COUPLING OF POWER EXCHANGES ALONG WITH SCED IN INDIA:

INTEGRATION OF MARKET SEGMENTS THROUGH OPTIMIZATION

Submission to the Central Electricity Regulatory Commission

Staff Paper on Market Coupling

South Asian Regional Unit

Energy and Extractives

World Bank

October 2023

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SUMMARY

This paper discusses the potential benefits of coupling Power Exchanges (PX) with the scheduling of interstate generators (ISGS) undertaken by Grid-India through its Security Constrained Economic Dispatch (SCED) mechanism, in the Indian Power System. The fundamental premise for the analysis presented here is to show that there is potentially significant arbitrage opportunity among interstate generators with regulated tariff and their counterparts participating in the PXs that can be elicited by adding a layer of market coupling. This coupling across the incumbent Real-Time Market (RTM) and interstate SCED should be implementable through a Market Coupling Operator (MCO) with relative ease. It may also be extended to the day-ahead market (DAM) in due course of time when the Day Ahead SCED/SCUC (Security Constrained Unit Commitment) is operationalized.

A preliminary analysis using the publicly available SCED and IEX data for August 1, 2022, to July 31, 2023, shows that the total annual benefits of coupling are close to Rs 1000 crores on RTM alone, i.e., daily benefits around Rs 3 crores/day. There would have been significant increase in liquidity on PX of 2,266 MUs or ~10% of annual trade on RTM which mainly comes from significant utilization of cheaper SCED generation that can be sold on PX of ~ 4,000 MUs during high price hours and there would also be the reverse opportunity for PX power of just below 3500 MU when prices are below SCED System Marginal Price (SMP). There will be a significant drop in price volatility – standard deviation of prices drops by a factor of 3.5 from Rs 2,141/MWh to Rs 639/MWh. Price cap events drop even more significantly by a factor of nearly 6 for a price cap of Rs 10,000/MWh and as high as 22-fold for a price cap of Rs. 12,000/MWh. The analysis has also been extended to consider optimization across SCUC and the DAM. Due to higher volume of trading on the DAM as well as a wider range of demand-supply bidding on it – annual benefits for the same year would have been substantially higher at Rs 2,173 crores.

Apart from potential benefits, there are other positive attributes, namely, the simplification of transmission corridor allocation, scope for further integration with state level SCEDs, scope for full-scale co-optimization of ancillary services to render the system more reliable, reduced curtailment of wind and solar capacities by harnessing flexibility over larger balancing areas, and, in the long run, facilitate a regional market to integrate cross-`border trade. As this is largely an extension of the SCED optimization to add an additional layer of coupling with it, the process should be relatively inexpensive to pilot and implement. It should also be easy to temporarily, or even permanently, suspend the coupling layer in extraneous circumstances should it interfere with efficient market operation or another policy. Value preservation is a key objective to ensure that market coupling implementation safeguards the value, innovation, and profitability independence of existing power exchanges.

In summary, the analysis makes a very strong case in favor of coupling SCED with PXs and also expand the scope of the current scope of SCED to include day ahead SCUC to elicit substantially higher benefits, extension of SCED/SCUC to state levels, and beyond.

INTRODUCTION[1]

The Indian electricity market currently comprises three Power Exchanges (PX or Exchange), namely, the Indian Energy Exchange Ltd. (IEX), the Power Exchange of India Ltd. (PXIL) and the Hindustan Power Exchange Ltd. (HPX), operating under the framework of Power Market Regulations (PMR) 2021. The collective trade across these three PXs, each of which operates at a national level, accounts for only ~7% of the total generation in the system with less than 10 GW being traded on average on a typical day. More than 90% of the generation is locked in long-term contracts predominantly between the state-owned generation and DISCOMs. There is a non-market Security Constrained Economic Dispatch (SCED) mechanism that the National Load Dispatch Center (NLDC) uses to optimize the unscheduled /Un requisitioned surplus (URS) generation from the Interstate /central sector generators (~50-60 GW capacity on a typical day). SCED has subsequently been also trialed in some of the states. A more extensive Market Based Economic Dispatch (MBED) idea, akin to a gross pool with full participation of all states and central sector generators, has been pursued since 2018 with plans for piloting the market in 2023. However, this has not yet been implemented.

The presence of independent multiple PXs was intended to create competition and encourage innovation of products. It, however, also led to different prices being realized on the PXs, which in part depends on the level of liquidity. In the core Day Ahead and Real Time Market (DAM and RTM), IEX has accounted for more than 99% of the volume traded in the Exchanges in 2022 (and has persistently maintained a similar market share over the preceding years since its inception 15 years ago). Since the NLDC has to make *a priori* allocation of inter-state transmission capacity for various players including the PXs, there is also a potential inefficiency issue if sub optimal transmission capacity is allocated to an Exchange with unused capacity in one while another Exchange sees significant price separation across bid areas (zones). This has been an issue in the past following which a pro-rata allocation of capacity based on trade volume was introduced. The PMR 2021 allowed for the provision of Market Coupling to (a) to create a single price across the Exchanges for a 15-minute time block in a bid area (b) allow optimal utilization of inter-state transmission corridors without requiring them to be allocated across the Exchanges; and thereby (c) increase social welfare relative to the *status quo*. There are pros and cons of market coupling that have been discussed in a recent CERC Staff Paper.[2] One of the reservations against market coupling is the simple fact that IEX already accounts for 99% share in the core markets and therefore the benefits are expected to be low with little improvements in overall prices/welfare or yield a discernible impact on the transmission utilization. Yet, there may be downsides as it may diminish the role of individual Exchanges, limit the complexity of products that can be accommodated in a coupled market, and generally foreclose innovations in product design and associated clearing algorithms.

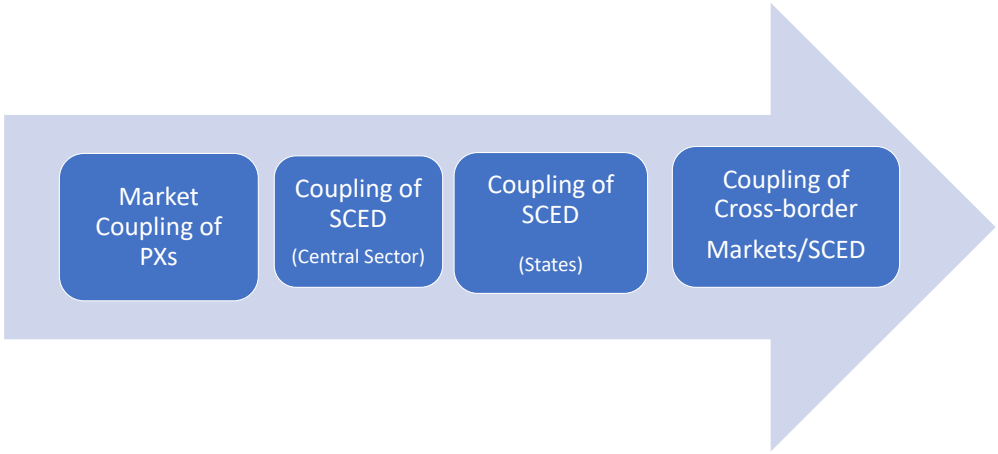
[1] The Bank team wishes to acknowledge many useful discussions with CEA, CERC, Grid-India, IEX, Power Foundation, PTC, participants in two recent workshops organized by IEEMA and IEEFA on the topic. We are grateful for the feedbacks received on the initial findings of our analysis that has helped to shape the analysis and the salient qualitative issues that are discussed in the section titled "Discussion on Issues that go beyond current analysis".

[2] CERC, Staff Paper on Market Coupling, August 2023.

