demand patterns, renewable energy fluctuations, and transmission constraints throughout the year. This will also allow stakeholders to evaluate and determine the appropriate distribution of savings generated by SCED between generators, consumers, and grid operators.

The SCED pilot will provide essential data on continuous operation, revealing infrastructure gaps like communication systems, and highlighting real-time data exchange needs. It will also identify human resource requirements, including operator training and opportunities for capacity enhancement. Overall, the pilot is a key step in preparing the grid for full-scale SCED implementation, enabling a smoother transition to a more secure and efficient power system.

12. Conclusion

"In the complexity of grids, every small efficiency unlocks massive savings."

The implementation **of SCED** offers clear advantages over the traditional **MOD** in terms of improving grid reliability, optimizing resource allocation, and enhancing market efficiency. SCED ensures that dispatch decisions respect system security constraints like generating plant constraints and transmission limits, while still focusing on cost minimization. However, to fully realize its long-term benefits, it is essential to conduct an extended study of SCED performance over different seasons, capturing the complexities of varying demand patterns, renewable energy fluctuations, and state grid constraints.

Additionally, continuous **capacity building of human resources** is crucial, particularly in emerging areas like **hydro optimization** and **OPF** integration. These areas represent the future of grid management and market development, and skilled operators are essential for the successful deployment and management of SCED. Training programs and knowledge-sharing initiatives should be prioritized to equip grid operators with the necessary expertise to handle advanced optimization techniques.

A long-term approach to SCED implementation, coupled with a focus on real-time data exchange, infrastructure upgrades, and capacity building, will lay the foundation for a smarter, more resilient, and efficient power system that can handle the evolving challenges of the modern energy landscape. This, in turn, will support the further development of electricity markets through mechanisms like **LMP** and improved grid security, creating a robust foundation for a sustainable energy future.

Annexure - I

Intra-State SCED

Capacity Building Initiatives

Course Curriculum

&

Reading Material

TABLE OF CONTENTS

Gist of discussion on capacity building of SLDC engineers on 5th August 2024

(Through Video Conferencing)

A meeting was held on 5th August 2024 through video conferencing to discuss the training course and various modalities of conducting the training on Optimization and its implementation at the Intra-state level through linear programming techniques.

The list of participants is attached as Annexure – I.

The discussions and the decisions on the following agenda points are as follows:

1. Course curriculum

The draft course curriculum was shared with all the member participants for discussion.

The suggestions of the members are listed below:

- The course could be divided into five modules, (i) What is Optimization; (ii) Introduction of various optimization problems; (iii) Brief details about Security Constrained Economic dispatch; (iv) Implementations of SCED at National Load Despatch Centre; (v) Fundamentals of GAMS language and hands-on.
- Highly technical sessions may be difficult to be absorbed by the proposed participants SLDCs, who are away from the technical studies and involved in their day-to-day activities. Hence more focus on the development aspects through GAMS is desired with more of hands-on sessions.
- The last session, which includes a brief discussion on how the basic model may be extended to include (a) transmission constraints (b) spinning reserves-optimization; and (c) unit commitment issues along with GAMS implementations, is a bit loaded and difficult to cover within the available time and needs a review.
- A session on nodal pricing could be included for better understanding which will be forward looking.
- Specific focus on the selected software will be preferred. Specific problems related to the concerned SLDCs would more likely attract the participants' interest.

It was agreed that two days of training with eight sessions of one and half hours each i.e. a total of 12 hours should be sufficient to cover the basics around dispatch optimization, LP, conversion of dispatch optimization LP into a GAMS code and hands-on sessions using GAMS, as decided to start with. However, a long-duration program could be arranged based on the feedback and if felt necessary to cover more complex topics such as transmission representation.

It was agreed that the proposed training course curriculum shall be revised to accommodate the suggestions. The revised training course curriculum is attached as Annexure – II which will be taken as the standard module for all the trainings concerning intra-state SCED version 101. The details of each session are in Annex III. The reading material is attached as Annexure – IV.

There was consensus that the GAMS language be selected for the development of the optimization engine in-house in the States to have uniformity across States and NLDC which can develop harmonization among the developers in the States as well as at NLDC/RLDCs. The advantages of using GAMS are also shared as below :

(i) **Time-tested and versatile:** Oldest (35 years) and most widely used math programming language specialized for optimization with a wide array of links to solvers, database options, and tools like GAMSPy to freely mix with python.

(ii) **Coding features:** Compact and highly transparent codes, easy to learn, debug, and compatible across different operating environments. Code is the documentation.

(iii) **Standardized and well supported**: Syntax and features have become the industry norms, backward compatible and well supported by the vendor (GAMS Development Corp)

(iv) **Relative cost:** Around $2000/perpetual license including advanced LP solver like CPLEX

(v) **Multiple applications**: It is an excellent platform for not just SCED but other investment and operational planning tools, market clearing engines, equilibrium models, pricing analysis, network models, etc.

It was agreed that the capacity building and hands-on session will be on GAMS language. While the educational version of GAMS license may be used for small samples, the World Bank was requested to extend assistance regarding arranging of GAMS.

On a query regarding whether the interface with the existing scheduling system is to be covered, it was clarified that the proposed training is purely for the development of skill-sets of the SLDCs engineers and engineers on implementation of Intra-State SCED on GAMS language.

It was opined by all that the presentations on the basic modules should be standardized. Specifically, the general presentation on SCED, GAMS, and Hands-on sessions also could be standardized. However, the presentations on purely technical sessions and the state-specific examples may differ from State to State which will be taken care of by the respective faculties.

2. Faculties and the training material

It was agreed that the trainers, professors & research scholars, from the local engineering institutes, shall preferably be engaged as faculties with the flexibility to invite from the pool. In this regard, the local engineering institute shall coordinate with the available faculties. Domain experts, RLDCs and NLDC shall also be involved in conducting the training.

The training material shall be arranged in advance and shared with the participants through mail.

3. Number of participants

There was consensus that the number of participants should be limited to maintain a focus on each of the participants. It was informed that SLDCs may recommend the developers also, to participate in training, who will be involved in development and implementation. It was agreed that the O&M and IT engineers, the members of the present system Integrator (SI) and their sub-vendors shall be included in the training to ensure sustainability. Considering these, it was agreed to have 10 – 15 participants for the two days program.

Suggestions to keep some age limit etc. for the selection of participants to ensure agility and interest were also discussed, however, it was also opined that the looking at the manpower availability, it will be difficult to find enough persons with domain knowledge at SLDCs. Hence such a strict restriction may be avoided

It was also proposed that an evaluation system for the participants could make participants more focused and attentive during the capacity building. It was agreed to have present-day tools like SLIDO, where questions could be configured and responses could be taken and recorded maintaining anonymity, and could be used to keep the participants connected and act as an evaluation system.

A feedback questionnaire could be developed on SLIDO for quick feedback from the participants on the training which could be used to refine and improve the subsequent programs.

4. **Venue of the proposed training**

   It was unanimously agreed that the Load Despatch Centre are the preferred venue for arranging such training. The associated arrangements and logistics shall be organised by the concerned LDCs. However, online training also could be arranged in case of non-availability of faculties to convene the training at SLDC.

5. **Formation of Help group and Portal**

   A help group, consisting of professors, research scholars and domain experts shall be formed to support the developers during the implementation process as well as during the operational phase.

   SAREP shall create a separate link for the Intra-State SCED in their existing portal to share the reading materials, standard presentations of the training, problem resolution details etc. so that anyone can access these documents and get himself acquainted. The training material, presentation and resources etc. for each course shall be loaded on the portal under Events and Training Link.

   The present WhatsApp Help group also shall be used for sharing knowledge as well as raising the issues faced during development and implementation.

6. **Honorarium for the Faculty**

   The honorarium shall be disbursed to the faculties/experts/resource persons directly based on per day/per session as per the norms of respective SLDC/ SAREP/Organiser which was also agreed to by all.

It was informed that the activity related to capacity building programme as elaborated above is a part of the bigger and overall objective related to implementation of the Intrastate SCED in the concerned states. To achieve this, in addition to Capacity Building, the other activities include – Development of the tool, handholding during implementation of the SCED in the state on pilot basis, formulation of the regulatory framework and constitution of the supporting group. These activities shall help the state in achieving the real objective.

It was opined that the commitment to working collaboratively on the development of skillsets among State Load Dispatch Center (SLDC) engineers is paramount for the successful implementation and refinements of Intra-State Security Constrained Economic Despatch (SCED). This joint initiative by academia and industry aims to enhance energy optimization and market efficiency. By LDC engineers with the latest knowledge and practical skills, academia can bridge the gap between theoretical advancements and real-world applications, ensuring that Indian engineers are well-prepared to handle the complexities of SCED.

Through these type of capacity building, India can achieve significant improvements in energy management, reduce operational costs, and enhance grid stability. The integration of intra-state SCED with the broader SCED framework will foster a more competitive and efficient energy market, ultimately benefiting consumers and contributing to national energy goals.

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(Prof Abhijit Abhyankar) IIT – Delhi	**(Prof Zakir Hussain Rather)** IIT – Bombay	**(V. K. Agarwal)** Former ED Grid-India & Sr Advisor SAREP
(Debasis De) Former ED, Grid-India	**(S K Soonee)** Former CEO, POSOCO	**(Dr. Deb Chattopadhyay)** Power System Expert, WB

Annexure - I

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Annexure – II

Proposed Training Module

Time	09:30-11:00		11:30-13:00		14:00-15:30		16:00-17:30
Day 1	Welcome and Optimization Fundamentals SCED in Indian Context	Tea Break (11:00 - 11:30)	Introduction to LP through a dispatch optimization example	Lunch Break (13:00 - 14:00)	Introduction to GAMS	Tea Break (15:30 - 16:00)	Modelling in GAMS: Hands-on of Toy Example (Homework: Single-Period SCED)
Day 2	Single-Period SCED Modelling: Hands-on and Interpretation		Multi-Period SCED Modelling		Multi-Period SCED Modelling: Hands-on and Interpretation		SCED Extensions and Post-Test

Annexure – III

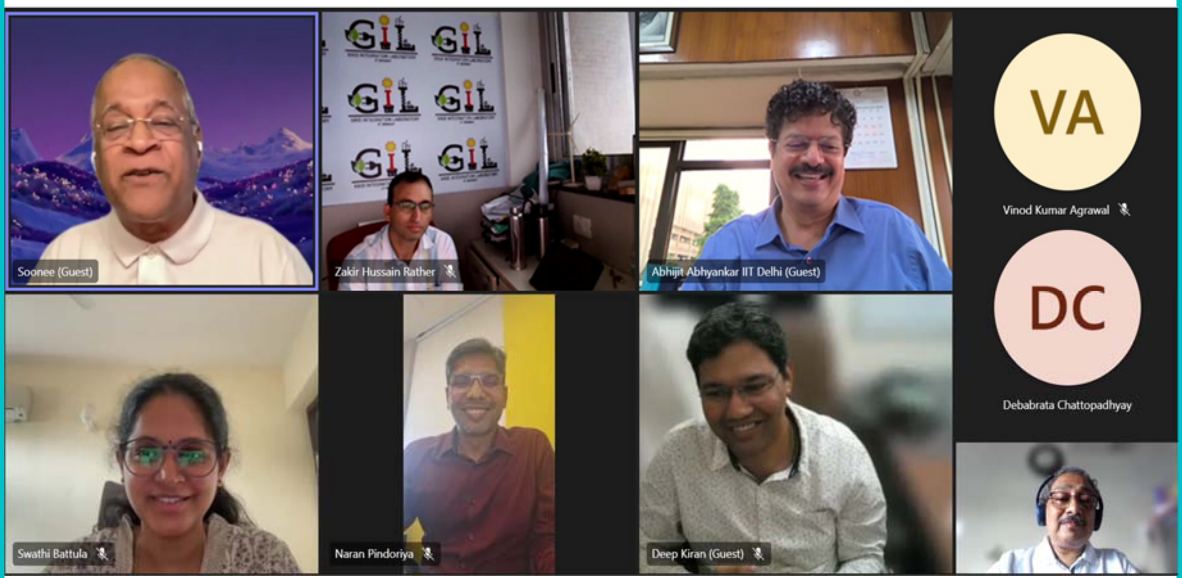
Program session details

Day - I

1:30Hrs	Topics	Details
Session - 1	Welcome and Optimization Fundamentals SCED in Indian Context	What is Optimization, Duality, and Solution Methods Understanding of SCED in the Indian Context
Session - 2	Introduction to LP through a dispatch optimization example	Basics of LP: Introduction to various optimization problems, primal vs dual, overview of solution techniques (Simplex and Interior Point), Demonstration of the graphical method. Usage of a dispatch optimization example – showing how it differs from a bucket-filling approach.
Session - 3	Introduction to GAMS	Fundamentals of GAMS language, explain what GAMS does as a matrix generator, options for inputs and outputs, options for solvers Go through the four building blocks of GAMS language (sets, parameters, variables, equations)
Session - 4	Modelling in GAMS: Hands-on of Toy Example (Homework: Single-Period SCED)	The instructor provides a live demonstration of how to write a basic dispatch optimization – single period SCED with a constraint with associated input source file and output file. Assignments for homework

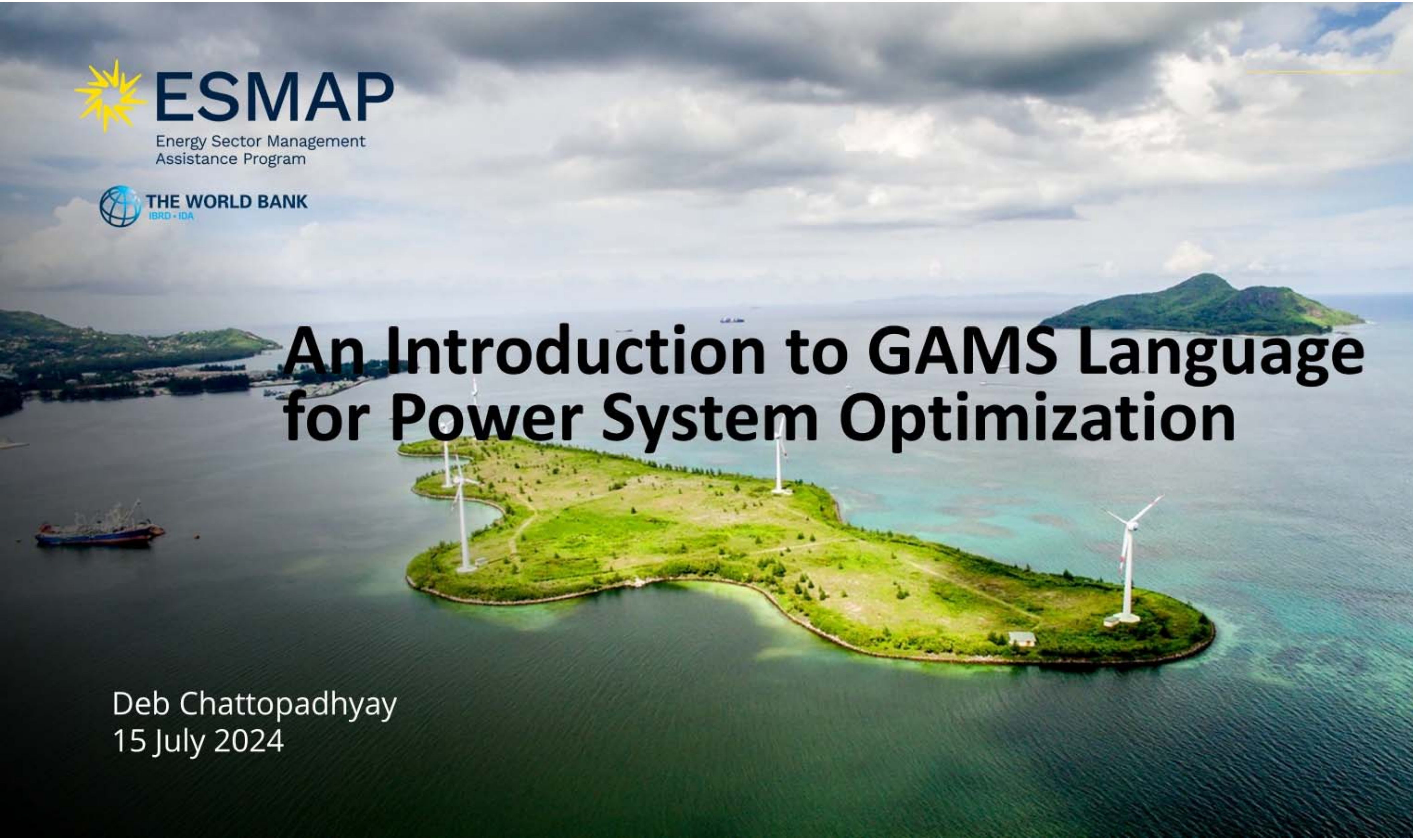
Day - II

1:30Hrs	Topics	Details
Session - 5	Single-Period SCED Modelling: Hands-on and Interpretation	Discussion on home assignments, and solution status (Optimal vs Infeasible). How to get around infeasibility. Demonstration of the dispatch outcomes and interpretation of results. Demonstration of the shadow prices and link them to the LP theory. Interpretation of the prices for demand and capacity
Session - 6	Multi-Period SCED Modelling	The instructor provides a live demonstration of how to write a basic dispatch optimization – multi period SCED along with ramping constraint. Task for home assignment on multi period SCED
Session - 7	Multi-Period SCED Modelling: Hands-on and Interpretation	Discussion on home assignments, solution status (Optimal vs Infeasible). How to get around infeasibility. Demonstration of the dispatch outcomes and interpretation of results.
Session - 8	SCED Extensions and Post-Test	A brief discussion on how the basic model can be extended to include (a) transmission constraints and (b) unit commitment issues along with GAMS implementations



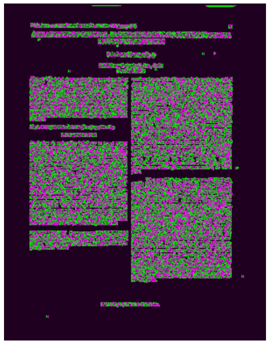
Meeting on 5th August 2024

Annexure - II


ESMAP
Energy Sector Management Assistance Program
THE WORLD BANK
IBRD • IDA
An Introduction to GAMS Language for Power System Optimization
Deb Chattopadhyay
15 July 2024

Purpose of this Discussion

- Introduce you to a language that is quite popular in power system optimization
  - Here is a short paper
  - And a popular text book: https://link.springer.com/book/10.1007/978-3-319-62350-4



- Discuss a bit about the Linear Programming methodology

- Show how to build simple LP models using GAMS e.g., dispatch optimization

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LET US START WITH THE DISPATCH OPTIMIZATION PROBLEM

Generator and VC	Timeblock (t-1) MW	Timeblock (t) MW	Critical Constraints
Gen-1 @Rs 2.5/kWh	100	?	Max ramp 30 MW
Gen-2 @Rs 3.0/kWh	100	?	Max ramp 40 MW
Gen-3 @Rs 3.3/kWh	100	?	Partial loss – must be lowered to 50 MW (FixedGen constraint)
Gen-4 @Rs 4.5/kWh	100	?	Must be => Gen2 level (Tx limit)
Gen-5 @Rs 6.1/kWh	100	?	Min loading is 100 MW
Demand to meet	500 MW	**550 MW**	

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ESMAP
Energy Sector Management Assistance Program

Why do we need an optimization model at all?