STAGES OF COUPLING

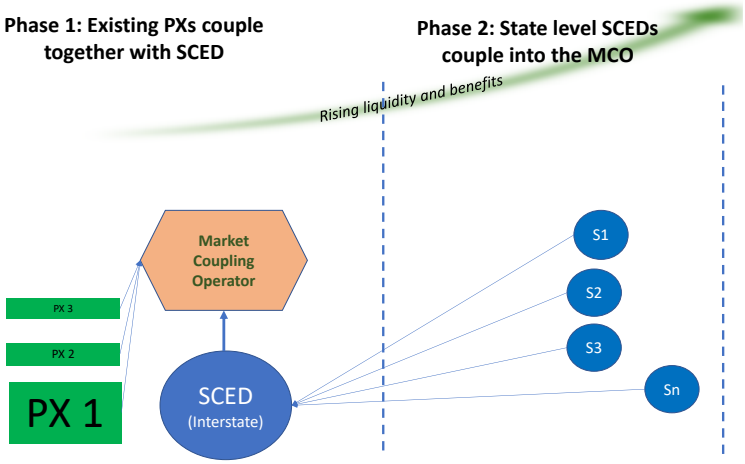
The discussion thus far has not fully embraced the idea of coupling that goes beyond PXs to include SCED of interstate generating stations and potentially SCEDs of individual states (Forum of Regulators, 2020) and even cross-border trade with Bangladesh, Nepal and Bhutan, with progressively higher level of benefits (Figure 1)

Figure 1 Four stages of coupling



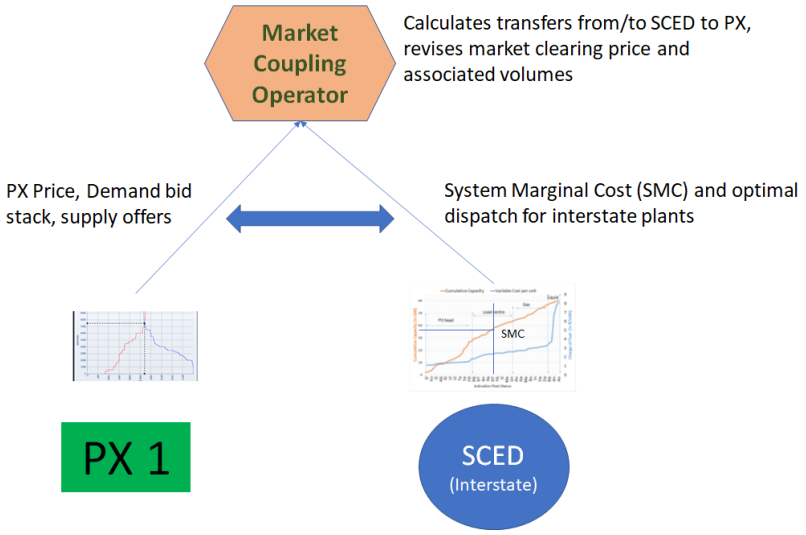
In fact, the concern over lack of sufficient benefits of coupling benefits may be overcome if the incumbent SCED for interstate generating stations is coupled in some fashion as the volume in SCED is several folds higher than the collective volume in three Exchanges. As Figure 2 shows, progressive coupling beyond PXs of (1) SCED-RTM (followed by SCUC-DAM), and (2) state level SCEDs in Phase 2 could also allow evolution of a national market that has been envisioned by CERC and various other stakeholders including the Multilateral Development Banks. The scope of coupling in the short to medium term may focus on the domestic market starting with the RTM.

Figure 2 Progressive coupling



Depending on how the coupling process is structured, it may also be possible to address some of the other concerns that have been raised on preserving the role of the PXs, innovation, etc. As Figure 3 shows, one potential coupling mechanism around the incumbent SCED and PXs is for both of these processes to retain the independent price discovery mechanisms, and add only a thin layer of optimization at the market coupling stage to calculate transfers across the SCED and PX. This will lead a "coupled" market clearing price that should settle in between the SCED System Marginal Price/Cost (SMP/SMC) and PX Market Clearing Price (MCP) before coupling.

Figure 3 Potential coupling mechanism



RELATIONSHIP BETWEEN SCED AND MARKET

It may be worth preempting a key point that we discuss in more detail later on the relevance of integrating SCED in a "marketplace" as this simple point seems to be surprisingly susceptible to misinterpretation. **SCED is NOT detached from the concept of a market**. **All markets attempt to optimize the dispatch in one form or another and has a process similar to SCED at its heart**. Markets, in their barest form as in cost-based pools, in fact employs a cost-based dispatch identical to the SCED and we give an example for the Korea Power Exchange in a later part of the discussion. More advanced markets in parts of the US, Canada, Australia, Singapore, New Zealand, etc. employ a security constrained co-optimized bid-based version of the SCED (and it is called SCED too in some of these cases). This is entirely in the spirit of the SCED process employed by Grid India with the difference that (variable) costs are replaced by bids which of course has significant connotation and renders it as the best solution. The proposal to connect SCED with PX should be seen as the second-best solution that has a far better chance of being implemented than a pan-India gross pool akin to US and other markets. It does not preclude, and in fact paves the way for, a liquid wholesale market as we discuss in more detail. The benefits of coupling even before we get to that stage are indeed numerous as we discuss in the next subsection.

BENEFITS OF COUPLING

In addition to a gain in social welfare and lower prices, there are going to be multiple other benefits of coupling including lower price volatility (and less frequent hitting of price caps), substantial ease in managing congestion, the potential to manage ancillary services, directly and indirectly disciplining bidding behavior in the PX, etc. If done right, progressive coupling may not only elicit greater liquidity and benefits from a bigger market, but also lay the foundation for a single market as was envisioned by CERC . In summary, we see the following set of benefits from market coupling:

1. Enhance the scope of optimization by connecting hitherto fragmented segments of the market;
2. Increase social welfare and discover robust and right prices;
3. Improve liquidity in the market;
4. Reduce price volatility and occurrences of extreme price events;
5. Creation of a single price for each time block. This reduces audit problems for DISCOMs who could end up procuring power from an exchange that has a higher price;
6. Ease of system operation and security considerations;
7. Intensify competition, lower market power, better market monitoring;
8. Avoid inefficient pro-rated allocation of transmission corridors during congestion;
9. Facilitate trading of ancillary services in a bigger control area;
10. Pave the way for introduction of SCED processes in the states; and
11. Further integrate state generators into PXs, as well as cross-border trades.

The analysis presented in this work is intended to complement the CERC Staff Paper and the ongoing discussion on the subject with analytical work to show the benefits of PX and SCED coupling. These benefits can be assessed by looking at past trades and prices as well as through forward-looking market simulations and price forecasts. The former is significantly easier even if they provide an estimate of foregone opportunities rather than future potential.

The remainder of this paper presents a preliminary analysis of benefits looking at the actual SCED dispatch and IEX aggregate demand-supply curves over August 1, 2022, to July 31, 2023, for both the RTM and DAM segments. This is followed by a discussion on a number of potential technical, economic and regulatory issues that the analysis currently does not handle to provide some insights before concluding with a set of recommendations on the way forward to undertake a more comprehensive analysis and pilots.

METHODOLOGY

A HIGH-LEVEL DESCRIPTION OF THE METHODOLOGY: SCED-RTM

The methodology used for the present analysis follows a simplified market clearing mechanism to mimic the (a) PX RTM process using aggregated demand bids and supply offers to calculate the Market Clearing Price (MCP), (b) a simple merit order stack to simulate SCED and the associated System Marginal Price (SMP), and then (c) merge the two to form a coupled market wherein supply and demand from both segments are combined. Since MCP and SMP will generally differ for any given time block, even if the difference may not necessarily be significant, the coupling process through the combined supply stack would always find a "coupled price" that sits somewhere between the MCP and SMP. **It is important to note that the cost imposed by an increase in SMP does not have the same implication as that for MCP as the ISGS generators are *not* paid the SMP but are compensated for their variable costs only.**

The reshuffling of supply and demand bids is cast as a linear programming model and implemented using General Algebraic Modeling System (GAMS). Annexure 1 to this note includes the GAMS code used for the SCED-RTM analysis.

The model maximizes social welfare for each block of time (since we deal with RTM, where markets are cleared in each block of time separately) for the entire year. Social welfare maximization is subject to regular market clearing constraints.