1. We need an automated and fast process to get to the least cost dispatch that checks out multiple possible conflicts across the constraints

2. Tell us which constraints bind (i.e., at the limit)? How much are they costing the system (i.e., if we could relax them a bit how much would cost reduce)?

3. What is the system marginal price?

Trial Solution

Generator and VC	Timeblock (t-1) MW	Timeblock (t) MW	Constraints
Gen-1 @Rs 2.5/kWh	100	**130**	Max ramp 30 MW
Gen-2 @Rs 3.0/kWh	100	**?**	Max ramp 40 MW
Gen-3 @Rs 3.3/kWh	100	**50**	Partial loss – must be lowered to 50 MW
Gen-4 @Rs 4.5/kWh	100	?	Must be => Gen2 level
Gen-5 @Rs 6.1/kWh	100	**100**	Min loading is 100 MW

Demand to meet	500 MW	550 MW

WHAT DO WE WANT TO TELL A 'MODEL IN THIS CASE?

Find a dispatch that gives the best possible sumproduct of generation and VC such that

1. Total generation is preferably 550 MW (no load is shed and no excess generation): Sum of generation => 550

2. Each generation sits between various limits:

   LastGen - RampDn <= Gen <= LastGen+RampUp

   Gen <= Max Capacity and Gen => MinLoad

3. Generation from Gen-4 => Generation from Gen-2

The Answers…

```
----      64 VARIABLE Gen.L  optimal dispatch

Gen1 130.000,    Gen2 135.000,    Gen3  50.000,    Gen4 135.000 Gen5 100.000

System marginal price          =        3.750

----      64 EQUATION RampUp.M shadow price of ramp up limits

Gen1 -1.250


----      64 EQUATION FixedGen.M            =       -0.450

----      65 EQUATION MinLoad.M  shadow price of the minimum loading limit

Gen5 2.350

----      66 EQUATION TxLimit.M             =        0.750
```

HERE IS A GAMS CODE TO SOLVE THIS

```
Set g generators /Gen1*Gen5/;

Table GenData(g,*) generator data

          Capacity    VC  RampUp  RampDn   MinLoad  LastGen
Gen1           150   2.5      30      30                100
Gen2           150   3.0      40      40                100
Gen3           150   3.3      50      50                100
Gen4           150   4.5      50      50                100
Gen5           150   6.1      70      70       100      100
;

Variables
Gen(g)    dispatch
Unmet     load shed
Excess    surplus generation
Cost      total VC
;
```

HERE IS A GAMS CODE TO SOLVE THIS

```
Equations

MeetDemand  meet demand
RampUp(g)   ramp up constraint for each g
RampDn(g)   ramp down constraint for each g
MinLoad(g)  min loading for each g
FixedGen    fix generation for gen 3
TxLimit     link generation 4 and 2 levels
Obj         system cost - total VC
;

Obj.. Cost =e= Sum(g, GenData(g,"VC")*Gen(g)) + 20*Unmet + 15*Excess;

MeetDemand.. Sum(g, Gen(g)) + Unmet - Excess =g= 550;

RampUp(g).. Gen(g) =l= GenData(g,"LastGen") + GenData(g,"RampUp") ;

RampDn(g).. Gen(g) =g= GenData(g,"LastGen") - GenData(g,"RampDn") ;

MinLoad(g).. Gen(g) =g= GenData(g,"MinLoad") ;

FixedGen..   Gen("Gen3") =e= 50;

TxLimit..  Gen("Gen4") =g=  Gen("Gen2");
```

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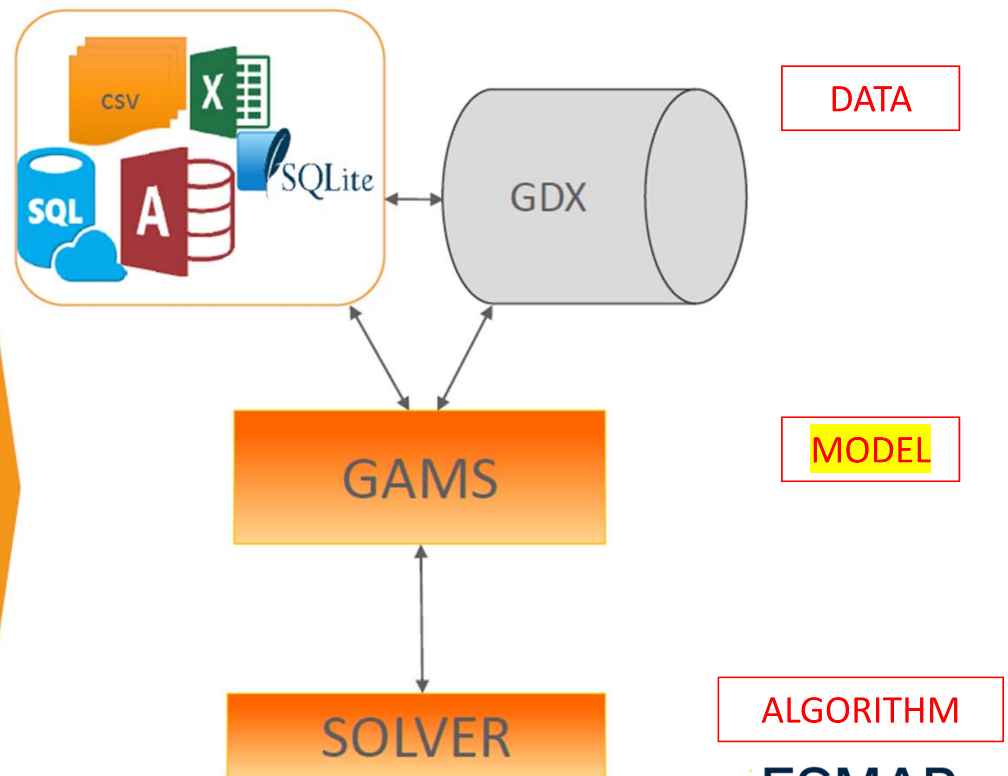
ESMAP
Energy Sector Management Assistance Program

GAMS Architecture

Independence of Model and Data

- Declarative Modeling
- ASCII: Initial model development

- GDX: Data layer ("contract") between GAMS and applications
  - Platform independent
  - No license required
  - Direct GDX interfaces and general API
  - ...



A Very Short Introduction to Linear Programming

- Linear programming problems are stated typically as min **c.x** subject to **Ax ≤ b**, where, c is the vector of costs, x are the decision variables, A & b are the constraint parameters

- Consider for example a simple dispatch problem:

Decision variables

Minimize 40*Gen1 + 100*Gen 2

Objective function

Subject to:

Constraint (mostly inequalities)

Meeting demand: Gen1 + Gen 2 ≥ 500

Capacity limits: Gen1 ≤ 600 and Gen2 ≤ 300

Min loading: Gen1 ≥ 240

Transmission limit: Gen2 ≥ Gen1 -200

Gen1, Gen2 ≥ 0

Nonnegativity constraints

c = [40 100] x = [Gen1 Gen2]

$$A = \begin{pmatrix} -1 & -1 \\ 1 & 0 \\ 0 & 1 \\ -1 & 0 \\ 1 & -1 \end{pmatrix} \qquad B = \begin{pmatrix} -500 \\ 600 \\ 300 \\ -240 \\ 200 \end{pmatrix}$$

A Very Short Introduction to Linear Programming

- Two solution techniques: Simplex (from 1940s) and Interior Point (1980's by Dr Narendra Karmarkar)
- Simplex solution process involves:
  1. Convert the constraint inequalities into equalities using 'slack variables'
  2. Pick a solution ($x = A^{-1}b$) keeping only the slacks, set all regular decision variables x to 0
  3. Then look at the objective function coefficients to find the most 'profitable' variable that can come in and replace one of the slacks
  4. Find how much of it can come in by solving the $x = A^{-1}b$ again
  5. Keep going until there is no profitable variable left
- 'Simplex iterations' swap one variable at a time and effectively jumps from one corner point to another as we will see in a graphical form

A Very Short Introduction to Linear Programming

- If we are asked to solve a system of equalities, the task is easy! For example,

  Gen1 + Gen2 = 500

  Gen2 = 200

  We can obviously solve this and get Gen1=300 which meet all constraints ("Feasible solution]. But, Cost = 32000 may not be minimum

- LP provides a systematic and efficient way to look through the entire solution space

- However, interestingly, it does so by basically solving a set of simultaneous equations iteratively by substituting out one variable at a time to reduce cost

A VERY SHORT INTRODUCTION TO LINEAR PROGRAMMING

- If we are asked to solve a system of equalities, the task is easy! For example,

  Gen1 + Gen2 = 500

  Gen2 = 200

  We can obviously solve this and get Gen1=300 which meet all constraints ("Feasible solution]. But, Cost = 32000 may not be minimum

- LP provides a systematic and efficient way to look through the entire solution space
- However, interestingly, the original (Simplex) method devised by Professor George Dantzig during World War II (and published in 1947) does so by basically solving a set of simultaneous equations iteratively by substituting out one variable at a time to reduce objective function value (cost in our example) until no further reduction in cost is possible

A Very Short Introduction to Linear Programming

- The method basically converts the inequalities into equalities by adding slack variables, e.g.,

  Gen1 + Gen2 + UnservedLoad= 500

- Then start with a (basic) solution that sets the original variables down to zero and finds a solution with the slack variables (e.g., UnservedLoad=500)
- Find which variable has the least coefficient in the objective function that enters the solution to reduce cost and the slack goes 'out of the basis'
- The process continues until no variable can enter the basis to reduce cost any further
- See the references below for a general exposure to LP (MIT_AMP_2 file) and a second one on Explanation of the Simplex Method


Solving Linear Programs

2

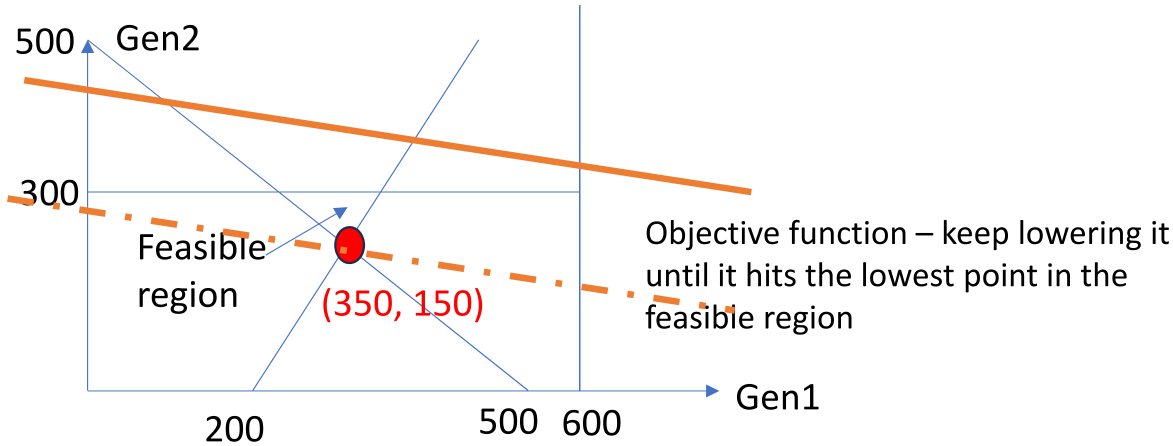

Explanation of Simplex Method

A Very Short Introduction to Linear Programming

Let us look at a graphical interpretation of the variables Gen1 (max value 600 MW) and Gen2 (max 300 MW) and constrains: (1) vertical and horizontal at the max values (2) 45 degree downward sloping line representing demand constraint (3) upward sloping line that cuts the Gen1 axis at 200 MW

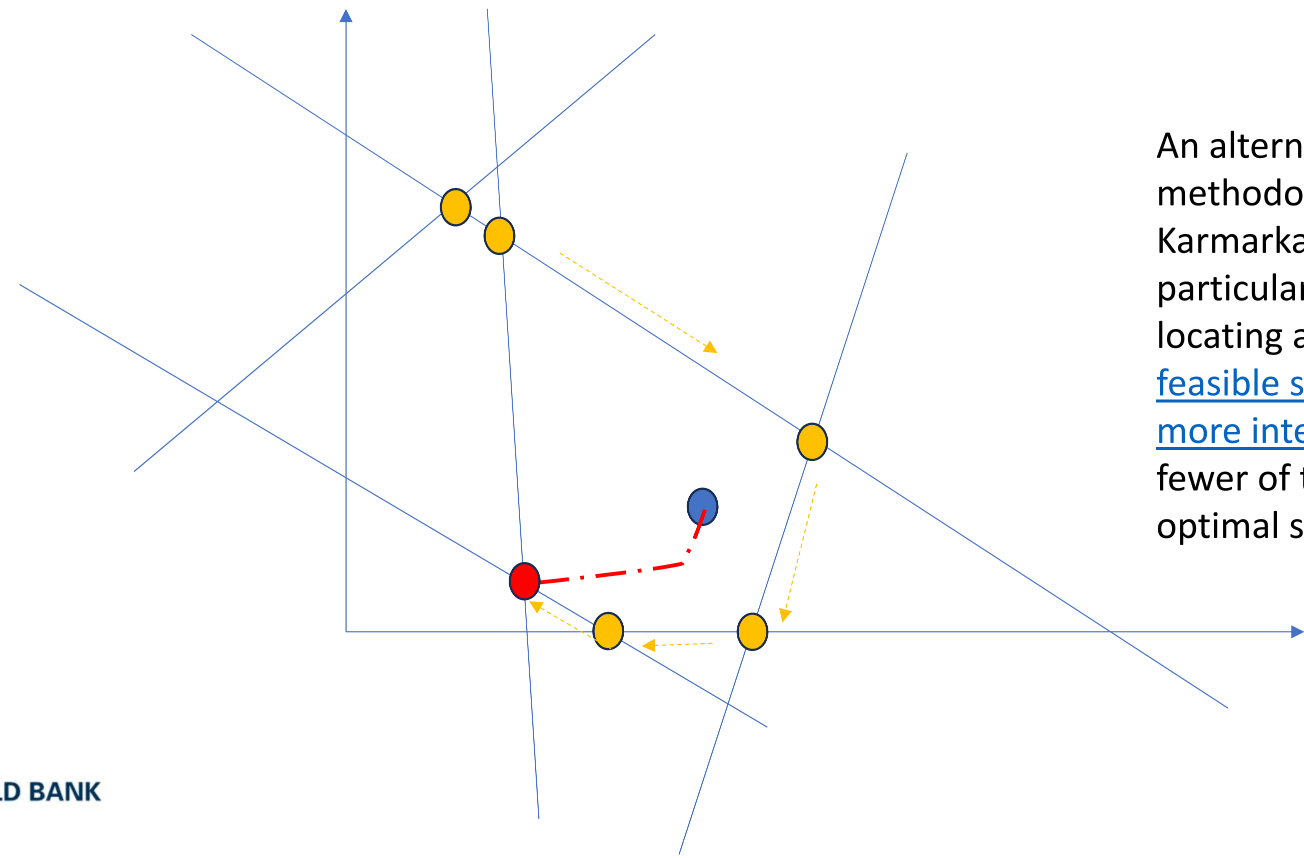
The small triangle formed by 300 MW limit, outer side of the demand constraint (as it is a => limit) and left hand side of the transmission limit, represents the FEASIBLE region

The orange line is the system cost (objective function) that we lower until we find the least cost point at the low vertex of the triangle yielding the optimal solution: Gen1 = 350 MW and Gen2 = 150 MW



A Very Short Introduction to Linear Programming

More generally, the Simplex method involves these pivot operations essentially to find better solutions and move from one 'corner point' to another alone the boundary until the optimal solution is reached. Each iteration involves solving a simultaneous system of equation: $Ax = b$ as $x = A^{-1}b$ with inequalities converted into equalities using slack variable, pivot to swap in a more profitable variable to replace a less profitable one until no improvement is possible.



An alternative powerful methodology was developed by Dr N. Karmarkar in 1984 that works particularly well on large LPs by locating an ['interior point in the feasible space and perform much more intensive matrix operations]() but fewer of them to move to the optimal solution

Here is a GAMS version of the LP

```
Variables gen1, gen2, cost
;
positive variables gen1, gen2;

Equations
obj, demand, cap1, cap2, txlimit;

obj.. cost =e= 40*gen1+100*gen2;
demand..   gen1 + gen2 =g=  500;
cap1..     gen1        =l=  600;
cap2..            gen2 =l=  300;
txlimit.. -gen1 + gen2 =g= -200;

model dispatch/ all/;
solve dispatch using LP minimizing cost;
```

Compare the code with the math formulation

(Don't worry about the exact syntax that are discussed at a later point)

Minimize Cost $= 40 * Gen1 + 100 * Gen2$, subject to

$Gen1 + Gen2 \geq 500$

$Gen1 \leq 600$

$Gen2 \leq 300$

$Gen1 \geq 240$

$-Gen1 + Gen2 \geq -200$

Let us Look at the Solution of the GAMS code

```
VARIABLE cost.L        =   29000.000  (System cost =350*40+150*100))
VARIABLE gen1.L        =     350.000  (Gen1 is limited by tx constraint)
VARIABLE gen2.L        =     150.000  (Gen2 is ‘constrained on’ by tx limit)
EQUATION demand.M      =      70.000  (Shadow price is $70/MWh)
EQUATION txlimit.M     =      30.000  (tightening the limit increases cost)
```

Let us increase demand from 500 MW to 501 MW and see what happens:

```
VARIABLE cost.L        =   29070.000  (cost increases by $70)
VARIABLE gen1.L        =     350.500  (Gen1 increases by 0.5 or $20)
VARIABLE gen2.L        =     150.500  (Gen2 meets the other 0.5 for $50)
EQUATION demand.M      =      70.000  (hence price is $70/MWh)
EQUATION txlimit.M     =      30.000  (congestion rent = diff in gen cost)
```

Here is a More Compact Version of the LP

```
Set g generators /gen1, gen2/ ;

Scalars Dem /500/, ATC /200/ ;

Table GenData(g,*) generator data

           Capacity   VC
Gen1            600   40
Gen2            300  100;

Variables gen(g), cost; positive variables gen;

obj..       cost =e= sum(g, GenData(g,"VC")*Gen(g));
demand..    Sum(g, Gen(g)) =g=  Dem;
Cap(g)..    Gen(g)  =l=  GenData(g,"capacity");
txlimit.. -Gen("Gen1") + Gen("Gen2") =g= -ATC;
```

More compact code

Complete separation of data from the model

What are the Differences with a 'Bucket filling' Approach?*

1. **Compact coding** (using GAMS)
2. **Fast and reliable solution** using a good LP solver of choice
3. **Enhance the model incrementally**, e.g., add variables/constraints to represent transmission related constraints, ancillary services co-optimization, unit commitment related constraints, coupling with the market, etc.
4. **Obtain the correct shadow prices** for constraints including the System Marginal Price for the demand-supply constraint
5. **Connect more easily with other optimization tools** like SCUC, market optimization, Optimal Power Flow etc.

* Some of the benefits relate to optimization methodology while others relate to use of the GAMS language

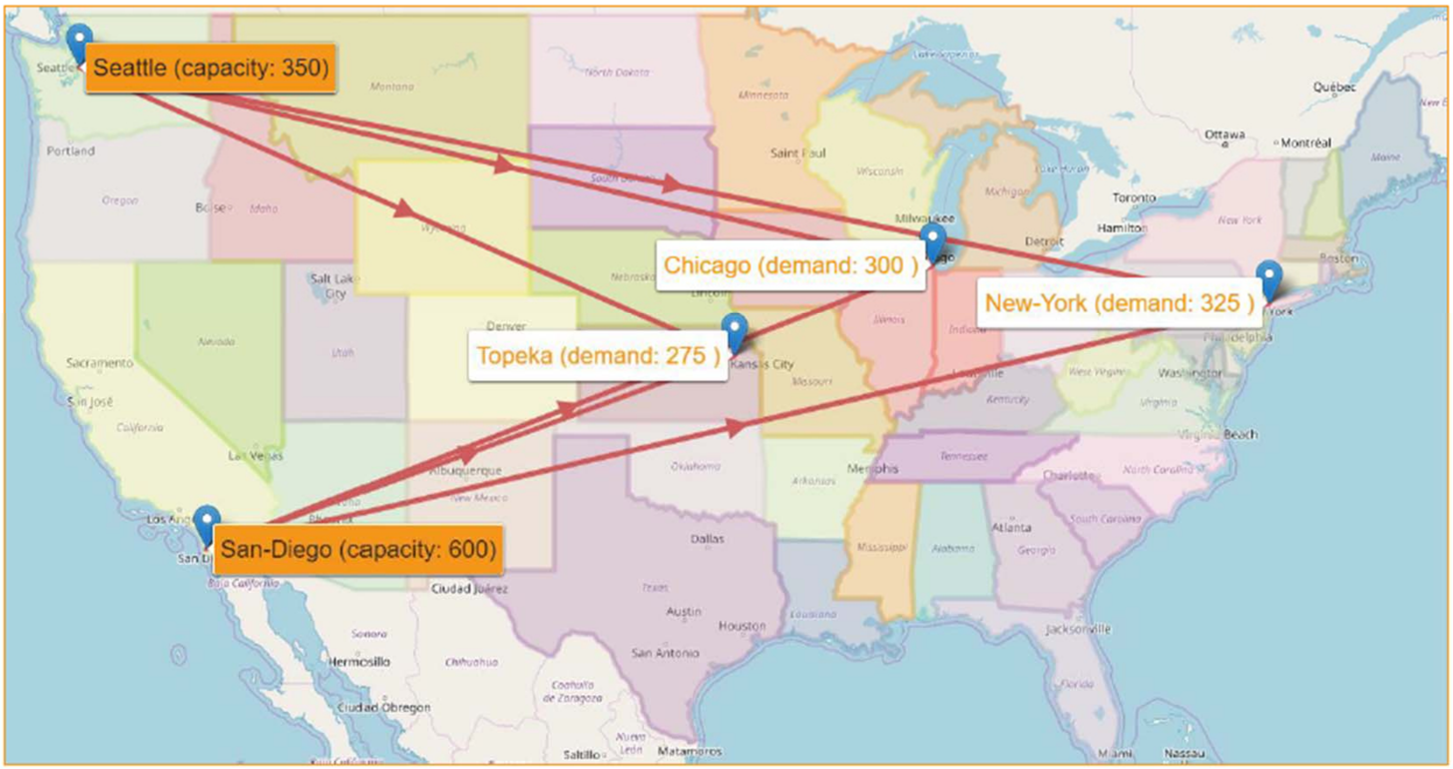
GAMS SYNTAX, CODING TIPS

EXPLAINED AROUND A POPULAR TRANSPORTATION EXAMPLE

HTTPS://WWW.GAMS.COM/LATEST/DOCS/UG_TUTORIAL.HTML

A Simple Example: Transportation Problem

Canning Plants (supply) → shipments (Number of cases) → **Markets** (demand)



Freight cost is \$90/case/’000 mi

Keep the transport cost to a minimum but

Demand must be met

Supply capacity limits must be observed

See if you can spot a solution!

Mathematical Formulation

Indices:	i	(Canning plants)
	j	(Markets)
Decision variables:	x_{ij}	(Number of cases to ship)
Data:	c_{ij}	(Transport cost per case)
	a_i	(Capacity in cases)
	b_i	(Demand in cases)

$\min \quad \sum_i \sum_j c_{ij} \cdot x_{ij}$ (Minimize total transportation cost)

subject to

$\sum_j x_{ij} \leq a_i \quad \forall\, i$ (Shipments from each plant ≤ supply capacity)

$\sum_i x_{ij} \geq b_j \quad \forall\, j$ (Shipments to each market ≥ demand)

$x_{ij} \geq 0 \quad \forall i, j$ (Do not ship from market to plant)

$i, j \in \mathbb{N}$

Hands-On

GAMS Syntax: Basics

Basic structure of a GAMS code:

1. **<u>Sets</u>** or indices that is at the heart of any algebraic representation
2. **<u>Scalars, Parameters and Tables</u>** to represent data (constants, one dimensional vectors and tables)
3. **<u>Variables</u>** or decision variables that are the unknowns for which we are solving a model
4. **<u>Equations</u>** or the constraints that define the feasibility range within which sensible solutions reside
5. **<u>Model</u>** statement that defines a collection of constraints that need to be included in a model
6. **<u>Display</u>** to show the results

Useful tips: (1) GAMS codes are NOT case sensitive; (2) In general, the order of equations, variables etc can be changed; (3) All of these key words typically start with declaration of the name, followed by explanatory text, followed by values/members within / / and (4) ending with a semi-colon

More Useful tips: GAMS is operating environment free (the same code runs on Windows, Unix, Linux) and there are lots of shorthands and format free options to make life easy

GAMS Syntax: Sets

Set definitions follow the syntax as follows: name, explanatory text, set members within / / end with a sem-colon, e.g.,

```
Sets
   i   canning plants   / seattle, san-diego /
   j   markets          / new-york, chicago, topeka / ;
```

One can also define set associations mapping members of two sets, e.g., if we want to allow only certain arcs along which transport is feasible

```
Sets map(i,j) /seattle.new-york,  seattle.Chicago, san-diego.new-York/ ;
```

GAMS Syntax: Data (Scalars, Parameters and Tables)

Scalars, Parameters and Tables also start with declaring the name, followed by explanatory text, followed by values and end with a semi-colon For example, f, a(i), b(j), d(i,j) are defined as follows:

```
Scalar f  freight in dollars per case per thousand miles  /90/ ;
Parameters
     a(i)  capacity of plant i in cases
       /    seattle     350
            san-diego   600  /
     b(j)  demand at market j in cases
       /    new-york    325
            chicago     300
            topeka      275  / ;

Table d(i,j)  distance in thousands of miles
                  new-york       chicago      topeka
    seattle          2.5           1.7          1.8
    san-diego        2.5           1.8          1.4   ;
```

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Energy Sector Management Assistance Program

GAMS SYNTAX: VARIABLES AND EQUATIONS

Variables are typically defined over the sets (domain), e.g., x(i,j) that defined transport volume from *i* to j; and Equations (including the objective function) finally connect the variables and data

Variables and Equations are both declared first before defining the details around them, e.g.,

```
Variables
     x(i,j)  shipment quantities in cases
     z       total transportation costs in thousands of dollars or the objective function;
Positive Variable x ;

Equations
     cost         define objective function
     supply(i)    observe supply limit at plant i
     demand(j)    satisfy demand at market j ;

cost ..        z  =e=  sum((i,j), c(i,j)*x(i,j)) ;
supply(i) ..   sum(j, x(i,j))  =l=  a(i) ;
demand(j) ..   sum(i, x(i,j))  =g=  b(j) ;
```

Some GAMS idiosyncrasies on equation definition: Repeat the name followed by two dots;
Equality is =e=
Less than or equal to =l=
Greater than or equal to =g=

GAMS Syntax: Model, Display and Solve Statements

Model is a collection of constraints – one can basically drop/add constraints to define different scenarios;

Solve is the call statement to invoke the optimization solver; and

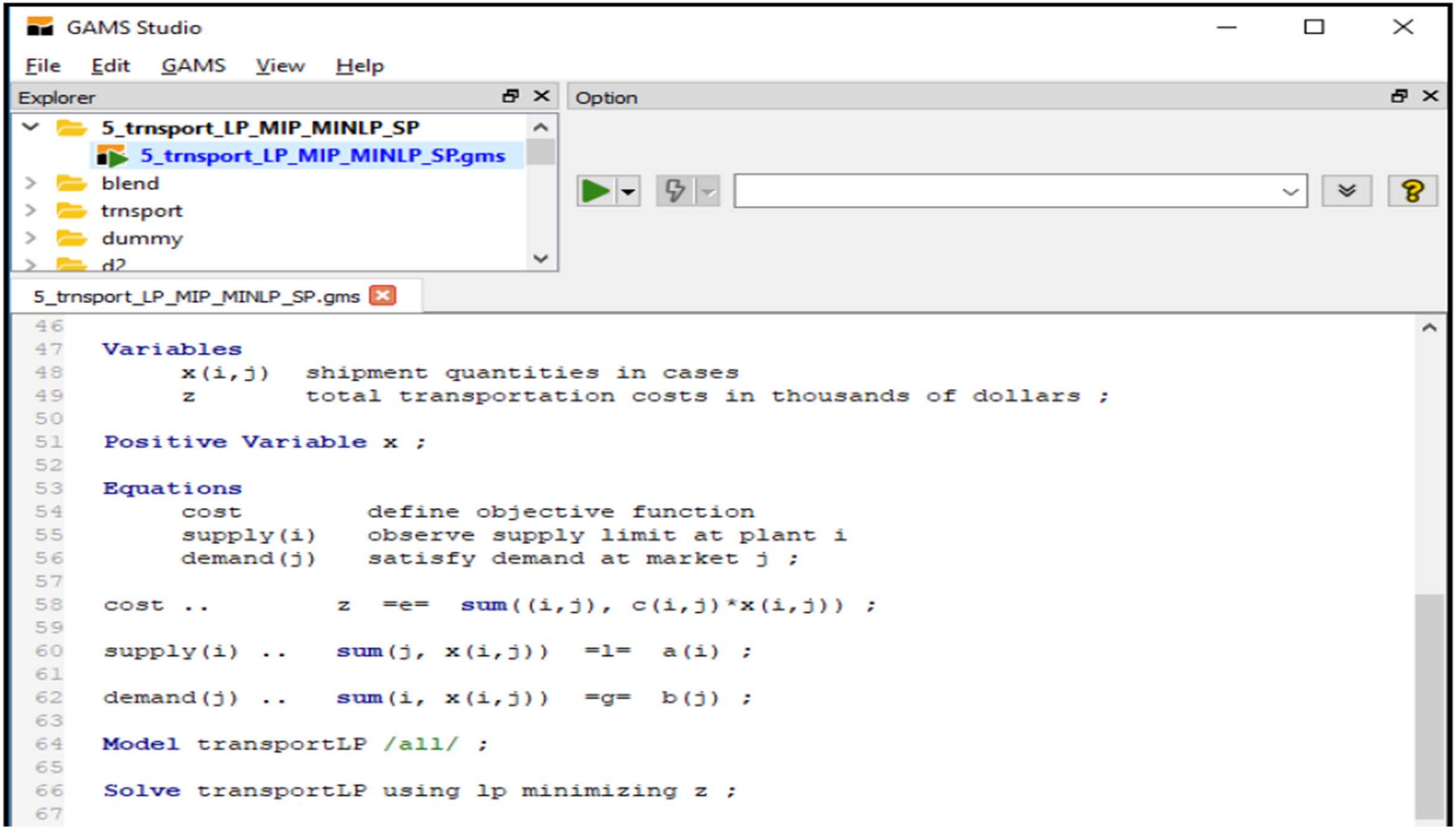
Display allows us to see the 'answers' – optimal level or .L for variables and .M for shadow prices of constraints

```
Model transport /cost, supply, demand/ ;

Solve transport using lp minimizing z ;

Display x.l, x.m, demand.m, c;
```

The full code is shown in the next slide (including how it can retrieved from the GAMS library)…


GAMS Studio
File Edit GAMS View Help
Explorer
Option
5_trnsport_LP_MIP_MINLP_SP
5_trnsport_LP_MIP_MINLP_SP.gms
blend
trnsport
dummy
5_trnsport_LP_MIP_MINLP_SP.gms
Variables
x(i,j) shipment quantities in cases
z total transportation costs in thousands of dollars ;
Positive Variable x ;
Equations
cost define objective function
supply(i) observe supply limit at plant i
demand(j) satisfy demand at market j ;
cost .. z =e= sum((i,j), c(i,j)*x(i,j)) ;
supply(i) .. sum(j, x(i,j)) =l= a(i) ;
demand(j) .. sum(i, x(i,j)) =g= b(j) ;
Model transportLP /all/ ;
Solve transportLP using lp minimizing z ;

Additional GAMS Syntax: Comments inside the code

Including comments in the code that GAMS does not process but useful for documentation – it can be done in three different ways:

1. Add a * at the start of the line

2. Or use $ontext to start comments and $offtext to turn off text mode for longer comments, e.g.,

   $ontext

   This is an example of an explanatory comment that is

   Not part of the code

   $offtext

3. Use $inlinecom { } to define curly brackets for inline commenting that one can insert anywhere in the code for very specific comments

ADDITIONAL GAMS SYNTAX: READING DATA FROM EXCEL

Data can be read from Excel using alternative ways and these routines changed over the years – they are not part of the core GAMS language, but links developed to facilitate data transfers – for instance, let us read all data from Excel file for the transport model [and basically we always copy these and change the names and cell addresses!}

```
Sets
   i  canning plants,     j  markets        ;

Parameters a(i), b(j), d(i,j), f;

$onecho > gdxxrwCM.in
par=f        rdim=0 cdim=0 rng=Sheet1!C2:C2
set=i        rdim=1 cdim=0 rng=Sheet1!B6:B7
set=j        rdim=1 cdim=0 rng=Sheet1!B9:B11
par=a        rdim=1 cdim=0 rng=Sheet1!B6:C7
par=b        rdim=1 cdim=0 rng=Sheet1!B9:C11
par=d        rdim=1 cdim=1 rng=Sheet1!B13:E15
$offecho
```

The syntax is to refer to parameter (as par) or set, put the row and column dimensions (rdim and cdim) and then point to the sheet (rng!) and cell address. A scalar has zero rdim and cdim (single cell), vectors have rdim=1 and cdim=0 and matrices may have rdim=1 (or more) and cdim=1

ADDITIONAL GAMS SYNTAX: READING/WRITING DATA FROM EXCEL

```
$call gdxxrw "TransportInput.xlsx" @gdxxrwCM.in MaxDupeErrors=1000
$gdxIn TransportInput.gdx
$load f,i,j,a,b,d
$gdxIn
```

And finally we load the Gams Data Exchange (GDX) file in the code and get the data into GAMS

Writing results back to Excel follows the opposite procedure to unload data into another GDX file which is then written to an Excel file (Results.xlsx in this example):

```
execute_unload "results.gdx", x.l, x.m, c, ShadowPrice;
```

```
execute 'gdxxrw results.gdx var=x rng=OptimalFlow!A5 par=c rng=TransportCost!A5 par=ShadowPrice rng=ShadowPrice_Demand!A5';
```

ADDITIONAL GAMS SYNTAX: READING/WRITING DATA FROM EXCEL

transport.gms

Here is the revised GAMS code with input/output through Excel

f	freight in dollars per case per thousand miles	90		
a(i)	Seattle	350		
	San-Diego	600		
b(j)	New-York	325		
	Chicago	300		
	Topeaka	275		
d(i,j)		New-York	Chicago	Topeaka
	Seattle	2.5	1.7	1.8
	San-Diego	2.5	1.8	1.4