- Social welfare is the sum of consumer surplus and producer surplus.
- Consumer surplus is defined as the difference between what the consumers are willing to pay (as reflected by the demand curve) and the total cost of purchase at the MCP.
- The producer surplus is the difference between what the producers receive from the market and their actual marginal costs of production (as reflected in their supply curves).

A number of the technical constraints on generation including ramping, minimum up/down time and minimum loading are ignored in the SCED-RTM analysis which is restricted to a single time-block. The SCUC-DAM analysis that is presented in a later section incorporates these constraints.

OVERVIEW OF INPUTS AND SCENARIOS ANALYZED

Input data for this analysis for August 1, 2022 – July 31, 2023, is obtained from:

1. IEX website for prices and aggregated demand and supply curves; https://www.iexindia.com/marketdata/rtm_demandsupply.aspx
2. SCED merit order stack by month; https://posoco.in/reports/monthly-reports/monthly-reports-2022-23/ https://posoco.in/reports/as3-details/
3. SCED demand is approximated and scaled using the national demand profile. https://posoco.in/reports/monthly-reports/monthly-reports-2022-23/

The following three scenarios are modeled:[3]

- **IEX only:** (based on discretized supply and demand curves available on IEX website (https://www.iexindia.com/marketdata/rtm_demandsupply.aspx). The data is available in the following format for each time block in coarse (Thousand rupee steps for prices and associated average demand):

Time Block	Price (in Rs./MWh)	Buy / Demand (in MW)	Sell / Supply (in MW)
13:30-13:45	0-1000	4282.8	489.3
13:30-13:45	1001-2000	4265.5	1582.66
13:30-13:45	2001-3000	4184.8	2480.88
13:30-13:45	3001-4000	3892.7	3161.93
13:30-13:45	4001-5000	3182.9	4147.36
13:30-13:45	5001-6000	2903.1	5856.19
13:30-13:45	6001-7000	2428.8	6857.61
13:30-13:45	7001-8000	2097.4	6911.04
13:30-13:45	8001-9000	2052.6	6932.47
13:30-13:45	9001-10000	2052.6	6953.9

- **SCED only**: SCED supply stacks are available for each month at (for example): https://posoco.in/download/ancillary-services-providers-sced-generator-rate-from-16th-aug23-to-15th-sept23/?wpdmdl=53052 The demand for each block of time was assumed to vary between 40 GW – 60 GW in tandem scaled with the national demand. The data on national demand was obtained for the duration of the study period from https://energymarketanalytics.com/

- **Coupled IEX and SCED**: this scenario effectively combines supply stacks of SCED and that of the PXs, as well as demand stacks.

The model is flexible to consider any other constraints as desired in the interest of a smooth transition, and acceptability across stakeholders, e.g., a limit on the level of transfer from SCED→PX or in the reverse direction. Imposing such constraints leads to a loss of social welfare.

CAVEATS THAT APPLY

In reality, there are many additional complications namely, block bids in a (Day Ahead) market, ramping and reserve related constraints in the SCED optimization that are not considered as part of the current analysis. This would render the estimates of benefits to be somewhat optimistic as the block bid, reserve and ramping constraints may restrict the transfers that are allowed in the simple model. For instance, if there is a cheaper thermal generator with seemingly surplus capacity in SCED, the incumbent model will fully transfer that capacity to meet demand in PX. But in reality, the generator may be ramp-constrained, or is needed to provide reserve response, and as such not all of its surplus be available to be cleared in the PX. The results from the current analysis may therefore be an overestimation of benefits in this regard. That said, these constraints do not bind for a significant part of the time and any degree of overestimation is likely to be small. As already noted, we have considered

[3] We have also considered a fourth scenario wherein the volume on PX is "conserved" following coupling for cases when there is a transfer from PX→SCED when the PX MCP is lower than the SMP. However, this implicitly assumes an uplift payment to demand that would need to be forced to stay on at a higher coupled MCP. This is probably an unrealistic assumption and as such the scenario has not been included in the analysis.

some of these constraints in the context of SCUC-DAM analysis that are discussed in a subsequent section.

Secondly, there are also other limitations on data, especially on the demand-supply curves for PX/IEX that rely on the coarse aggregated demand and supply curves with price steps of Rs 1000/MWh. The resultant PX prices are therefore approximate, and as it turns out, significant underestimates for prices > Rs 6000/MWh and overestimates prices at the lower end. The benefits of SCED→PX transfers are therefore also underestimated for the high price and that for the PX→SCED transfers are also underestimates for the lower prices.

Thirdly, the current analysis deliberately omitted extreme price/demand time blocks and that effectively significantly curtails benefits limiting it to only those time blocks that have demand/prices in a narrower range.

Finally, we also needed assumptions around how much volume can be shifted across SCED and PX especially in the SCED→PX direction as there is potentially spurious demand on PX of several GW at price cap that may or may not transpire in reality. We have therefore clamped the transfer somewhat arbitrarily at 5 GW maximum in both directions, which also means we forego part of the social welfare gains that would have been associated with transfers beyond these (arbitrary) limits.

MOTIVATING EXAMPLES

Figure 4 shows the modeling process for a case when PX (IEX in this example) price exceeds the SCED SMP. SCED sell (or merit order) stack meets the vertical (perfectly inelastic) demand at the SMP. IEX demand-supply is typically an order of magnitude smaller than that of SCED as shown towards the left of the plot (green and red lines for demand and supply, respectively). As some of the IEX supply bids are cheaper than some of the SCED generators that are high on the merit order, the combined/coupled supply curve shifts down and right (orange line). The combined demand curve also shifts to the right essentially adding the SCED demand getting attached to the IEX demand curve. The resultant coupled price in this case ends up marginally higher than the SCED SMP but well below the IEX MCP. The transfer from SCED→IEX is significant, most of which displaces IEX bids that are more expensive. Since some of the additional demand bids are also cleared due to lower prices, there is a net increase in IEX volume as shown in the figure.

Figure 4 IEX, SCED and Market Coupling Illustrative Example 1: MCP > SMP

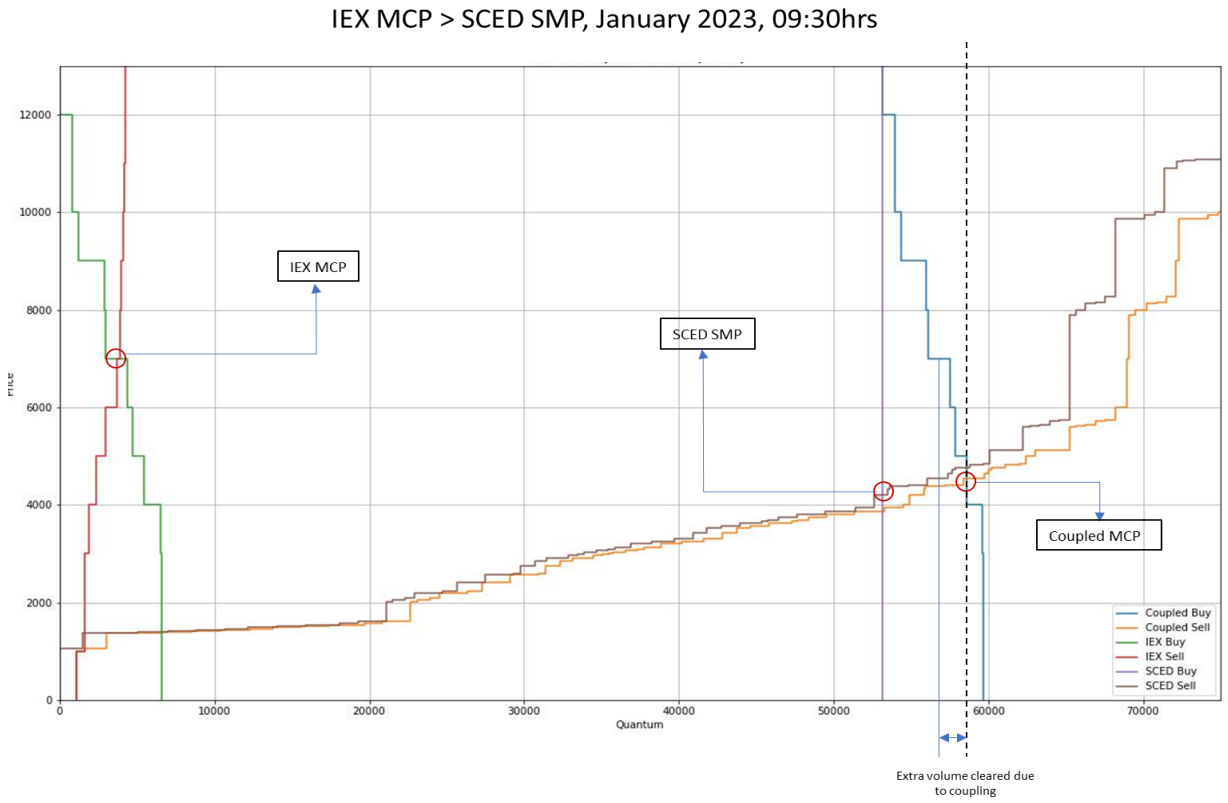
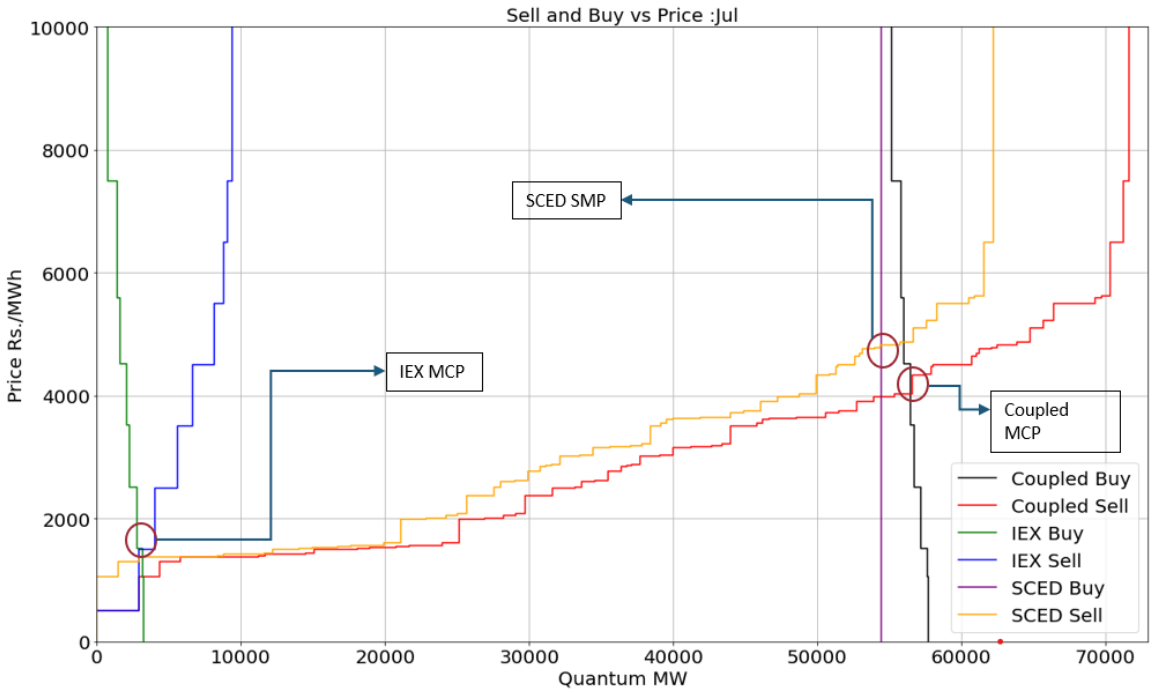


Figure 5 shows the transfer in the reverse direction from IEX→SCED as the IEX MCP was lower than the SCED SMP. The combined supply curve drops in this instance because of cheaper bids in the PX and the coupled price drops below SCED SMP, albeit the higher volume in SCED means this drop is not as steep as the one we see in the previous example. As the coupled price ends up higher than the original IEX price, some of the price responsive demand bids are no longer cleared. As some of the IEX bids effectively meet the demand that would have otherwise been met through more expensive ISGS generators *and* part of the demand is lost due to higher price faced by the PX in the coupled case, PX volume will shrink. This outcome maximizes social welfare (benefits) gain. While some extra demand was being served on the PX absent coupling, higher coupled prices clear additional supply in the PX that replaces costlier SCED generators. Overall, the costs of power system operation decline for the coupled scenario.

Figure 5 IEX, SCED and Market Coupling Illustrative Example 1: MCP < SMP



Annexure 2 provides five sample cases including the key numbers for market clearing volumes (MCV) and prices (MCP) before and after coupling.

All of the cases discussed so far including the ones presented in the Appendix are relatively benign ones that do not bring to light one of the arcane aspects of bidding in the PXs. Bidding behavior and prices on the PXs under stressed condition are particularly noteworthy as coupling to lower prices can be particularly beneficial under those circumstances and avoid hitting the price cap. Bids on IEX in recent years have shown a trend with significant overbidding by demand side at the price cap and the supply offers often shrinking at the same time, leaving a gulf between demand and supply with price set at the cap. Figure 6 shows a recent example from October 11, 2023 (830-845 pm) wherein demand bids at price cap (of Rs 10,000/MWh) added to close to 24 GW and supply stacks quickly escalated to the cap level after 3 GW leaving a gap of 21 GW. If the ISGS system has capacity sitting well under Rs 10,000/MWh as is usually the case (see the previous two figures), this would discipline the bidding behavior and would probably also provide comfort to the demand side not to unduly inflate their demand. The upshot in many such instances would be prices falling (well) below the price cap settling closer to the SCED SMP with transfer from the ISGS system to the PX. As our analysis presented in a later part of the report demonstrates, price cap events over the last year would have gone down by an order of magnitude had a coupling mechanism be put in place.

Figure 6 Extreme bidding behavior? [Price event: 11 Oct, 830-845 pm]

Source: IEX website

DISCUSSION OF RESULTS

This section gives a summary of the key findings of the analysis conducted for Aug 1, 2022 – July 31, 2023 using IEX and SCED data at 15-minute time block (TB) resolution to calculate SCED SMP, IEX MCP (from aggregate demand-supply curves), Coupled MCP, transfers in both direction, resultant social welfare increase ("benefits" of coupling) and changes in market liquidity.

The current analysis is restricted to the RTM segment only at this stage.

KEY BENEFITS FROM SCED-RTM

Table 1 shows the IEX/PX1[4], SCED and then PX1+SCED Coupled attributes. Annual benefits represent the social welfare increase (producer surplus increase in PX1 and SCED, plus consumer surplus in PX1). These benefits are primarily derived from an efficient dispatch as cheaper surplus capacity in SCED or PX1 can be utilized better to meet total demand faced by the two market segments.