Inputfile: TransportInput.xlsx

	New-York	Chicago	Topeaka
Shadow price:$/case	225	153	126

outputfile: results.xlsx (but note that this is automatically created when the model is run; Make sure to close the file down else it will not be overwritten)

Annexure - III

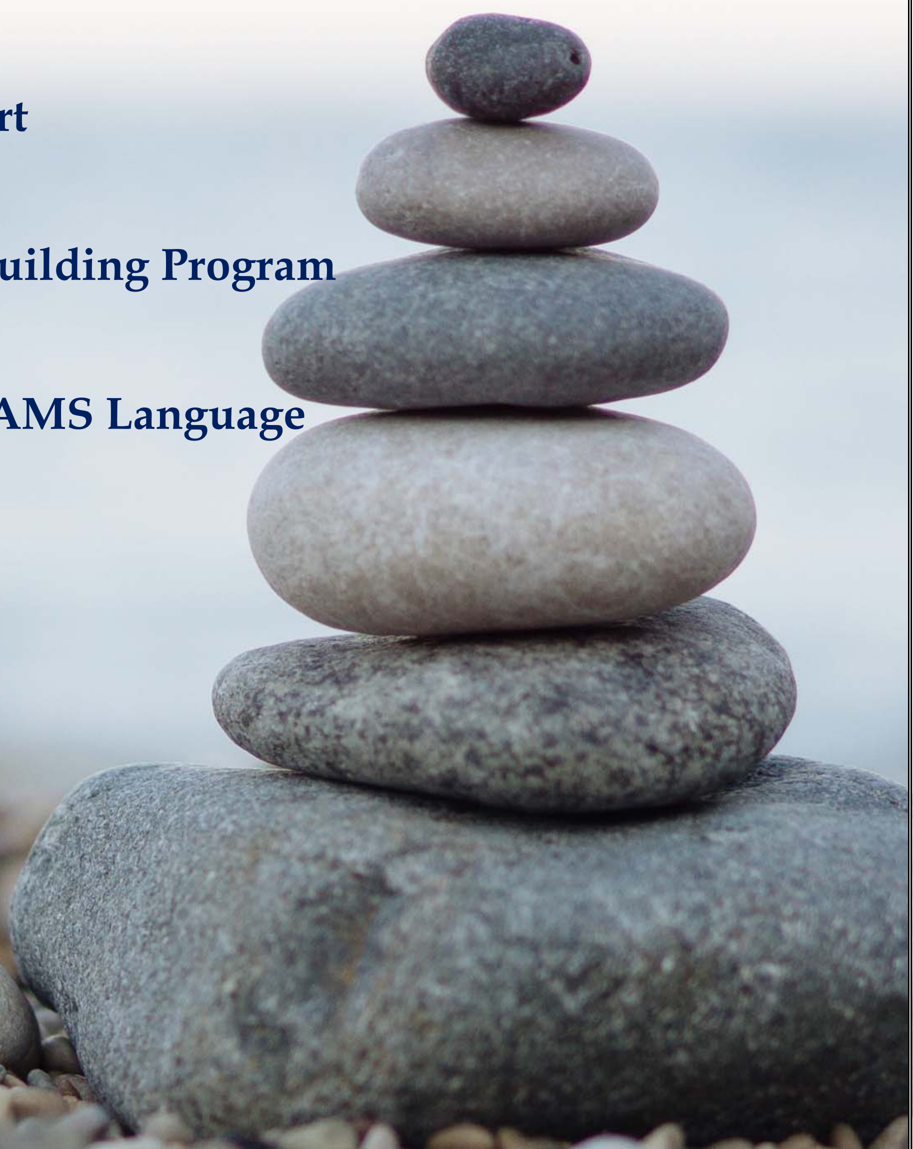
Report

on

Two-day Capacity Building Program

on

Optimization & GAMS Language



2nd & 3rd September 2024

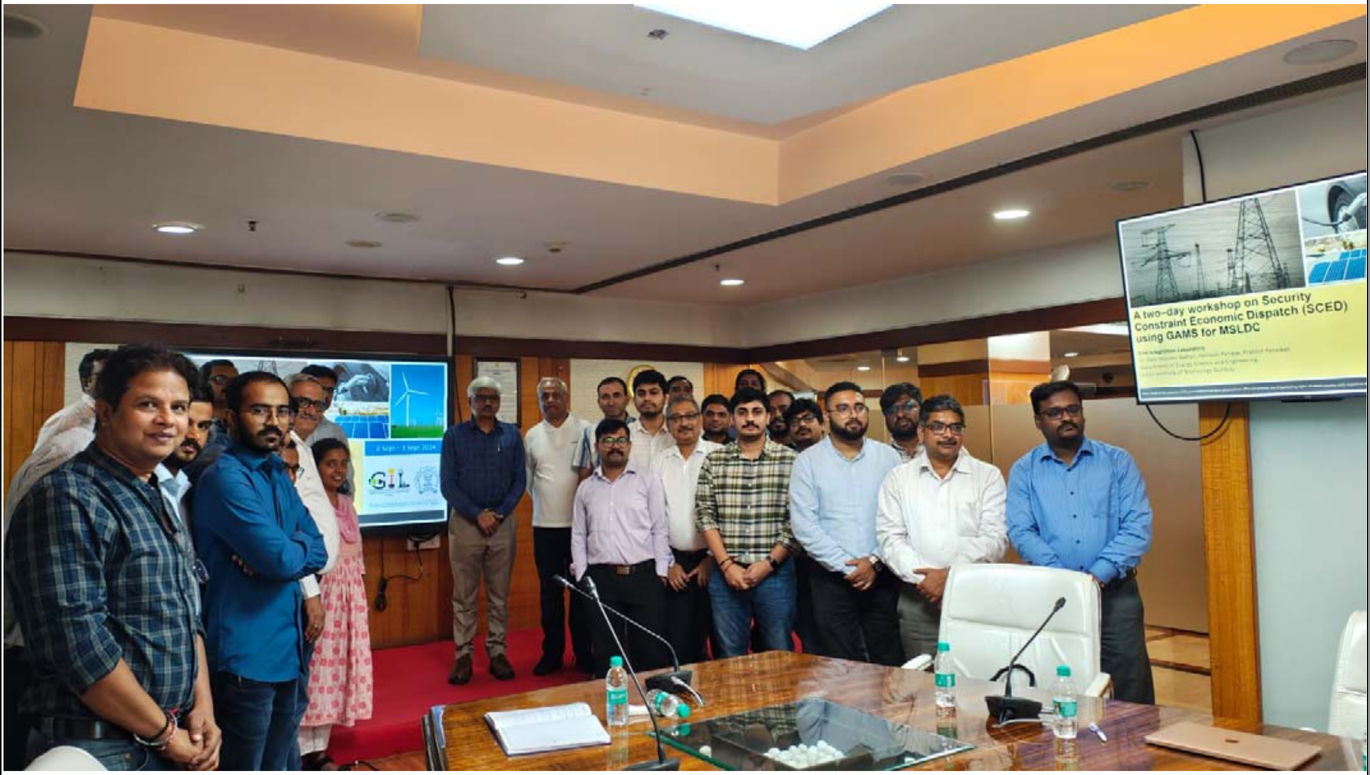


Table of Contents

1 Introduction

The two-day training sessions on Optimization and the GAMS (General Algebraic Modeling System language were held on 2^{nd} & 3^{rd} of September 2024 and were organized by the Maharashtra State Load Despatch Centre. The training aimed to enhance participants' knowledge and skills in optimization techniques, particularly in power systems and economic dispatch, using the GAMS software. The training also discussed the differences between traditional Merit Order Despatch and Security Constrained Economic Dispatch (SCED), focusing on Karush-Kuhn-Tucker (KKT) criteria.

Prof. Zakir Hussain Rather from IIT-Bombay had agreed to conduct the training sessions.

In his opening remark by the Executive Director, MSLDC profusely thanked Prof. Zakir for agreeing to take up the training session and assured him that his team would put up hard work in making this study on optimization successful and will be the leader state in India in transforming the scheduling process from MOD based principle to optimization through linear programming.

Shri S. K. Soonee, Founder & Former CEO, POSOCO in his address mentioned that this is the maiden training program on optimization and GAMS towards capacity buildings of SLDC engineers on optimization in association with IIT-B which is a great opportunity for learning and thanked Prof. Zakir and his two research scholars, Sh Akhilesh Panwar & Sh Pratosh Patankar for extensive research done by them on the data shared by MSLDC. He requested Prof. Zakir to share his views on the improvement in the data quality based on his observations on the data shared so that the data quality could be further improved.

An internal office order was issued which is attached as Annexure – I. The participants from MSLDC included the scheduling team, the Power System Study team IT team of SLDC, team from the system integrator of the scheduling software, PwC. The representative from the National Load Despatch Center and Western Regional Load

Despatch Center also participated to extend their cooperation and motivate the team of SLDC in developing the optimization code.

Lists of participants is attached as Annexure – II.

2 Objectives of the Training

The primary objectives of the training were:

- To familiarize participants with the basic and advanced concepts of optimization.
- To compare and contrast Merit Order Despatch and SCED using KKT criteria.
- To provide hands-on experience with the GAMS software, focusing on modeling and solving optimization of the day-to-day schedules being prepared presently based Merit Order Despatch principle.
- To discuss the output results of the optimization done using GAMS for one day of data received from MSLDC.

3 Overview of Training Sessions

Day 1: Introduction to Optimization and GAMS

Introduction to Optimization

- The day began with an overview of optimization, covering linear programming and its different algorithms.

- Participants were introduced to the mathematical formulation of optimization problems, including objective functions, constraints, and feasible regions.
- The session emphasized the importance of optimization in scheduling honouring different constraints like Tech-Min, Pmax, ramp-up, ramp-down, Transmission constraints etc

Introduction to GAMS Language

- The second session introduced the GAMS language, focusing on its syntax, data handling, and model formulation capabilities.
- Participants learned how to define sets, parameters, variables, equations, and models in GAMS.
- A step-by-step demonstration of a simple linear programming problem was provided, allowing participants to follow along and build their models

Day 2: Advanced Topics in Optimization and GAMS

- Discussions on the output results of optimization done on the one-day data and issues related to data quality.
- Participants worked on a series of exercises designed to reinforce their understanding of the GAMS language.
- Hands-on exercise on modeling of generation optimization honouring technical constraints and generators (Pmax/Pmin, ramp Up/down) and transmission constraints.

The time schedule and session details are attached as Annexure – III.

4 Merit Order Despatch vs. SCED Based on KKT Criteria

The difference between generation cost optimization through the Merit Order Despatch (MOD) method and optimization through linear programming was deliberated in detail.

4.1 Merit Order Despatch

Merit Order Despatch (MOD) is a traditional approach used in power systems to determine the order in which different power plants should be dispatched to meet the demand at the lowest possible cost. The key characteristics of MOD include:

- **Objective Function:** Minimize the total generation cost by dispatching the cheapest available generation units first.

- **Constraints:** These include power balance and generation limits.

The solution is obtained through a bucket-filling method and constraints are checked repeatedly while allocating the generation. Naturally solving such a problem takes more time and other constraints like transmission constraints are not included.

4.2 Security Constrained Economic Dispatch (SCED)

SCED is an advanced approach that extends MOD by incorporating security constraints to ensure the reliable operation of the power system. The key characteristics of SCED include:

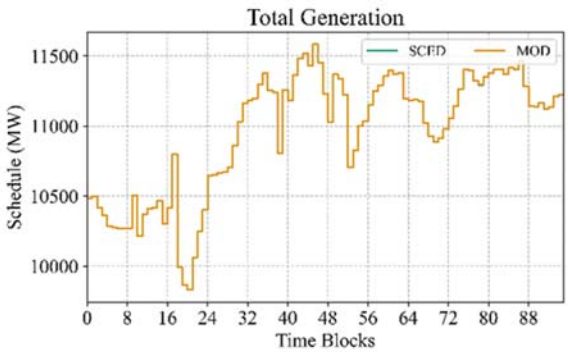
- **Objective Function:** Similar to MOD, SCED aims to minimize the total generation cost but also considers the reliability of the system by including security constraints.
- **Constraints:** In addition to the constraints considered in MOD, SCED includes security constraints such as line flow limits, voltage limits, and contingency constraints.
- **Optimality Conditions:** The SCED problem is generally solved using nonlinear programming techniques, where the Karush-Kuhn-Tucker (KKT) conditions are used to determine the optimality of the solution. The KKT conditions provide the necessary conditions for a solution to be optimal, considering both the cost minimization and security constraints.

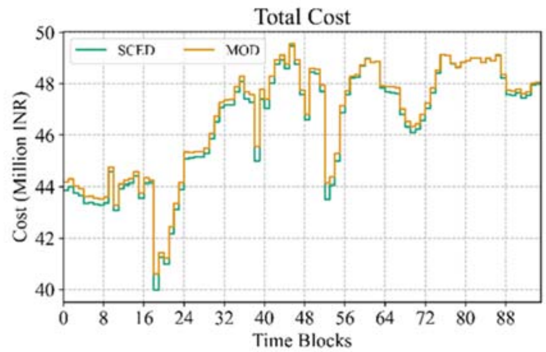
MOD ensures that the demand is met at a low cost honouring some constraints of the generators but in SCED, it ensures that the dispatch not only meets the demand at the lowest cost but also satisfies the security constraints.

While MOD focuses on economic feasibility, SCED ensures both economic and security feasibility. The inclusion of security constraints in SCED makes the optimization problem more complex but also more robust.

5 Discussions on results of optimization on one-day data

One day data was shared by MSLDC which was further corrected through rounds of discussion between IIT-B and the MSLDC team. It was informed that the data quality needs further improvement and more clarity is required on the data shared by MSLDC for further research on the possible optimization**.**





It was shown that optimization through Linear Programming (LP) will result in further savings and also generate information like System Marginal Price (SMP), Dual for different constraints (Pmax / Pmin, ramp up/down) and optimized schedule will also lead to ease of operation of the thermal fleet which is under optimization.

Different charts and plots were prepared which was discussed in detail and modifications were also proposed for better clarity.

6 Feedback and Conclusion

A paper-based test was conducted as an assessment of the participants at the end of the training.

The training sessions received very positive feedback from the participants. Many appreciated the hands-on approach, which allowed them to apply theoretical concepts in practical exercises. The discussions on the differences between Merit Order Despatch and SCED, particularly the application of KKT criteria, were found to be particularly insightful.

The training provided a solid foundation for further exploration of these topics and their application in real-world scenarios.

It was decided that data will be checked based on the observations discussed and shall be shared with IIT-B for further study.

It was also decided that the data for 30 days shall be shared with IIT-B for further study by 6th of September 2024 and IIT-B shall share the study results by 15th of September 2024 for further analysis.

****

MAHATRANSCO

MAHARASHTRA STATE ELECTRICITY TRANSMISSION CO.LTD.
CIN NO. U40109MH2005SGC153646
Maharashtra State Load Dispatch Centre

Tele :91-22-27601765/1766/1931/2937
Fax :91-22-27601769/2936
Email : cesldc@mahasldc.in
website : http://www.mahasldc.in

Office of The Chief Engineer
Maharashtra State Load Dispatch Center
Thane-Belapur Road, P.O. Airoli
Navi Mumbai Pin – 400 708.

RIGHT TO INFORMA

Ref: CE/MSLDC/HR/Trg/GAMS No 0 1 6 5 2 **Date:** 12 11 AUG 2024

OFFICE ORDER

To,
All Participants,

Subject: Training Program on General Algebraic Modelling System (GAMS) applied for SCED

A working Group on SCED is formed on dated 12.08.2024 to study the Pilot Operation of Intra State Security Constrained Economic Dispatch in Maharashtra.

In pursuance of the approval accorded by the Competent Authority following Engineers / officers shall attend the training program on "General Algebraic Modelling System (GAMS) applied for SCED" on 2nd and 3rd September 2024 at MSLDC, Arioli, Navi Mumbai

List of Participants

Sr. No.	Name of officer and Designation	Zone / Office
1	Shri. Girish Pantoji, SE (Operations)	MSLDC
2	Shri. Dinesh Patil EE (Operations)	MSLDC
3	Shri. Sachin Lomate, AEE (Operations)	MSLDC
4	Shri. Vaibhav Ahinave, Programmer (IT)	MSLDC
5	Shri. Pankaj Shinde, AEE, ALDC Nagpur	MSLDC
6	Shri. Avinash Dhawade DYEE (Operations)	MSLDC
7	Shri. Shiva Kumar Gourishetti, AE (Operations)	MSLDC
8	Shri. Nitesh Dongare, AE, ALDC Nagpur	MSLDC
9	Shri. Akshay Gadagkar, AE SCADA	MSLDC
10	Shri. Vijay Kamble, AE (Operations)	MSLDC
11	Shri. Pravin Shinde, Dy EE	EHV PC O&M Zone, CSN
12	Smt. Asaawari Tulshi Kakade, AE	EHV PC O&M Zone, Pune
13	Shri. Dyutiman Choudhari, Consulting Director	PWC
14	Shri. Sukumal Sengupta, Senior Associate	PWC

All participants are requested to make sure their presence in this training program.

PRE-REQUISITES FOR TRAINING PROGRAM:

1. Basic knowledge of GAMS and optimization techniques
2. Familiarity with coding in software programming.
3. Participants need to carry Laptop with installed GAMS trial version.