Table 1 Benefits of coupling: SCED and RTM

	PX1	SCED	PX1+SCED Coupled
	A	B	C
Annual Benefits (Rs crores)	N/A	N/A	1067
Daily benefits range and average			Rs 4 lakhs to 13 crores; Rs 3.17 crores/day
Average price (Rs/MWh)	~Rs. 5000/MWh	Rs. 4608/MWh	Rs. 4679/MWh (6% lower than average PX1 prices)
MCP PX/ SMP SCED (Rs/MWh)	500-11500	3503 - 5537	3391-11500
Annual transfer (GWh)	-	-	SCED → PX1 3964 MUs (43 % of the time) PX1 → SCED 3480 MUs (57 % of the time)
Volatility/St Dev Rs/MWh	2141	374	639 (71% reduction with respect to PX1)
Cap hit % times	4.8%	-	0.6%
Number of times Cap	561 for Rs 12 price cap 880 for Rs 10 price cap		25 for Rs 12 price cap 151 for Rs 10 price cap
Number of Buy Bids/Sell Bids (average per timeblock)	~300 (number of buyers) ~70 (number of sellers)	No. Of generators = 66	HHI improves considerably when PX1 and SCED are coupled

- Benefits over the 35,040 time blocks for the year add up to Rs 1,067 crores or over Rs 3 crores per day. There is massive variability of the benefits over the days that range from Rs 4 lakhs/day

[4] We have referred to IEX and PX1 interchangeably in the discussion in this section because the numerical analysis has been carried out using publicly available IEX data to illustrate estimate of benefits and price impacts. The analysis can and should be repeated for other PXs.

to as high as Rs 13 crores on days when there are high prices on IEX with significant underutilized thermal in the ISGS fleet;
As noted, before, prices in IEX may go up or down depending upon the direction of arbitrage. On balance, there is a net transfer from SCED to IEX given the specific year that saw high and highly volatile prices on PX and Coupled MCP is lower by approximately Rs 321/MWh or 6% relative the calculated IEX prices. This is achieved predominantly through SCED→IEX transfer close to 4,000 MU;

- While prices go down on average, coupling also helps to avoid extreme low prices as some generators struggle to stay on and offer prices as low as Rs 500/MWh in that effort. This generation can be "soaked up" in the ISGS system and prices during off-peak hours increas to lead to a tighter and more stable price range in the Coupled regime. The standard deviation of prices drops by a factor of 3.5 from Rs 2,141/MWh in IEX down to Rs 639/MWh in the Coupled regime;

- Prices in IEX sat at the price cap for a total of 1,441 time blocks which would come down to 176 in the Coupled scenario, i.e., a reduction by a factor of 8; and

- We note that the coupled market will include a substantially higher number of players that would also introduce a greater level of competition.

DISTRIBUTION OF BENEFITS, PRICES AND TRANSFERS: SCED AND RTM

Figure 7 shows the benefits for each time block from the highest to the lowest level. As the figure makes it abundantly clear, the high value time blocks are less than 10% of the total time blocks that are often associated with high prices at or close to price cap in the IEX with significant volume to spare from the ISGS stations to supplant for high prices supply bids (up to a 5 GW cap).

Figure 7 Cumulative distribution of social welfare increase ("benefits")

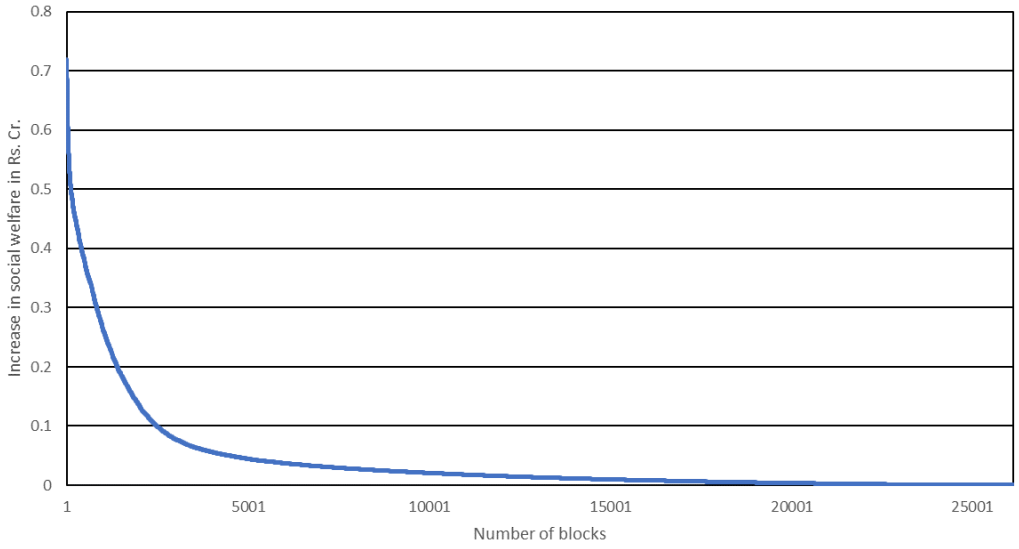
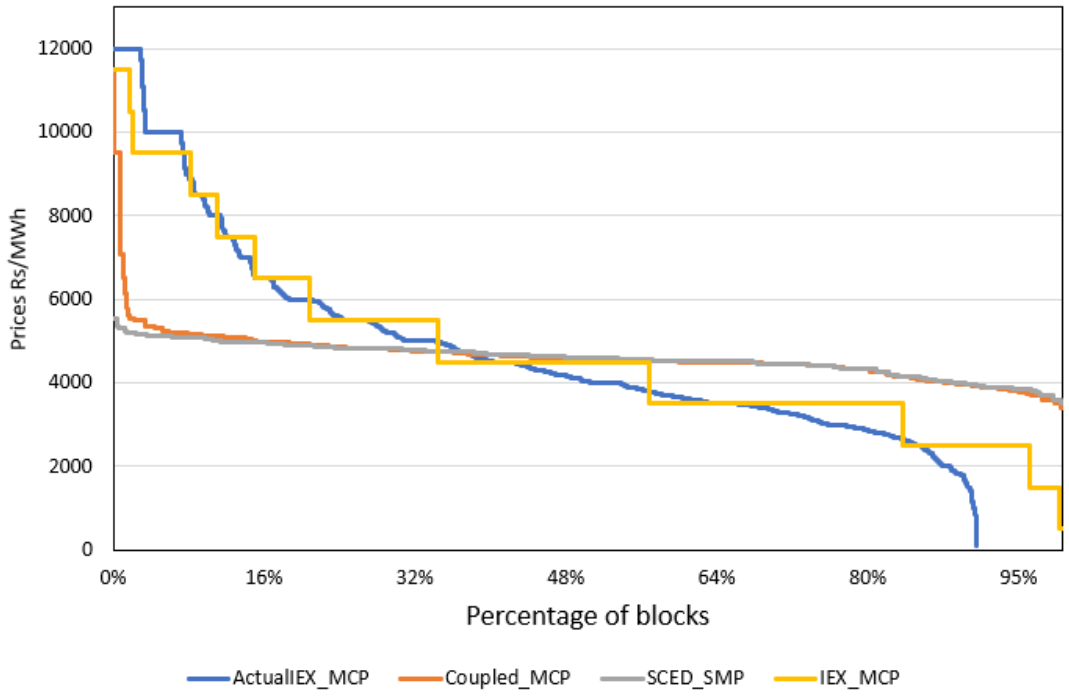


Figure 8 shows the price duration curves that explain how high IEX MCPs (at the left end of the plot) can drop massively to less than half the original price through coupling. If a price cap event of Rs 12,000/MWh can be avoided by replacing the IEX supply bid with SCED supply at Rs 6,000/MWh, and there is up to 5,000 MW available at that price, the resultant social welfare increase is Rs 3 crores for an hour or Rs 0.75 crore for a 15-minute time block. This is what explains the peak period benefits in the preceding plot. It should be noted that the bulk of the savings occur for less than 10% of the time blocks. A salient aspect of the Coupled MCP is also that the off-peak prices lift significantly above the IEX prices which indicates significant opportunity to transfer power from IEX → SCED segment to take advantage of low-cost supply in the Exchanges for the off-peak periods.

This outcome, however, needs to be cross-checked against minimum loading and ramping constraints for the ISGS generators – some considerations we have covered in SCUC-DAM analysis. It is possible, for instance, that the minimum loading of coal generators during off-peak will not necessarily allow the ISGS generation to be backed off as much as needed (by up to 5 GW in our current assumption).

Another limitation of the study is the approximation of the IEX MCP (Actual) using the aggregate demand-supply curve (IEX MCP line). As we generally underestimate the IEX prices for the high price range, the benefits are also underestimated. This can be overcome if more granular demand-supply bid data is made available for the study.

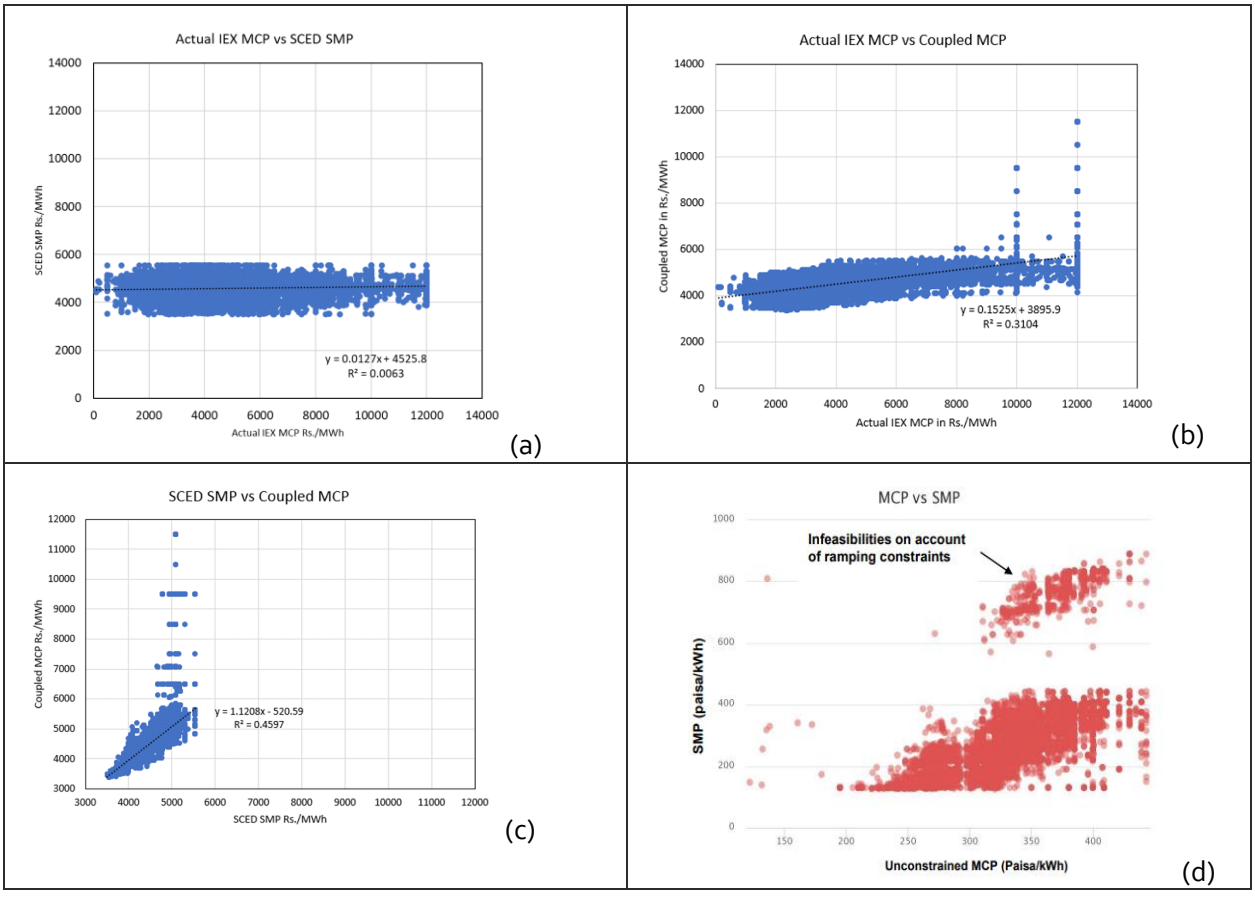
Figure 8 Price duration curves for IEX (Actual), IEX (modeled), SCED SMP and Coupled MCP



CORRELATION BETWEEN MARKET PRICES AND SYSTEM MARGINAL COSTS

Figure 9 brings out an interesting change in correlation patterns between SMP and MCP. Although these prices represent different fleets of generators, they are both predominantly coal generators that serve similar demand profiles. As such, these prices are expected to be correlated as high prices in one segment should also be associated with high prices in the other segment. However, as Plot (a) shows, there is virtually no correlation between IEX MCP (actual) and SCED SMP for 2022/23. Plot (d) from 2019 cited from POSOCO (2019) SCED report[5], shows that these prices were in fact reasonably well correlated (barring infeasible outcomes due to ramp constraint violations that show up as very high price aberrations) – a pattern that seems to have been disrupted over the last 12 months as very high prices continued in IEX while SCED SMP has largely remained unchanged. Coupled MCPs seem to restore the correlation as these prices remove a significant part of the high price events and brings prices much closer to the SCED SMPs.

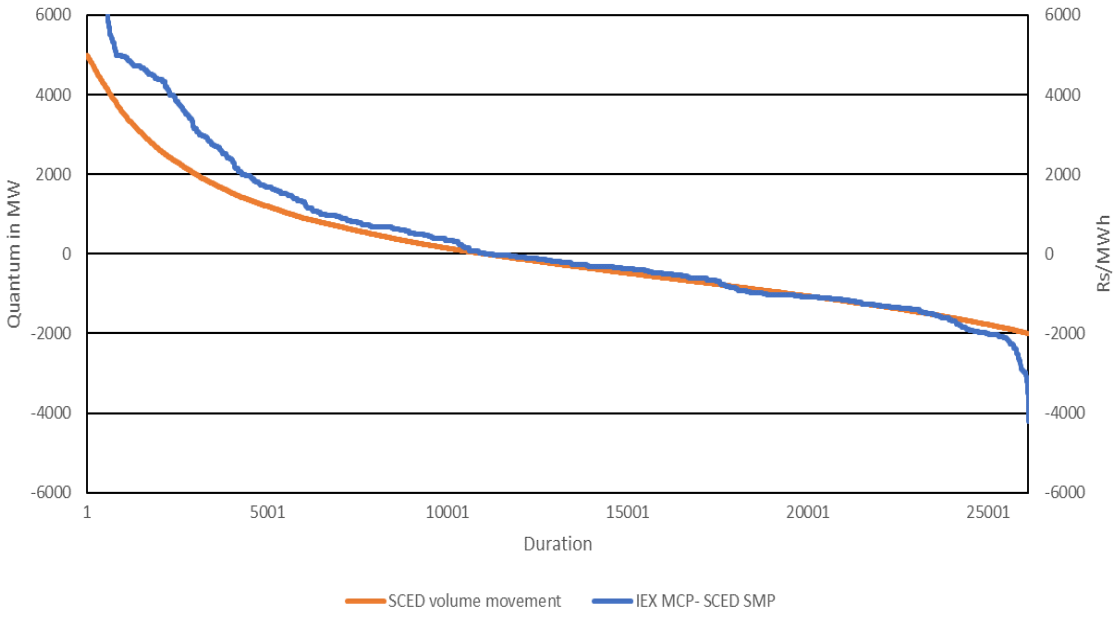
Figure 9 Correlation between market (MCP) and SCED SMP



[5] https://posoco.in/wp-content/uploads/2022/04/Detailed-Feedback-on-SCED-Mar-2022.pdf

Figure 10 shows the SCED to IEX flows for the Coupled scenarios and how it is strongly correlated to the MCP vs SMP differences especially if demand could adjust freely on IEX in response to prices. Note that volume of transfer is clamped in both directions to 5 GW.

Figure 10 SCED to IEX volume transfer



DISCUSSION ON SCUC-DAM

The Indian Electricity Grid Code (IEGC) for 2023 mandates the implementation of Security Constrained Unit Commitment (SCUC) on both a day-ahead basis (D-1) and, in specific cases, on a D-3 basis. In the SCUC process, only gas-based generators and certain coal-based generators (with variable costs equal to or greater than Rs 4,000/MWh and employing supercritical technology) were taken into consideration for unit commitment. Other generators were assessed based on their ability to adjust their power output (ramp-up/down) and technical minimum constraints.

Data for the Day-Ahead Market (DAM) from the Indian Energy Exchange (IEX) was extracted from their website, like the Real-Time Market (RTM) simulations. Consequently, data on block bids is not available. Out of the 365 days in a year, spanning from August 01, 2022, to July 31, 2023, a subset of 31 sample days was chosen through k-medoids clustering. The clustering process was based on several factors, including peak demand, energy supplied, market clearing price (MCP), and market clearing volume (MCV) price vectors, the chronological pattern of the national demand curve, and the inter-time block changes in demand.