PROGRAM DETAILS:

- Date: 2nd September 2024 and 3rd September 2024
- Time: 09:30 AM to 17:30 AM
- Venue: 3rd Floor Conference Hall, MSLDC, Arioli, Navi Mumbai

For any clarification or further information, please contact:

CONTACTS:

Shri. Dinesh Patil, Executive Engineer (Operations)-**9769213848**
Shri. Avinash Dhawade, Dy. Ex. Engineer (Operations)- **9167009921**

General Condition:

1. The participants have to make their own Accommodation and travel arrangements.
2. There is No cost for participant, The all expenses of the programme will be paid from MSLDC Airoli, Navi Mumbai
3. Effective feedback, both positive and negative, is very helpful. Feedback is valuable information that can be used for betterment of Training programs. Thus, it is compulsory to submit the Training feedback. Participants are requested to fill the feedback format genuinely and submit feedback forms to the Training co-ordinator.
4. The Participant have to attend Training Program as per the schedule. No leave shall be granted during the Training period.
5. The completion of Training Program shall not be ground for any accelerated promotion of participants.
6. Use of mobile phone is strictly prohibited during the Training Program.
7. Declaration of Training Program Attendance' (copy attached) should be submitted to custodian of service book for entry in service book and SAP system and acknowledgment of same declaration should be submitted along with TA bills.
8. The custodian of the Service book of these participants shall take entry of this Training attendance in service book and concerned officer of HR Department shall take entry in SAP system about the said Training undergone by the participant.
9. Every employee shall follow the code of conduct of MSETCL during Training period. Any type of misconduct in any form during Training period will be viewed seriously and dealt accordingly which may please be noted.
10. No pickup &drop facility will be provided from Airport/railway/bus station. The participants will have to make their own arrangements.

Encl: Annexure-'A' (Training Program).

(Shashank Jewalikar)
Executive Director
SLDC, Airoli

Copy to: -

1) Shri. S. K. Soonee, Senior Advisor, Consultant, & Former CEO, POSOCO.
2) Shri. Debasis De, Former Executive Director, Grid-India.
3) The Chief Engineer, EHV PC O&M Zone, Pune / CSN
   - is requested to depute the employees (Sr. No. working under your zone.
4) The Superintending Engineer, (Operations) /(SCADA), SLDC, Airoli
5) The Superintending Engineer, ALDC Nagpur
6) The DGM, IT, MSLDC, Airoli
   – For arrangement of Internet facilities at conference hall 3 rd floor
7) The Director, PWC, Kolkatta.
   —is here by requested to depute 2 Nos. employees from your organization.
8) All officers as above through their respective Controlling Officer.

MSETCL

Maharashtra State Load Despatch Centre, Airoli

Sub :- Attendance for Training Program on "General Algebraic Modelling System" (GAMS) on 02.09.2024 "

Sr No.	Name of the Employee	Designation	Signature
1	Girish S. Pantoji	SE(OP)/CE, I/C MSLDC	
2	DHEERAJ GUPTA	DM(IT), WRLDC	
3	Pulla Nagasudhir	Manager(IT), WRLDC	PN
4	Ramlakhan Meena	DM(MO), WRLDC	
5	Saif Rehman	Chief Mgr(MO), NLDC	
6	Pravin Shinde	Dy. Exe. Eng.	
7	Dinesh Patil	EE MSLDC	
8	Vijay Kamble	A.E. MSLDC	
9	Shivakumar G.	A.E. MSLDC	
10	Nitesh Dongre	A.E. ALDC	
11	Satyendra Kumar Tripathi	AEE, MSLDC	Satyendra
12	ABHISHEK SAMANT	Dy EE, MSLDC	
13	Pankaj M. Shinde	Ad. E.E. ALDC	
14	Sachin R. Lomate.	A.E.E.	
15	Gajanan Mirashe	AP(IT), ALDC	
16	Vaibhav Ahirrao	Prog(IT), SLDC	
17	Akshay Gadagkar	AE, MSLDC	
18	Asawari R. Tulshi	AE, Pune	Tulshi 02/09/24
19	Sourav Das	Manager, PWC	Sourav Das 02/09/24
20	Sukamal Sengupta	Sr. Associate, PWC.	
21	Rounak Sikder	Sr. Associate PWC	Rounaksikder 02/09/24
22	Zakir Rather	IIT Bombay	
23	Akhilesh Panwar	IIT Bombay	
24	Pratosh Pratapkar	IIT Bomby	
25	Debasis De	ED, NLDC, Grid India.	
26	S. R. SOONEE	Former CEO POSOCO.	
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ANNEXURE'A'

TRAINING PROGRAMME

Day	Session	Topic
Day-1	Session-1 09:15 AM to 10:45 AM	A general introduction to security constraint economic dispatch (SCED) (EconomicDispatch,Unitcommitment,Meritorderdispatch,SCED,Needofanoptimization)
	Teak/Coffeebreak:11:00AMto11:15AM	
	Session-2 11:00AMto 01:00PM	Linear programming, solution techniques ,and software (Graphical Method, Simplex Method, Duality, Shadow Price)
		Lunch Break: 01:00 PM to 02:00 PM
	Session-3 02:00PMto03:00PM	Introduction to GAMS studio (GAMSStudioInterface,Modellibraries,CompilationandExecutionErrors,Debugging)
		Teak break: 03:00PM to 03:15 PM
	Session-4 03:15PMto05:00PM	Programming in GAMS (SETs, Parameter, Data Exchange, Variable, Equation, Model)
Day-2	Session-1 09:15AMto10:45AM	Basic SCED implementation in GAMS (Modellingofpowerflow,spinningreserve,multiperiodSCED,rampingconstraint,unit commitment)
		Teak break: 11:00 AM to 11:15 AM
	Session-2 11:00AMto01:00PM	A generalized GAMS model using excel data (GDXXRW)
		Lunch Break: 01:00 PM to 02:00 PM
	Session-3 02:00PMto5:00PM	Implementation of case studies by participants
	5:00PMto5:30PM	Short assessment of participant learning

(*All sessions are planned based on case studies, tool demonstration and Hands on practice.)

Maharashtra State Load Despatch Center, Thane - Belapur Rd, P. O. Airoli, Navi Mumbai, Maharashtra 400708, India

A two–day workshop on Security Constraint Economic Dispatch (SCED) using GAMS for MSLDC

3 Sept – 3 Sept 2024

Annexure - IV

Grid Integration Laboratory

Zakir Hussain Rather, Akhilesh Panwar, Pratosh Patankar,

Department of Energy Science and Engineering,

Indian Institute of Technology Bombay

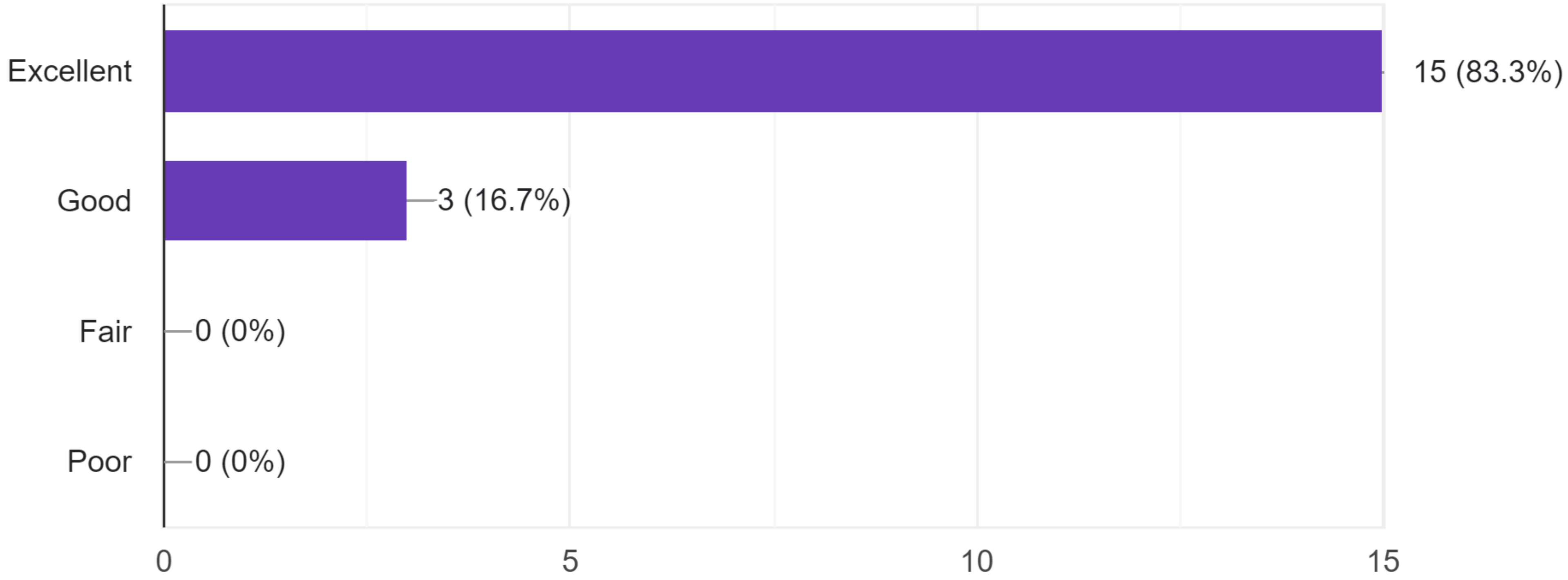
GRID INTEGRATION LABORATORY

IIT BOMBAY

https://www.ese.iitb.ac.in/~gil/

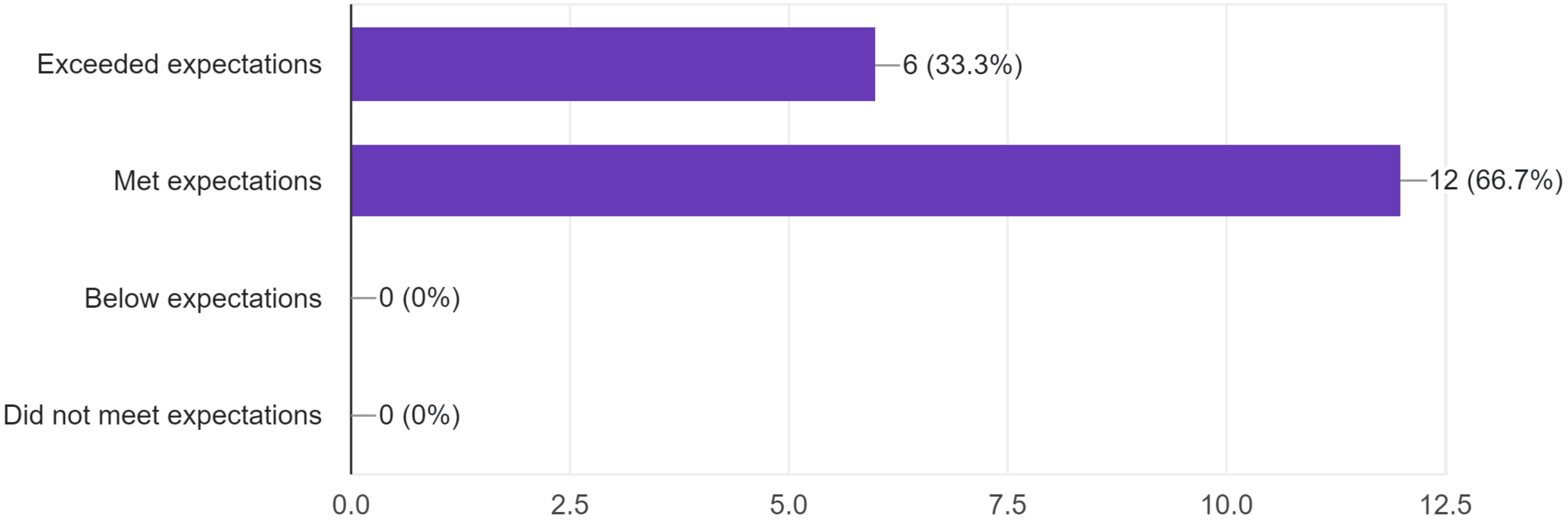
How would you rate the overall experience of the workshop?

18 responses

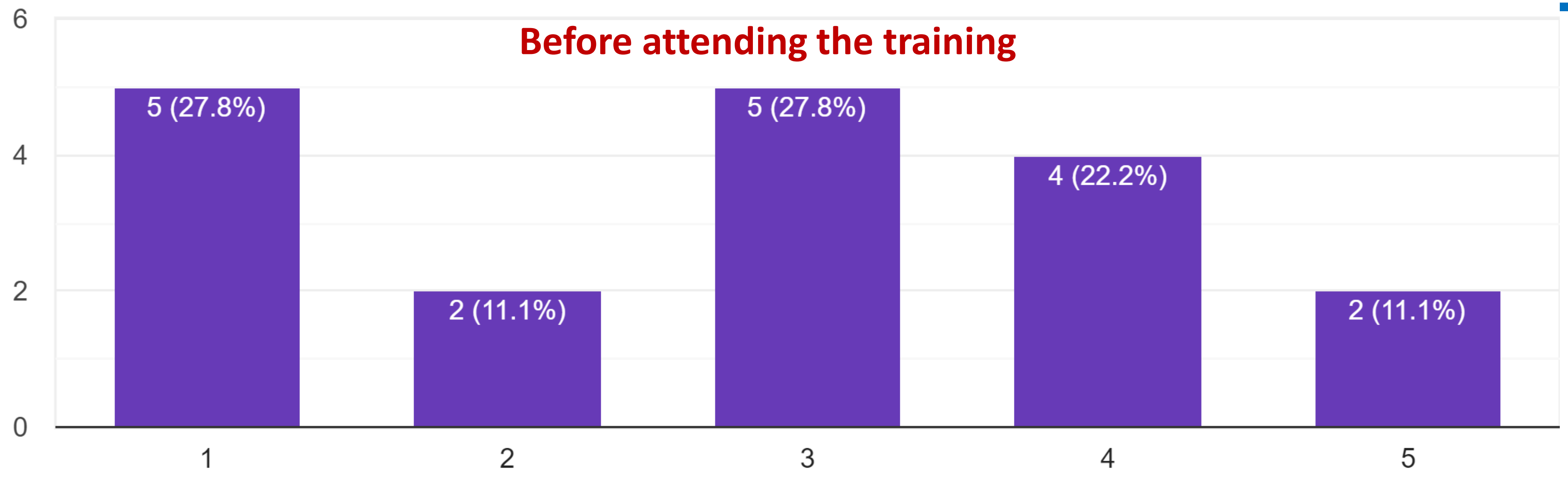


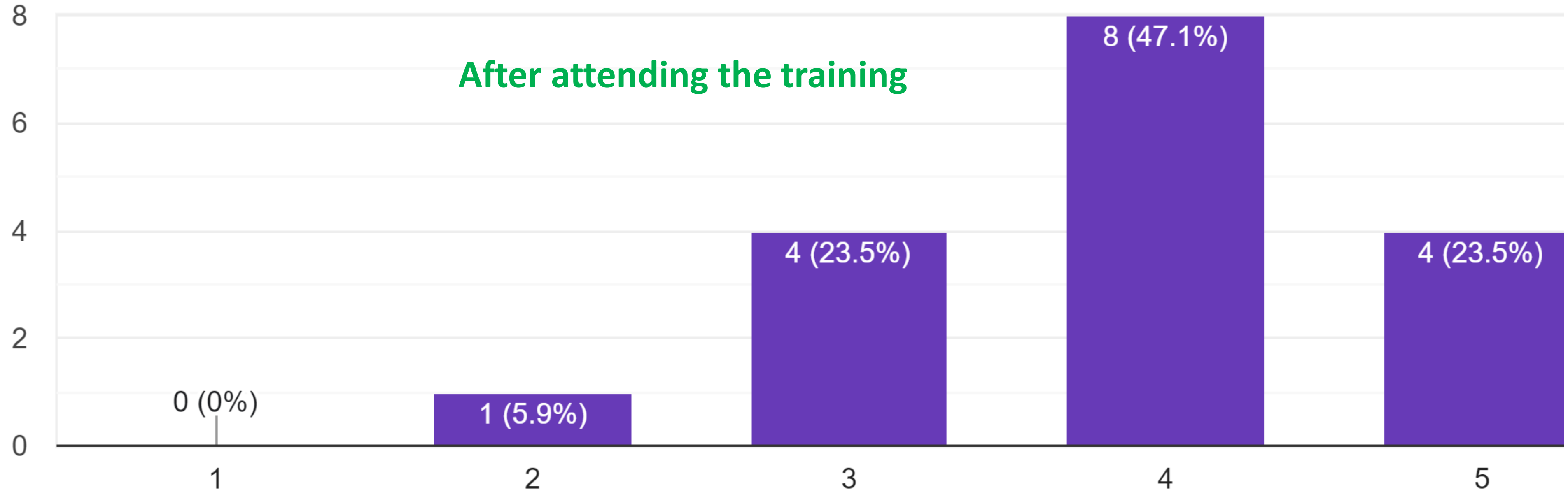
How well did the sessions meet your expectations?

18 responses



How would you rate your understanding of the topics before and after the workshop (5 meaning very good understanding)?



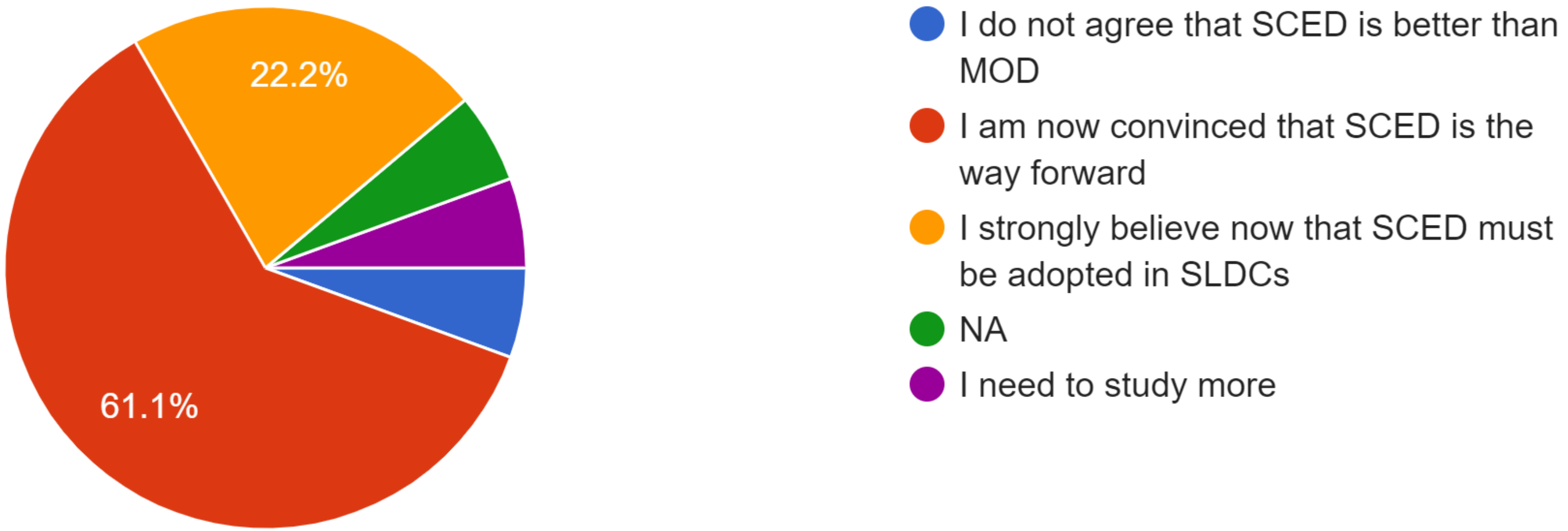


How convinced were you about the potential benefit of SCED Before attending the training

18 responses

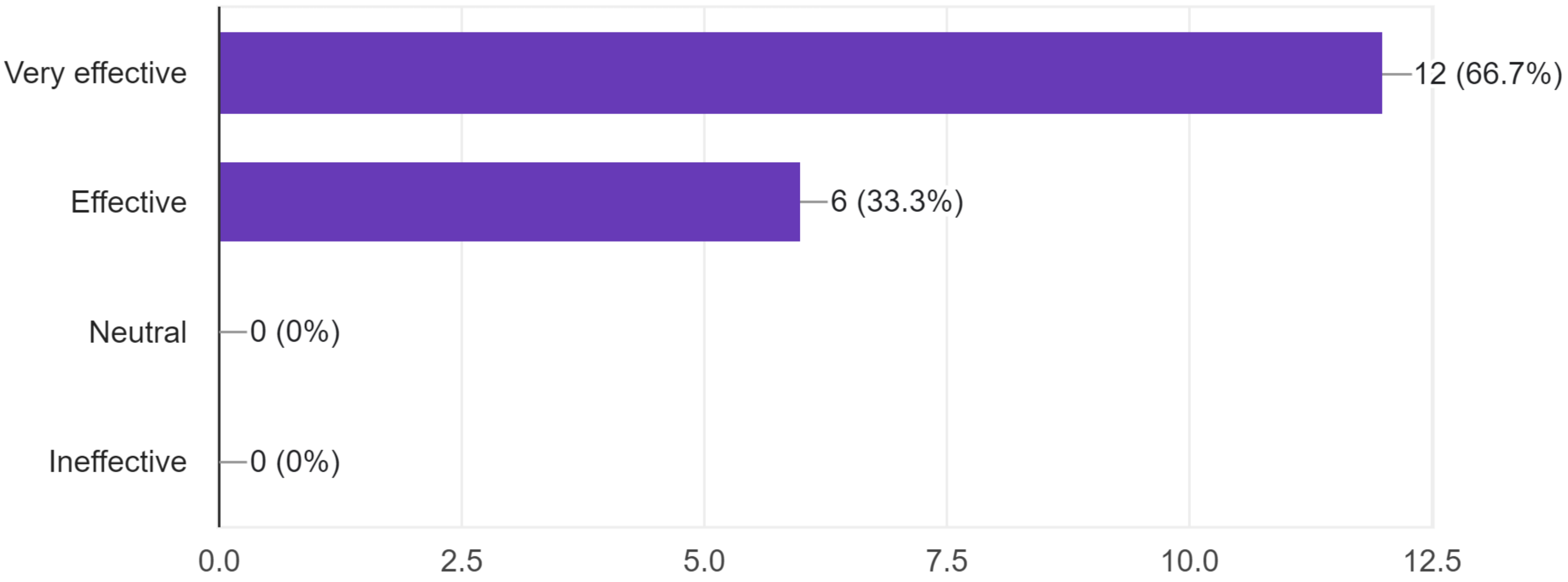
How convinced are you now (after attending the training workshop) about potential benefit of SCED

18 responses

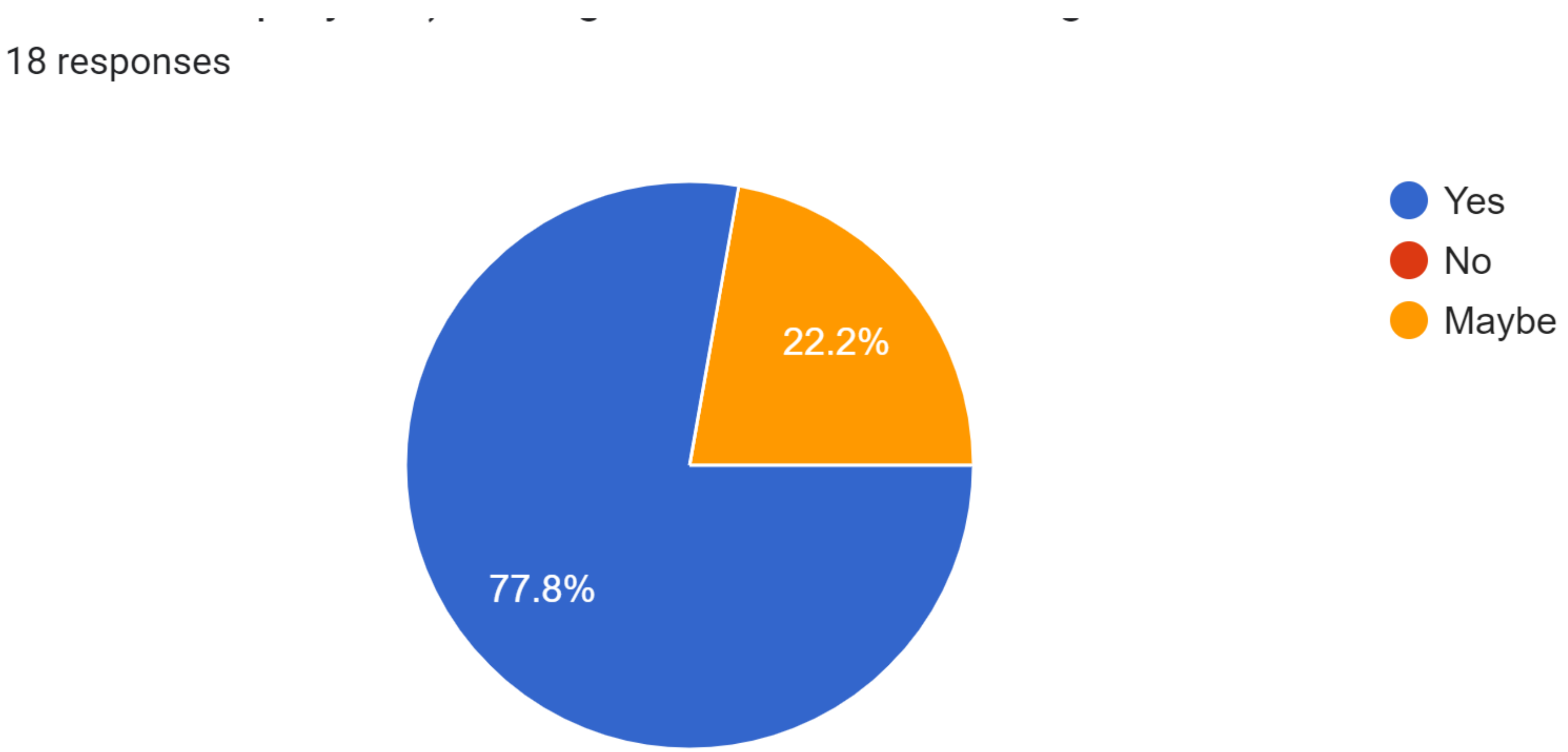


How effective were the speakers in delivering the content?

18 responses



Would you be interested in joining the core SCED group for further enhancement of SCED skills through further handholding



What were your key takeaways from the workshop?

- Understanding sced
- Gams Coding knowledge
- SCED as scientific proven method towards power scheduling
- GAMS is user friendly
- Working on different technology.
- My Basics are more clear now
- MOD and SCED result comparison
- Features of GAMS and coding.
- Necessity of minimising generator operation's may be explored
- Knowledge of gams
- GAMS coding
- Increasing my participation in SCED for MSLDC
- Marginal price helps to make decision
- Learning of GAMS tool for optimization purposes.
- Good understanding of the SCED and the GAMS application
- The concepts of GAMS and the implementation of SCED using GAMS and the various types of optimizations especially the duality method.
- Optimization on every resources is need of future.
- Basic information of GAMS

What could be improved/strengthened in future such training programmes?

- More hands on
- Duration should be increased.
- More examples with data
- GAMS Coding
- More time may be provided for understanding code logics.
- More Hands on sessions be included
- more case study and real world integration scenarios
- Practicing the DATA for various solutions
- Coding syntax practice
- Sufficient for learning the GAMS for SCED purposes.
- More interaction with the Real Time Data to be used by MSLDC and plotting of the output data.
- More hands on training.
- next sessions to be conducted in continuous

Annexure – V

GAMS code developed for SCED implementation by GIL, IIT Bombay

Details of Sets:

```
gen set of all generators
gen_mod(gen) set of generators that has the MOD
gen_nomod(gen) set of generators that do not have the MOD applicability
gen_mod_oa(gen) set of generators that has the MOD under OA
gen_nomod_oa(gen) set of generators that do not have the MOD under OA
gen_hydro(gen) set of hydro generators
tb time block
discom set of all DISCOMs;
```

Variables

```
cost objective function;
pg(gen,tb) generator dispatch schedule
pg_oa(gen,discom,oa_type,approval,tb) Subcontract dispatch schedule
rampdown_short(gen,tb) ramp down shortage
rampup_short(gen,tb) ramp up shortage
loadShed(discom,tb) violation due to insufficient generation
excess_gen(discom,tb) violation due to the excess generation;
```

Objective Function:

```
objective..cost=e=sum(tb$(ord(tb)>1),(sum(gen$gen_mod(gen),pg(gen,tb)*gen
_data(gen,'MOD_Rate'))+
sum((gen,discom,oa_type,approval)$((gen_mod_oa(gen) and
gen_oa_data (gen,discom , oa_type, approval, 'MOD_Applicability')
=1)),pg_oa
(gen,discom,oa_type,approval,tb)*gen_oa_data(gen,discom,oa_type,approval,
'MOD_R te'))+sum(gen$(gen_mod(gen) or gen_mod_oa(gen)),
20*rampup_short(gen,tb)+
20*rampdown_short(gen,tb))+sum(discom,loadshed(discom,tb)*25)+sum(discom,
excess_gen(discom,tb)*30))*1000);
```

Subcontract Mapping to Physical Unit:

```
OAmapping(gen,tb)$(gen_mod_oa(gen) and ord(tb)>1) .. pg(gen,tb)=e=
(sum((discom,oa_type,approval),gen_schdata_details(gen,discom,oa_type,app
roval,tb)$(gen_oa_data(gen,discom,oa_type,approval,'MOD_Applicability')=0
))+sum((discom,oa_type,approval),pg_oa(gen,discom,oa_type,approval,tb)$(g
en_oa_data(gen,discom,oa_type,approval,'MOD_Applicability')=1)))*(1-
gen_unittrip(gen,tb));
```

Lower Bound on generators that do not have the subcontracts:

```
LBMoD(gen,tb)$(ord(tb)>1 and
gen_mod(gen))..pg(gen,tb)=g=gen_min(gen,tb)*(1-gen_unittrip(gen,tb));
```

Lower Bound on generators that have the subcontracts:

```
LBMoD_OA(gen,tb)$(ord(tb)>1 and gen_mod_oa(gen) and
gen_schdata_new(gen,tb)>0).. pg(gen,tb)=g=gen_min_oa(gen,tb)*(1-
gen_unittrip(gen,tb));
```

Upper Bound on generators that do not have the subcontracts:

```
DCMOD(gen,tb)$(gen_mod(gen) and
ord(tb)>1)..pg(gen,tb)=l=gen_dc(gen,tb)*(1-gen_unittrip(gen,tb));
```

Upper Bound on the subcontracts:

```
DCMOD_OA(gen,discom,oa_type,approval,tb)$(gen_mod_oa(gen) and
(gen_oa_data (gen,discom,oa_type,approval,'MOD_Applicability')=1) and
ord(tb)>1)..
pg_oa(gen,discom,oa_type,approval,tb)=l=gen_oa_data(gen,discom,oa_type,ap
proval,tb)*(1-gen_unittrip(gen,tb));
```

Generation transmission limit:

```
trans_limit(gen,tb)$(gen_translimit(gen,tb)>0 and ord(tb)>1)..
pg(gen,tb)=l=1.05*gen_translimit(gen,tb);
```

Ramp Up limit of the generator:

```
RampUp(gen,tb)$(ord(tb)>1)..
pg(gen,tb)-pg(gen,tb 1)=l=gen_rampup(gen,tb)+rampup_short(gen,tb);
```

Ramp Down limit of the generator:

```
RampDown(gen,tb)$(ord(tb)>1)..
pg(gen,tb-1)-pg(gen,tb)=l=gen_rampdown(gen,tb)+rampdown_short(gen,tb);
```

State Load Generation Balance:

```
stateLGB(tb)$(ord(tb)>1)..
sum(discom,gen_centre(discom,tb)+gen_remc(discom,tb)+gen_rtm(discom,tb)+g
en_px(discom,tb)+gen_standby(discom,tb)+gen_interdiscom(discom,tb))+sum(g
en$(gen_mod(gen)),pg(gen,tb))+sum(gen$(gen_nomod(gen) and not
gen_hydro(gen)),pg(gen,tb))+ sum(gen$(gen_mod_oa(gen)),pg(gen,tb))+
sum(gen$(gen_nomod_oa(gen) and not
gen_common(gen)),pg(gen,tb))+sum(gen$(gen_hydro(gen)),pg(gen,tb))+sum(dis
com,LoadShed(discom,tb)))=e=sum(discom,discom_load(discom,tb))+sum(discom
,excess_gen(discom ,tb)));
```

DISCOM Load Generation Balance:

```
discomLGB(discom,tb)$(ord(tb)>1)..
```

```
gen_centre(discom,tb)+gen_remc(discom,tb)+gen_rtm(discom,tb)+gen_px(disco
m,tb)+gen_standby(discom,tb)+gen_interdiscom(discom,tb)+
sum(gen$(gen_mod(gen) and
gen_discom_share(gen,discom)),0.01*gen_discom_share(gen,discom)*pg(gen,tb
))+ sum(gen$(gen_nomod(gen) and gen_discom_share(gen,discom)), pg(gen,tb)
*0.01 * gen_discom_share(gen,discom)$(not gen_hydro(gen)))+
sum(gen$(gen_hydro(gen) and
gen_discom_share(gen,discom)),hydro_final(gen,discom,tb))+
sum((gen,oa_type,approval),gen_schdata_details(gen,discom,oa_type,approva
l,tb)$(gen_oa_data(gen,discom,oa_type,approval,'MOD_Applicability')=0))+
sum((gen,oa_type,approval),pg_oa(gen,discom,oa_type,approval,tb)$(gen_oa_
data(gen,discom,oa_type,approval,'MOD_Applicability')=1))+loadshed(discom
,tb) =e= discom_load(discom,tb)+excess_gen(discom,tb);
```

Annexure - VI

MAHATRANSCO
Maharashtra State Electricity Transmission Co. Ltd.

MAHARASHTRA STATE ELECTRICITY TRANSMISSION CO.LTD.

CIN NO. U40109MH2005SGC153646

MAHARASHTRA STATE ELECTRICITY TRANSMISSION CO.LTD.

CIN NO. U40109MH2005SGC153646

Maharashtra State Load Dispatch Center
Office of the Executive Director
Office Address: Thane-Belapur Road, P.O. Airoli, Navi Mumbai - 400708
Contact No: (O) 022-2760 1765, 1766, 1931, 2937, (Fax) 022-2659 0808
Email id: edmsebholding@gmail.com
Website: http://www.mahasldc.in

Ref. No. ED/MSLDC/Airoli/ No 01799

Date: 05 SEP 2024

OFFICE ORDER

Sub: Pilot Operation of Intra State Security Constrained Economic Dispatch in Maharashtra- formation of working sub group thereof.

Ref.: ED/MSLDC/Airoli/No.1617 dt. 12.08.2024

With reference to the officer order under reference for pilot operation of Intra state Security constrained Economic dispatch in Maharashtra, and discussion during training on 3rd sept 24 the working sub group is hereby constituted for phase I off-line study for the state. The officers in the sub-Group and activity allotted are as below: -

Sr. No.	Name of subgroup	Name of officer and Designation under subgroup	Sub Group activities
1	Automatic Data Retrieval and Verification	Shri. Shiva Gourishetti AE Operations (sub group leader)	1)Formation of data template in coordination with IITB 2) Automatic retrieval of data of last 3 months as per template finalized 3) Verification and correction of data and forwarding to IIT-B by ensuring LGBR for each date
		Shri. Vaibhav Ahinave, Programmer, IT	
		Shri. Avinash Dhawade DYEE Operations	
		Shri. Pankaj Shinde, AEE , ALDC Nagpur	
		Shri. Vijay Kamble , AE Operations	
		Shri. Sukumal Sengupta, Senior Associate PWC	
2	GAMS Programming	Shri. Nitesh Dongare , AE , ALDC Nagpur(Sub group leader)	1)Problem formulation related to SCED , Developing logics etc 2)Defining objective functions, constraints, assumptions etc. 3)Programming in GAMS i.e sets/parameter/equations/models/display etc 4) Data flow from Excel to GDX and vice versa
		Shri. Shiva Gourishetti AE Operations	
		Shri , Pravin Shinde , DYEE , MSETCL, CSN	
		Shri. Gajanan Mirashe , IT, ALDC Nagpur	
		Shri. Nishant Harjal , AE , ALDC Nagpur	
		Shri. Akshay Gadagkar, AE SCADA	
		Shri. Sukumal Sengupta, Senior Associate PWC	

Sr. No.	Name of subgroup	Name of officer and Designation under subgroup	Sub Group activities
3	Report and compilation	Shri. Sachin Lomate, AEE Operations (Sub group Leader)	1) Analysis of Excel output file and charts preparation as per requirement 2) Finalization of Report structure to be submitted to MERC 3) Compilation and editing of Report.
		Mrs. Asawari Tulshi , AE , MSETCL , Pune	
		Shri. Akshay Gadagkar, AE SCADA	
		Shri. Vijay Kamble , AE Operations	
		Shri. Abhishek Samant	
4	Data integration and storage,	Shri. Vaibhav Ahinave, Programmer, IT (Sub group leader)	Handling input and output data files of GAMS engine, and its storage, integration, APIs, etc.
		Shri. Gajanan Mirashe , IT, ALDC Nagpur	
		Shri. Nishant Harjal , AE , ALDC Nagpur	
		Shri. Akshay Gadagkar, AE SCADA	
		Shri. Shiva Gourishetti AE Operations	

The Sub- group shall undertake above activities and submit the progress on weekly basis to the undersigned. The timeline for the above activities 30.09.2024

(Shashank Jewalikar)
Executive Director,
MSLDC, Kalwa

Copy to: -

1) The Chief Engineer, MSLDC, Airoli
2) The Superintending Engineer, Operations/SCADA/ALDC Nagpur
3) The DGM, IT, MSLDC, Airoli
4) The Director, PWC, Kolkatta
5) All officers as above through respective section head.