It should be noted that the analysis structured here effectively subsumes benefits from:

1. **Optimal unit commitment;**

2. **Optimal dispatch through the SCED dispatch; and**
3. **Additional reserve that may become available under the coupled scenario.**

In other words, the present analysis effectively reports the benefits of coupling of ISGS commitment/dispatch with the PX assuming both commitment and dispatch are already optimized and there is no value attached to any surplus reserve that may eventuate with greater number of units being committed for ISGS to meet additional demand in PX. While the dispatch is optimized on the margin through Grid India's SCED process (i.e., the un-requisitioned surplus part), there is currently no mechanism to optimize day-ahead unit commitment. There is potentially significant additional savings from the UC optimization that is subsumed in the calculation. This is a separate exercise but one that should be conducted to assess these benefits as it may provide additional motivation to fast-track implementation of SCUC (including state generators). Coupling creates a bigger pool and it would allow for effective sharing of reserve across the hitherto isolated segments of PX and ISGS systems. Although we do not present the full results here, we do notice that the coupled scenario may in some time-blocks render up to 2 GW of additional reserve available as generators are committed in ISGS to target high price events but are not necessarily fully utilized for all other time-blocks. The SCUC process, as implemented, also has some practical limitations that may lead to overestimation of benefits. For instance, we have not considered plant specific constraints including fuel availability and effectively assume all units that are under the purview of the SCED process are always fuel-ready and can be started up whenever needed and potentially many more times in a year than they were typically started up historically. On the other hand, there are intrinsic flexibilities in the system such as hydro (and cross-border hydro) that we have not considered in the analysis that may obviate the need for reliance on fuel-limited plants or frequent toggling of units. Extending the SCUC process to states would further create a much larger pool at a national level with commensurate significant increase in flexibility too.

In essence, the topic of SCUC even before we go to coupling, has many complex issues that merit a proper study and processes to be developed. Nevertheless, the objective of the present analysis is to present a reasonable approximation of benefits of coupling SCUC-DAM using a well-established methodology and best available dataset.

KEY BENEFITS OF SCUC-DAM

It is important to note that Security Constrained Unit Commitment (SCUC) has not yet been fully implemented although it is already legislated and will eventually be introduced. The results presented here should therefore be interpreted as indicative of outcomes that are expected when it is introduced. The optimization models for IEX , and SCUC were run (with all the limitations such as block bids not being available, and based on the IEX data available in public domain, but technical constraints on ramping, minimum loading, minimum up time and minimum down times are included in the SCUC-DAM analysis). Notwithstanding the limitations on the data and approximations made (e.g., sample days) – the benefits are very significant as we discuss next. One of our key recommendations is therefore for CERC to take up studies with more detailed data available from the power exchanges. It is important to note that the outcomes are influenced by specific assumptions, such as the permissible number of generators that can be committed and, consequently, the application of minimum up/down time constraints. Creation of a better dataset ratified by the generators and relevant authorities will

need to be part of any future analysis. The modeling analysis at this stage does not consider the provision of reserves since reserves were not obligatory during the period we analyzed. The results do indicate that coupling in some cases will enable certain expensive gas and coal-fired generators to operate for two shifts in a day and be available for supplying spinning reserves. As we have discussed before, it is a benefit that we have not considered in our analysis.

Table 2 Benefits of coupling: SCUC and DAM

	PX1/IEX	SCUC	PX1/IEX+SCUC Coupled
	A	B	C
Annual Benefits (Rs Crore)	NA	NA	2173 Crores
Daily Benefits Range and Average			Benefits for extreme cases: INR -22 Lakhs per day (11 days*) INR 60 Lakhs per day (15 days*) INR 18 Crores per day (13 days*) Average 6 Crores per day
Average Price (Rs/Mwh)	Rs 4.89/kWh	Rs 4.35 / kWh	Rs 4.44 / kWh (9.2% reduction)
Annual Transfer			SCED -> IEX: 7235 MUs (47% time blocks) IEX -> SCED: 6180 MUs (42% time blocks)
Reduction in price volatility (%)			50% reduction in price volatility over PX1 (shown in the figure below)
Number of times price cap was hit	1079 (Rs 12/kWh) 1577 (Rs 10/kWh)		123 (Rs 12 /kWh) (88% reduction) 340 (Rs 10/kWh)(78% reduction)

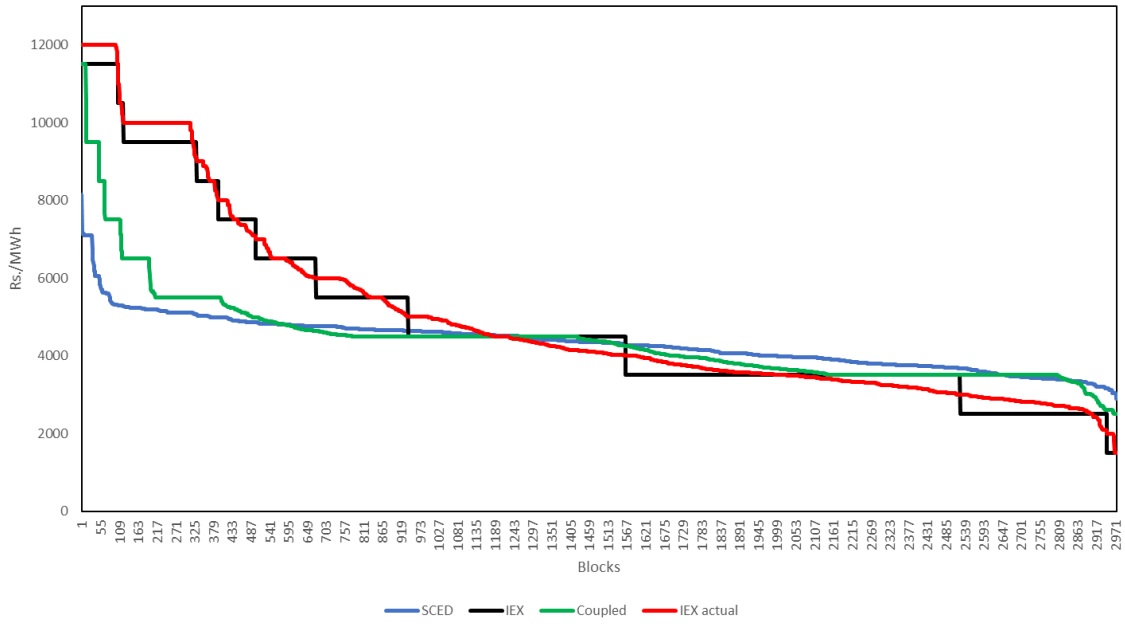
* Out of 365 days

The integration of SCUC and the Day-Ahead Market (DAM) effectively optimizes power plant generation across all the days we examined. Notably, some intriguing findings emerge, particularly when generators committed under SCUC displace supplies from the Indian Energy Exchange (IEX), even if those IEX supplies are cheaper. This, in turn, leads to a reduction in social welfare on specific days (11 days in a year), as illustrated in Table 2.

These results are understandably influenced by the assumptions concerning which generators are permitted to start and stop, but on the whole, they contribute to an increase in social welfare over the entire year, with certain days yielding benefits ranging from INR 18 crores (13 days).

The volatility, and the number of times price cap hits are considerably reduced. This is also shown in the price duration curve shown in Figure 11.