Annexure – VI A

Status of Sub-group – 1 Activities

This group was formed, for automatic retrieval of scheduling data as input to GAMS in coordination with IITB.

Accordingly, the data template for extraction of data on daily basis was finalized. The data for 30 days were extracted and LGBR for each day was verified by MSLDC team. There were various meetings conducted between IITB and MSLDC group 1 members regarding understanding of data verifications, Validation, conceptual understating's, any nuances etc.

The details of understandings and problem formulation are furnished by MSLDC as below for the sample date of 10.08.2024:

Discom wise Load generation Balance:

Target injection Schedules (Discom wise) = Σ Schedules of (Intrastate Gen + Open access+ PX (DAM)+ RTM + REMC+ Center +Standby+ Intra discom Trades +Hydro Schedule).

*Target injection schedules (Discom wise) are considered as the demand of that Discom.

State wise Load generation Balance:

Sum of Target injection Schedules of all Discoms= Σ Schedules of (Intrastate Gen + Open access+ PX (DAM)+ RTM + REMC+ Center +Standby+ Intra discom Trades +Hydro Schedule).

*Sum of Target injection schedules of all Discoms are considered as the state demand.

Intrastate Generator Schedules (Discom wise): If the MOD applicability given as "1". Then these Schedule are variable between limits DC (Pmax) and Tech min (P min) for optimization. Considering the share allocation with respective discom and DC & Ramp rate submitted by the generator.

DC is provided under "Gen DC _DATA" sheet,

Share allocation details are provided under "GEN_ DISCOM_ Share" sheet,

MOD applicability and MOD rate (Variable charges) data provided under the "GEN Info" Sheet

Ramp Up/Down data Provided under the " GEN Ramp up data & GEN Ramp down data" Sheets

Tech min data provided under the "GEN_TECH_MIN_DATA" Sheet

Open Access Schedules (Discom wise): Bilateral contract-based schedules, If MOD applicability given as "1" , then these schedules are variable between the limits Requisition data (Pmax) and Tech min (P min) for optimization.

OA requisition data, discom details, MOD applicability, MOD rates are provided under "OA Requisition _DATA" sheet,

Contract wise (Approval No.) Ramp Up/Down data Provided under the " GEN Ramp up data & GEN Ramp down data" Sheets

Tech min data provided under the "GEN_TECH_MIN_DATA" Sheet

Hydro Schedule: Hydro requisitions given by the respective discom are considered as schedule. In case of surplus or shortfall condition, Hydro schedules of some specific generators like MSPGCL Koyna and TPCL _Hydro are varied between the DC and Tech min. (After completion of all optimization in thermal and Gas).

In case of Shortfall of MSEDCL, MSPGCL Koyna schedule is picked up to its DC value to meets the MSEDCL demand requirement. In case of shortfall its schedule will reduced to the tech min value.

As TPCL hydro has allocations with TPCL and BEST discom.

In case of shortfall of TPCL, TPCL-Hydro schedule is picked up to its DC value to meets its demand requirement, In case of shortfall its schedule will reduced to the tech min value. (Up to TPCL discoms share)

In case of shortfall of BEST, TPCL-Hydro schedule is picked up to its DC value to meets its demand requirement, in case of shortfall its schedule will reduced to the tech min value. (Up to BEST discoms share)

Hydro requisition Data is provided under " Hydro requisition Data" Sheet

Ramp Up/Down data Provided under the " GEN Ramp up data & GEN Ramp down data" Sheets

Tech min data provided under the "GEN_TECH_MIN_DATA" Sheet

PX(DAM), RTM, REMC, Center, Standby, Intra discom trades are considered as must run.

Zero schedule details to de-commitment of the unit & Generator transmission constraints and unit tripping details are also provided with data sheet.

Note: If DC or Requisition value (In case of OA) given below the Tech min value, Then P max and P min are considered as DC/ requisition value. (Ride through infeasibility criteria). As the data templet and automatic retrieval of required data (except Pmin) from existing scheduling software is done by PWC, it will help in future during pilot operation of SCED in Maharashtra.

Annexure – VI B

Status of Sub-group – 2 Activities

This group was formed for Problem formulation related to SCED, developing logics, defining objective functions, constraints, assumptions etc. MSLDC shared the logics, formulas for current LGBR in MOD to IITB.

The 10 Nos. Licensed version GAMS software were installed at MSLDC and ALDC Nagpur with help of World Bank. The workshop was held on 2nd and 3rd Sept.2024 regarding optimization techniques in power system and GAMS coding.

Accordingly, the GAMS coding was done by IITB and MSLDC team, The results in this report was taken based on code written by IITB,

This group has familiarized with GAMS coding and needs further capacity building. The group has carried out some development activity which is reproduced below:

1. Scope

The coding team is responsible for developing the GAMS code for SCED and ensuring proper data preprocessing and model implementation. The following challenges were faced:

(i) **Unstructured polluted input data:** The input data was unstructured, requiring significant cleaning and preprocessing before it could be used in the SCED model.

(ii) **Diverse contract rates for open access (OA) generators:** Handling multiple contracts with varying rates for open-access generators increased the complexity of the cost calculations and constraints

(iii) **Complex hydro Scheduling:** Modeling the complexities of hydro generation schedules was difficult due to varying constraints, unpredictable water inflows, and operational dependencies.

2. Assumptions

The following assumptions were made:

(i) Generator names are unique.

(ii) Discom names are unique.

(iii) Approval numbers are unique (for OA contracts).

(iv) Hydro generation is kept equal to the mod generation schedule.

(v) Only decentralized mod is studied (for now).

(vi) Generation feeding to VSE is not considered in the calculation.

(vii) Ls and surplus penalty is ₹ 20

(viii) MoD demand=Demand – Central requisition – PX – RTM – REMC - Must run generation.

(ix) CPLEX solver is used in GAMS

3. Actions taken

Actions taken for cleaning the data and making the same readable by the GAMS optimization module:

(i) Python language is used for data pre-processing.

(ii) Intra-state generation and OA generation are used separately.

(iii) Hydro generator schedules are kept equal to the generation schedule calculated by MoD

4. Methodology adopted

(i) Excel is read, and the data is preprocessed and converted into a simple Excel file.

(ii) GAMS reads the Excel file using gdxxrw.

(iii) Sets and parameters are defined.

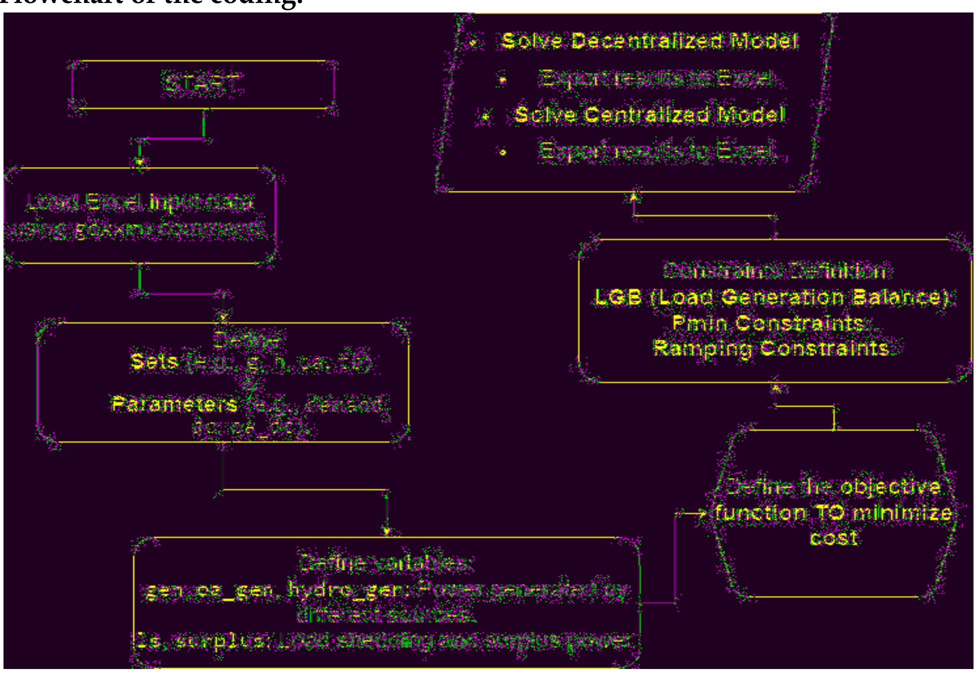
(iv) Constraints and equations are modeled.

(v) An objective function is created to minimize costs.

(vi) Data is exported to Excel using gdxxrw.

(vii) Data is visualized using a dashboard developed in Python (Dash Plotly Library are used).

5. Flowchart of the coding:



6. Equations

The equations details are as follows:

(i) The objective is to minimize the total cost of generation, including penalties for load shedding and surplus generation:

$$z = \sum_{d}\sum_{tb}\left(\sum_{g} \mathrm{gen}(g,d,tb) \times \mathrm{mod}(g,d) + \sum_{---} \mathrm{oa\_gen}(oa,d,c,tb) \times \mathrm{mod\_oa}(oa,d,c) + \sum_{h} \mathrm{hydro\_gen}(h,d,tb) \times 15 + \mathrm{ls}(d,tb) \times 20 + \mathrm{surplus}(d,tb) \times 20\right)$$

(ii) Load Generation Balance (LGB) Constraint (Decentralized Operation)

$$\sum_{g} \mathrm{gen}(g,d,tb) + \sum_{oa,c} \mathrm{oa\_gen}(oa,d,c,tb) + \sum_{h} (\mathrm{hydro\_gen}(h,d,tb) + \mathrm{ls}(d,tb) - \mathrm{surplus}(d,tb) = \mathrm{demand}(d,tb)$$

(iii) Minimum Generation Constraint

$$\sum d \ \ Gen(g,d,tb) \geq Pmin(g,tb) \ \ if \ Pmin < DC$$

$$\sum d \ \ Gen(g,d,tb) = DC \ \ if \ Pmin > DC$$

$\sum(d,c) \ \ OAGen(oa,d,c,tb) > Pmin(oa,tb)$ if Pmin < DC

$\sum(d,c) \ \ OAGen(oa,d,c,tb) > DC$ if Pmin > DC

(iv) Maximum Generation Constraints

$$Gen(g,d,tb) < Pmax(g,d,tb)$$

$$OAGen(oa,d,c,tb) < Pmax(oa,d,c,tb)$$

(v) Ramp-Up Constraints

$\sum d \ \left(Gen(g,d,tb+1) - Gen(g,d,tb)\right) < Ramp\_Up(g,tb)$ if Unittrip(g,tb)=0

$\sum(d,c)(\ OAGen(oa,d,c,tb+1) - OAGen(oa,d,c,tb)) < Ramp\ Up(oa,tb)$
if Unittrip(oa,tb) = 0

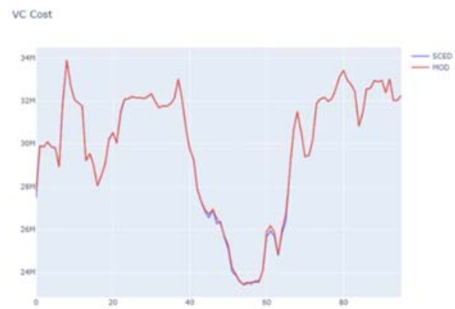
(vi) Ramp-Down Constraints

$\sum d \ \left(Gen(g,d,tb) - Gen(g,d,tb+1)\right) < Ramp\_Down(g,tb)$ if Unittrip(g,tb)=0

$\sum(d,c)(\ OAGen(oa,d,c,tb) - OAGen(oa,d,c,tb+1)) < Ramp\ Down(oa,tb)$
if Unittrip(oa,tb)=0

7. Observations

The above code was successfully executed. The following plots were also made:



It was observed that there was cost savings on running SCED.

8. Future Scope

1. Transmission Constraint Modelling
2. Hydro Generation Modelling
3. Dashboard Development (Currently under progress)
4. Automation for Calculation for Large dataset

Annexure – VI C

Status of Sub-group – 3 Activities

This group was formed for analysis of GAMS output files and compare the results between SCED Vs MOD principle of scheduling like, compare the cost savings, impact on schedules of generators etc. Accordingly, this report is prepared with help of IITB.

In future this group needs to acquire skills like data handling, data presentation and various analysis tools which further helpful in data analysis during pilot operation of SCED in Maharashtra.

Annexure – VI D

Status of Sub-group – 4 Activities

This group was formed considering future, pilot operation of SCED, as currently this report was based on offline SCED study for 30 days only, this group was not involved at this stage. During pilot operation of SCED in Maharashtra, this group may help in online input of data to GAMS engines thorough API and storage of file, providing customized visualization to Grid operator etc.

Annexure - VII

GAMS Code developed by MSLDC as a part of sub-group activity

```
$onUNDF
$title SCED Implementation in Maharashtra(Rev01)
$call gdxxrw input0812.xlsx output=input.gdx @read.txt MaxDupeErrors =1000
Set
g Generator Set
d Discom Set
c Contract Set
h Hydro Generator
tb /1*96/
;
$gdxIn input.gdx
$load g,c,h,d
Parameter
demand(d,tb) Discomwise demand
dc(g,d,c,tb) Generator DC
tech_min(g) Technical Minimum of Generator
ramp_up(g) Ramp Up Rate of Generator
ramp_down(g) Ramp Down Rate of Generator
hydro_dc(h,d,tb) Hydro Availability
hydro_sc(h,d,tb) Hydro Schedule in Current system
rates(g,d,c) Generator MOD Rate
unittrip(g,tb) Unit tripped
schedule(g,d,c,tb) Schedule of Genertor in Current System
;
$load
dc,tech_min,ramp_up,ramp_down,demand,hydro_dc,hydro_sc,rates,unittrip,schedule
$gdxIn
Variable z COst;
Positive Variable
gen(g,d,c,tb),
ls(d,tb)
surplus(d,tb)
hydro_gen(h,d,tb)
;
* Current hydro schedule is kept equal to schedule in current mod
hydro_gen.lo(h,d,tb)=hydro_sc(h,d,tb);
hydro_gen.up(h,d,tb)=hydro_sc(h,d,tb);
Equation
obj Objective function
LGB(d,tb) Generation Load Balanc equation
Pmax(g,d,c,tb) Upper bound equation
Pmin(g,tb) Lower bound equation when DC>Technical Minimum
Pmin1(g,tb) Lower bound equation when DC<Technical Minimum
Rampup_Const(g,tb) Ramp up Constrant
```

```
RampDown_Const(g,tb) Ramp down Constrant
;
obj..
sum(d,
   sum(tb,
      sum((g,c),gen(g,d,c,tb)*rates(g,d,c))+
      (ls(d,tb)*20)+
      (surplus(d,tb)*20)
   )
)=e=z;
LGB(d,tb)..
sum((g,c),gen(g,d,c,tb))+sum(h,hydro_gen(h,d,tb))+ls(d,tb)-
surplus(d,tb)=e=demand(d,tb);
Pmax(g,d,c,tb)..
gen(g,d,c,tb)=l=dc(g,d,c,tb);
Pmin(g,tb)$(sum((d,c),dc(g,d,c,tb))>=tech_min(g))..
sum((d,c),gen(g,d,c,tb))=g=tech_min(g);
Pmin1(g,tb)$(sum((d,c),dc(g,d,c,tb))<tech_min(g))..
sum((d,c),gen(g,d,c,tb))=g=sum((d,c),dc(g,d,c,tb));
Rampup_Const(g,tb)$(ord(tb)>1 and unittrip(g,tb)=0)..
sum((d,c),gen(g,d,c,tb))-sum((d,c),gen(g,d,c,tb-1))=l=ramp_up(g);
RampDown_Const(g,tb)$(ord(tb)>1 and unittrip(g,tb)=0)..
sum((d,c),gen(g,d,c,tb-1))-sum((d,c),gen(g,d,c,tb))=l=ramp_down(g);
Model scheduling_decentralised
/
all
/
;
Solve scheduling_decentralised using LP minimizing z;
$call gdxxrw sced.gdx output=output0812.xlsx @write.txt MaxDupeErrors = 1000
```

Annexure – VIII

List of Training / meetings held on Intra-state SCED and report preparation

Sr.No.	Training / Meetings details	Date
1	Training on GAMS by World Bank	29th July, 2024
2.	Meeting- assessment of progress of work	7th August 2024
3.	Meeting for installation of GAMS license	9th August 2024
4.	Follow-up meeting on SCED preparation	14th August 2024
5.	Meeting for data preparation at IIT Bombay	22nd August 2024
6.	Preparatory meeting for training with IIT Bombay	29th August 2024
7.	On site training at SLDC on GAMS by IIT Bombay	2nd & 3rd September 2024
8.	Initial meeting for data sharing with IIT Bombay	13th September 2024
9.	Finalization of data template with IIT Bombay	20th September 2024
10.	Initial results- meeting on SCED	7th October 2024
11.	Follow-up meeting on SCED	17th October 2024
12.	Capacity Building for code development by IIT Bombay	18th October 2024
13.	Meeting to finalize report	25th October 2024
14.	Online review of all the graph and results with IIT Bombay	26th October 2024
15.	Online Meeting to finalize report with IIT Bombay	28th October2024

MoD stack is preapared as per Clause 33 of State Grid Code Regulation 2020 issued by Hon. MERC on dtd. 02.09.2020

DISCOM WISE MOD STACK OF VARIABLE CHARGES (VC) FOR JULY-2024 (R0)

(*Effective from 16.07.2024 to 15.08.2024)

Sr. no.	Generating Station	OWNER/TYPE	Installed Capacity/ Share in ISGS (MW)	Type of Fuel	Variable Charge Rs./KWh in Descending Order		
					Approved Variable Charge(Rs/KWh)	Impact for approved change in law (if any) Rs./KWh)	Total Variable Charge(Rs/ KWh)
1	2	3	4	5	6	7	8
	DECENTRALISED MOD STACK FOR MSEDCL						
1	KAWAS (LIQ)	CS	-	Gas	25.0707	0.0000	25.0707
2	KAWAS (NAPM-COM GAS)	CS	-	Gas	11.4425	0.0000	11.4425
3	KAWAS (RLNG)	CS	-	Gas	11.3513	0.0000	11.3513
4	JGPS (RLNG)	CS	-	Gas	11.2819	0.0000	11.2819
5	GANDHAR (NAPM-COM GAS)	CS		Gas	11.1182	0.0000	11.1182
6	Uran GTPS (Open cycle operation)	MSPGCL	-	Gas	7.2820	0.0000	7.2820
7	KAWAS (APM GAS)	CS	200	Gas	5.9253	0.0000	5.9253
8	GANDHAR (APM GAS)	CS	204	Gas	5.8942	0.0000	5.8942
9	Uran GTPS (Combined cycle operation)	MSPGCL	840	Gas	5.2190	0.0000	5.2190
10	Nasik Unit - 03 to 05	MSPGCL	630	Coal	5.1170	0.0000	5.1170
11	Parali Unit -08	MSPGCL	250	Coal	5.0310	0.0000	5.0310
12	Parali Unit - 06 & 07	MSPGCL	500	Coal	4.9550	0.0000	4.9550
13	Bhusawal Unit - 03	MSPGCL	210	Coal	4.8790	0.0000	4.8790
14	Solapur STPS	CS	642	Coal	4.4761	0.0000	4.4761
15	Chandrapur Unit - 03 to 07	MSPGCL	1920	Coal	4.2450	0.0000	4.2450
16	Khargone	CS	85	Coal	4.1231	0.0000	4.1231
17	Bhusawal Unit - 04 & 05	MSPGCL	1000	Coal	4.0960	0.0000	4.0960
18	APML, Unit 2 & 3 (1320 MW PPA)	IPP	1320	Coal	1.7040	2.2129	3.9169
19	Paras Unit - 03 & 04	MSPGCL	500	Coal	3.9050	0.0000	3.9050
20	JSW U1, Jaigad	IPP	300	Coal	3.8900	0.0000	3.8900
21	CGPL	CS	760	Coal	3.8683	0.0000	3.8683
22	Khaperkheda Unit - 01 to 04	MSPGCL	840	Coal	3.6990	0.0000	3.6990
23	Chandrapur Unit - 08,09	MSPGCL	1000	Coal	3.6100	0.0000	3.6100
24	APML U-1,4 &5 (440 MW PPA)	IPP	440	Coal	2.4068	1.1546	3.5614
25	IEPL TO MSEDCL	STOA	180	Coal	3.5070	0.0000	3.5070
26	APML, Unit 1,4 & 5 (1200 MW PPA)	IPP	1200	Coal	2.3468	1.1546	3.5014
27	APML, Unit 1,4 & 5 (125 MW PPA)	IPP	125	Coal	2.3468	1.1546	3.5014
28	MSTPS-I	CS	394	Coal	3.4671	0.0000	3.4671
29	MSTPS-II	CS	531	Coal	3.4402	0.0000	3.4402
30	Gadarwara	CS	46	Coal	3.4367	0.0000	3.4367
31	Khaperkheda Unit - 05	MSPGCL	500	Coal	3.1850	0.0000	3.1850
32	Koradi Unit - 08 to 10	MSPGCL	1980	Coal	3.1240	0.0000	3.1240
33	Koradi Unit - 06	MSPGCL	210	Coal	3.0640	0.0000	3.0640
34	SWPGPL TO MSEDCL	LTOA	240	Coal	2.5268	0.4199	2.9467
35	RattanIndia Power Ltd, Amravati	IPP	1200	Coal	2.3785	0.5266	2.9051
36	EMCO	CS	200	Coal	2.7596	0.0000	2.7596
37	KHTPS-II	CS	148	Coal	2.4167	0.0000	2.4167
38	VSTP-I	CS	432	Coal	1.9103	0.0000	1.9103
39	VSTPS-V	CS	161	Coal	1.8335	0.0000	1.8335
40	VSTP-II	CS	336	Coal	1.8038	0.0000	1.8038
41	VSTPS-III	CS	275	Coal	1.7810	0.0000	1.7810
42	VSTP-IV	CS	294	Coal	1.7628	0.0000	1.7628
43	SSTPS-II	CS	274	Coal	1.7525	0.0000	1.7525
44	SSTPS-I	CS	556	Coal	1.7056	0.0000	1.7056
45	KSTPS I AND II	CS	635	Coal	1.6643	0.0000	1.6643
46	KSTPS-III	CS	120	Coal	1.6137	0.0000	1.6137
47	Lara	CS	114	Coal	1.5964	0.0000	1.5964
	DECENTRALISED MOD STACK FOR AEML						
1	ADTPS U-1 & 2	DTPS	500	Coal	4.1521	0.0000	4.1521
	DECCENTRALISED MOD STACK FOR TPCL-D						
1	TPC U-7 (RLNG)-NAPM	TATA	xxx	Gas	11.5890	0.0000	11.5890
2	TPC U-5	TATA	500	Coal/Oil/Gas	5.8680	0.0000	5.8680
3	TPC U-8	TATA	250	Coal	5.7480	0.0000	5.7480
4	TPC U-7 (APM) *	TATA	180	Gas	5.0500	0.0000	5.0500
	DECENTRALISED MOD STACK FOR BEST						
1	TPC U-7 (RLNG)	TATA	xxx	Gas	11.5890	0.0000	11.5890
2	TPC U-5	TATA	500	Coal/Oil/Gas	5.8680	0.0000	5.8680
3	TPC U-8	TATA	250	Coal	5.7480	0.0000	5.7480
4	TPC U-7 (APM) *	TATA	180	Gas	5.0500	0.0000	5.0500
5	SWPGL TO BEST	MTOA	100	Coal	2.2700	0.0000	2.2700
NOTE-							

1) Prepared as per Clause 33 of State Grid Code Regulation 2020 issued by Hon'ble MERC dtd. 2nd sept 2020 .

2) "R0 updated on mahasldc.in website on dated 15.07.2024

3) Actual rates of NTPC Kawas and Gandhar are displayed on WRLDC web-site daily.
4) Hydro generation is not considered for MOD.
5) Gas and RE and Nuclear Generation is considered as MUST RUN except TPCU-7 RLNG.

MoD stack is preapared as per Clause 33 of State Grid Code Regulation 2020 issued by Hon. MERC on dtd. 02.09.2020

DISCOM WISE MOD STACK OF VARIABLE CHARGES (VC) FOR AUGUST-2024 (R0)

(*Effective from 16.08.2024 to 15.09.2024)

Sr. no.	Generating Station	OWNER/TYPE	Installed Capacity/ Share in ISGS (MW)	Type of Fuel	Variable Charge Rs./KWh in Descending Order		
					Approved Variable Charge(Rs/KWh)	Impact for approved change in law (if any) Rs./KWh)	Total Variable Charge(Rs/ KWh)
1	2	3	4	5	6	7	8
	DECENTRALISED MOD STACK FOR MSEDCL						
1	KAWAS (LIQ)	CS	-	Gas	25.3912	0.0000	25.3912
2	KAWAS (NAPM-COM GAS)	CS	-	Gas	13.5818	0.0000	13.5818
3	GANDHAR (NAPM-COM GAS)	CS		Gas	13.5154	0.0000	13.5154
4	KAWAS (RLNG)	CS	-	Gas	11.3161	0.0000	11.3161
5	JGPS (RLNG)	CS	-	Gas	11.2601	0.0000	11.2601
6	Uran GTPS (Open cycle operation)	MSPGCL	-	Gas	7.2890	0.0000	7.2890
7	KAWAS (APM GAS)	CS	200	Gas	5.9395	0.0000	5.9395
8	GANDHAR (APM GAS)	CS	204	Gas	5.9083	0.0000	5.9083
9	Uran GTPS (Combined cycle operation)	MSPGCL	840	Gas	5.2250	0.0000	5.2250
10	APML U-1,4 &5 (440 MW PPA)	IPP	440	Coal	2.4103	2.7373	5.1476
11	Nasik Unit - 03 to 05	MSPGCL	630	Coal	5.0970	0.0000	5.0970
12	APML, Unit 1,4 & 5 (1200 MW PPA)	IPP	1200	Coal	2.3503	2.7373	5.0876
13	APML, Unit 1,4 & 5 (125 MW PPA)	IPP	125	Coal	2.3503	2.7373	5.0876
14	APML, Unit 2 & 3 (1320 MW PPA)	IPP	1320	Coal	1.7040	3.3576	5.0616
15	Parali Unit -08	MSPGCL	250	Coal	5.0240	0.0000	5.0240
16	Parali Unit - 06 & 07	MSPGCL	500	Coal	5.0210	0.0000	5.0210
17	Bhusawal Unit - 03	MSPGCL	210	Coal	4.9680	0.0000	4.9680
18	Solapur STPS	CS	642	Coal	4.5553	0.0000	4.5553
19	Chandrapur Unit - 03 to 07	MSPGCL	1920	Coal	4.2770	0.0000	4.2770
20	Khargone	CS	85	Coal	4.2110	0.0000	4.2110
21	JSW U1, Jaigad	IPP	300	Coal	4.0100	0.0000	4.0100
22	Bhusawal Unit - 04 & 05	MSPGCL	1000	Coal	3.9980	0.0000	3.9980
23	CGPL	CS	760	Coal	3.9943	0.0000	3.9943
24	Khaperkheda Unit - 01 to 04	MSPGCL	840	Coal	3.8760	0.0000	3.8760
25	Paras Unit - 03 & 04	MSPGCL	500	Coal	3.8040	0.0000	3.8040
26	MSTPS-I	CS	394	Coal	3.6467	0.0000	3.6467
27	Chandrapur Unit - 08,09	MSPGCL	1000	Coal	3.6040	0.0000	3.6040
28	MSTPS-II	CS	531	Coal	3.5824	0.0000	3.5824
29	IEPL TO MSEDCL	STOA	180	Coal	3.5070	0.0000	3.5070
30	Koradi Unit - 08 to 10	MSPGCL	1980	Coal	3.3340	0.0000	3.3340
31	Koradi Unit - 06	MSPGCL	210	Coal	3.2660	0.0000	3.2660
32	Khaperkheda Unit - 05	MSPGCL	500	Coal	3.2510	0.0000	3.2510
33	Gadarwara	CS	46	Coal	3.2201	0.0000	3.2201
34	RattanIndia Power Ltd, Amravati	IPP	1200	Coal	2.3829	0.5634	2.9463
35	SWPGPL TO MSEDCL	LTOA	240	Coal	2.5303	0.4096	2.9399
36	EMCO	CS	200	Coal	2.7962	0.0000	2.7962
37	KHTPS-II	CS	148	Coal	2.5388	0.0000	2.5388
38	VSTP-I	CS	432	Coal	2.0324	0.0000	2.0324
39	VSTPS-V	CS	161	Coal	1.9498	0.0000	1.9498
40	VSTP-II	CS	336	Coal	1.9218	0.0000	1.9218
41	VSTPS-III	CS	275	Coal	1.8957	0.0000	1.8957
42	VSTP-IV	CS	294	Coal	1.8762	0.0000	1.8762
43	SSTPS-II	CS	274	Coal	1.8193	0.0000	1.8193
44	SSTPS-I	CS	556	Coal	1.7694	0.0000	1.7694
45	KSTPS I AND II	CS	635	Coal	1.6197	0.0000	1.6197
46	KSTPS-III	CS	120	Coal	1.5688	0.0000	1.5688
47	Lara	CS	114	Coal	1.5331	0.0000	1.5331
	DECENTRALISED MOD STACK FOR AEML						
1	ADTPS U-1 & 2	DTPS	500	Coal	4.6118	0.0000	4.6118
	DECCENTRALISED MOD STACK FOR TPCL-D						
1	TPC U-7 (RLNG)-NAPM	TATA	xxx	Gas	11.4550	0.0000	11.4550
2	TPC U-5	TATA	500	Coal/Oil/Gas	5.8330	0.0000	5.8330
3	TPC U-8	TATA	250	Coal	5.6430	0.0000	5.6430
4	TPC U-7 (APM) *	TATA	180	Gas	5.0770	0.0000	5.0770
	DECENTRALISED MOD STACK FOR BEST						
1	TPC U-7 (RLNG)	TATA	xxx	Gas	11.4550	0.0000	11.4550
2	TPC U-5	TATA	500	Coal/Oil/Gas	5.8330	0.0000	5.8330
3	TPC U-8	TATA	250	Coal	5.6430	0.0000	5.6430
4	TPC U-7 (APM) *	TATA	180	Gas	5.0770	0.0000	5.0770
5	SWPGL TO BEST	MTOA	100	Coal	2.2700	0.0000	2.2700

NOTE-

1) Prepared as per Clause 33 of State Grid Code Regulation 2020 issued by Hon'ble MERC dtd. 2nd sept 2020 .

2) "R0 updated on mahasldc.in website on dated 15.08.2024 .

3) Actual rates of NTPC Kawas and Gandhar are displayed on WRLDC web-site daily.
4) Hydro generation is not considered for MOD.
5) Gas (closed cycle), RE and Nuclear Generation is considered as MUST RUN except TPCU-7 RLNG.

Annexure - X

Timeline for implementation

1. **Proposal for Expedited Implementation of Intra-State SCED Pilot Project**
   (i) Project Duration: 6 Months
   (ii) Implementation Timeline: 3 Months for Initial Setup and Deployment

2. **Objective:** This proposal outlines an accelerated approach for the implementation of an Intra-State Security-Constrained Economic Dispatch (SCED) pilot project. By focusing on the efficient use of existing infrastructure and streamlined processes, we aim to complete the system design, agency finalization, and pilot deployment within six months, including three months for core implementation. This compressed timeline supports rapid deployment and early operational insights.

3. **System Design and Configuration**

   3.1 Infrastructure Optimization: Leveraging the current system infrastructure with minor upgrades, the pilot project will utilize available server resources, such as processor cores, RAM, and storage, with a dedicated domain for the SCED pilot.

   3.2 GAMS Optimization Module Integration: Integration of the already developed GAMS optimization module will enable 15-minute interval dispatch calculations, with outputs stored in a selected database for further analysis.

   3.3 Data Traffic and Interface

   - **Data Flow:** Initiate one-way data traffic, with a separate database for SCED output.
   - **Excel Interface:** Facilitate data transfer between the current system and the GAMS module.
   - **Database Selection:** Use Oracle or an open-source database like MongoDB, with front-end tools for data visualization.

4. **Implementing Agency**
   - **Agency Selection**: The present service provided maintaining the system, has proven capabilities in system configuration and data extraction, aligning them well for the pilot phase.
   - **Responsibilities:** The service provider will modify data extraction to block-wise processing and develop visualization tools for output analysis and report generation.
   - The optimization module configuration, performance monitoring, and analysis could be monitored in-house

- Report preparation and analysis and review by experts

5. **Implementation Timeline and Phases:** To ensure timely completion, the implementation plan is divided into three primary phases, each with specific milestones and duration.

   Phase 1: System Design (1 Month)

- Design and configure system architecture for SCED.
- Confirm hardware availability and make necessary configurations.

   Phase 2: Implementing Agency Finalization (1 Month)

- Formalize agreements
- Set up collaboration for seamless execution.

   Phase 3: Pilot Implementation (4 Months)

- Install and configure the optimization module for operational readiness.
- Develop the visualization interface, enabling real-time analysis and management reporting.

6. **Total Project Timeline: 6 Months**

	Activity	Time
1.	System Design	1 Month
2.	Firming of Implementing Agency	1 Month
3.	Pilot Implementation	4 Months
4.	Total Project Duration	6 Months

7. **Post-Pilot Review and Expansion Potential:** Upon successful pilot completion, results will guide further system refinements. The project will then evaluate the feasibility of expanding the SCED pilot for broader intra- and inter-state applications.

Annexure – XI

Input data format and output data requirements

1. Input Data Format

Excel could be used as input data.

Separate sheets could be prepared as below:

1. Generator parameter (Block-wise)
   i. Generator Name
   ii. Generator type (under MoD or not)
   iii. Variable cost (VC)
2. Declared Capability (DC / Pmax)
3. Technical Minimum (Pmin)
4. Ramp-up
5. Ramp-down
6. Generator schedule
7. Discom drawl schedule data as per contract
8. Discom Demand parameter (block-wise)
9. Discom Allocation

2. Data validation and checking

3. Output data

The following output is to be extracted:

1. Optimized Generator Schedule
2. Discom drawl schedule
3. Discom wise System Marginal Price (SMP)
4. Centralized Marginal Price (SMP)
5. Marginal price of Generator Pmax
6. Marginal Price of generator Pmin
7. Marginal price of Ramp-up
8. Marginal price of Ramp-down
9. Comparison of Central SMP and Are SMP
10. Comparison of SMP and MCP of the corresponding duration
11. No. of perturbations reduced after optimization
12. Total Cost savings
13. Block-wise cost saving
14. Block-wise difference if station-wise generation after optimization
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