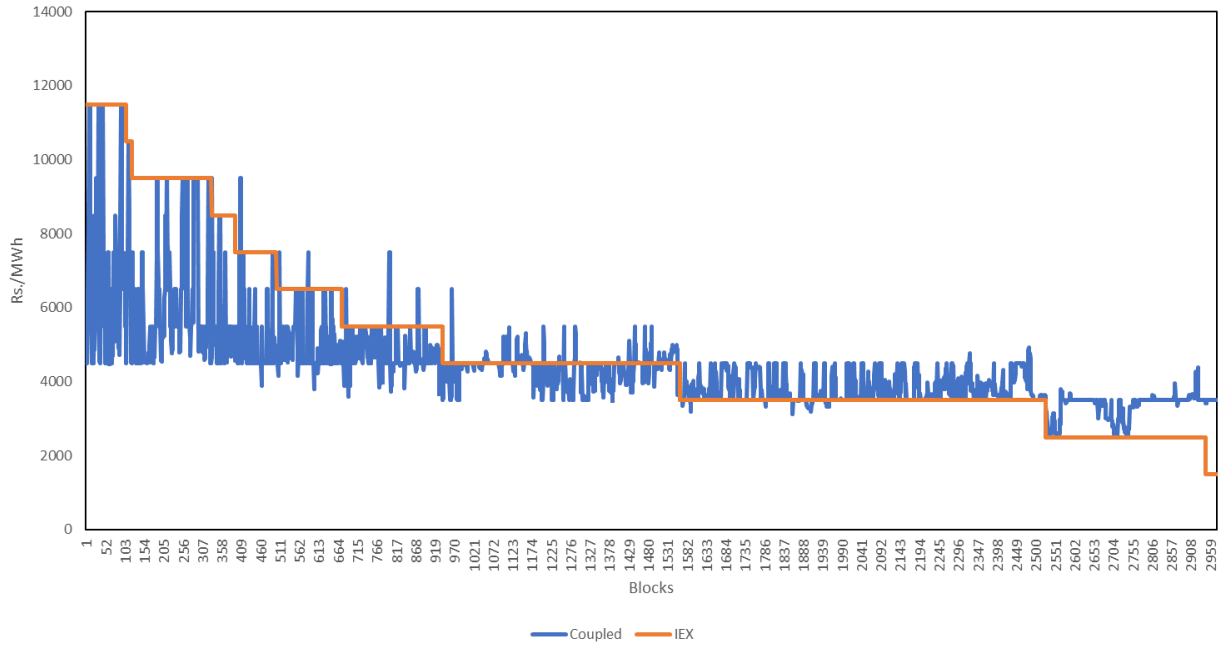
Figure 11 Price duration curves: Day ahead market with and without coupling



Note: The horizontal axis indicates time-blocks for 31 representative days (31X96 or 2,976 blocks)

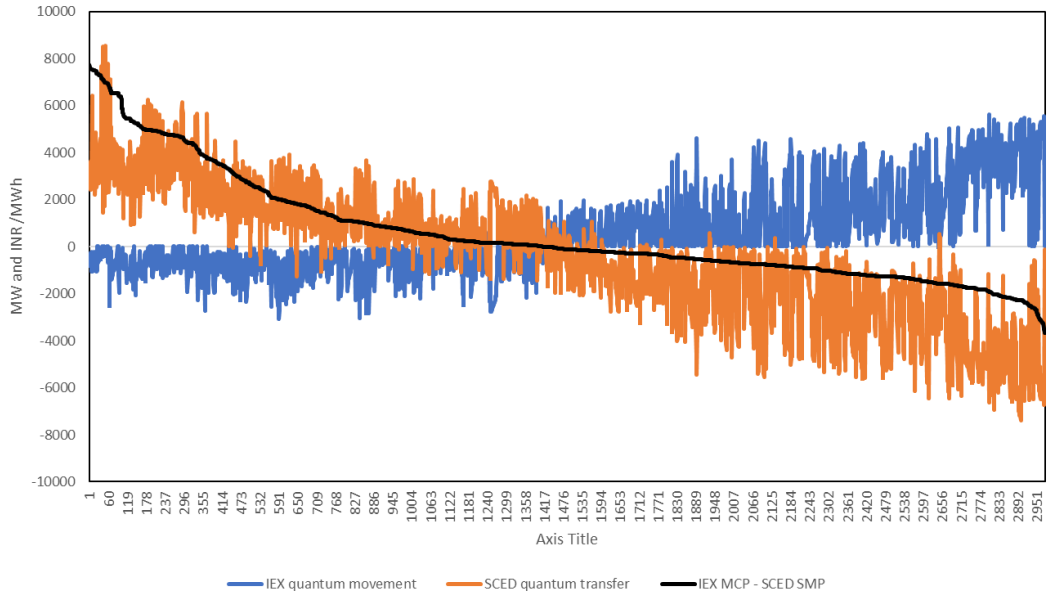
The prices (indicated in green) are seen to move in a narrower range (as compared to the red (the actual prices on IEX, and block (the prices determined by the model used in this paper based on data available on IEX website). The volatility pre and post coupling of SCUC and IEX, is also shown in Figure 12.

Figure 12 IEX price duration curve and coupled prices



As observed in the case of RTM, the movement from SCUC to PX1 and from PX1 to SCUC is also even:

Figure 13 Transfer from SCUC to IEX and IEX to SCUC



Note: The horizontal axis indicates time-blocks for 31 representative days (31X96 or 2,976 blocks)

These benefits should also be seen as conservative because of limited consideration of flexibility (in ramping of generators) – some coal fired generators have ramping rates that exceed 1% per minute, and gas fired generators could have ramping rates that exceed 3% per minute. Similarly, as generators

invest in reducing their technical minimum further, the benefits could increase. Extending the scope of the optimization to include hydro (and further cross-border hydro) can drastically improve flexibility too – an issue that we have not considered. On the other hand, the benefits could also reduce because of explicit consideration of block bids on the Exchanges. But then, when block bids on PXs interact through the model with minimum up/down constraints on generators, the result could be in either direction especially when we consider the possibility of reserve sharing across the two fleets of generators. This merits a detailed analysis. Given the significant level of benefits of 6 crores per day, we consider taking up such a study as a high priority issue.

DISCUSSION ON ISSUES THAT GO BEYOND CURRENT MODELING ANALYSIS[6]

While the modeling analysis presented in the preceding section shows significant benefits even erring on the side of conservatism, market coupling is a significant step especially when it comes to integrating markets with the ISGS/SCED process. In this section, we briefly touch upon some of the potential issues in qualitative terms as the current scope of analysis cannot deal with these issues, or they are intrinsically outside the realm of any form of quantification. Our objective is to record our thoughts on these and identify areas where more work is needed including modeling work that should be undertaken with better data and models, and also prioritize these tasks to the extent possible including a more detailed SCUC-DAM analysis identified in the preceding discussion.

TECHNICAL ISSUES

SPINNING RESERVE:

This is one of the key constraints that might restrict transfer from SCED→PX especially during time blocks when the system is facing high demand that often would coincide with high prices on the PX that may in turn drive high level of transfer from ISGS stations. If the ISGS systems may itself be reserve constrained, any additional generation may have ramifications for adjusting the dispatch for generators that would otherwise be on reserve duty or bring on additional generators to provide that service. There may be an opportunity cost in both cases. This is, however, unlikely to offset a significant part of the benefits let alone wipe it out completely for the following reasons:

- Spinning reserve costs internationally where there is a spot market for it, are typically a fraction of generation cost (e.g., Rs 150-350/MWh)[7] and may also be significantly lower than the difference in PX and SCED prices at the high end; and

- The deficit in spinning reserve may not be there for majority of the time blocks and even when there is a deficit, it may not necessarily incur an opportunity cost for the entire amount of transfer.

In order to provide a crude estimate, if we assume the additional transfer up to 5 GW would render 1 GW of spinning reserve deficit for 25% of the time blocks (4 hours of evening peak every single day) in a year that would incur an opportunity cost of Rs 350/MWh – all of these are potential overestimates – would yield an additional cost of Rs 51 crore which still remains a small fraction of the savings (of more than Rs 1000 crores). If we bring in unit commitment decisions as part of a SCUC-DAM process,

[6] This section in part reflects many useful discussions with CEA, CERC, GCIL, IEX, Power Foundation and PTC among others primarily around the SCED-RTM analysis. We are grateful for the feedbacks received on the initial findings of our analysis that has helped to shape the analysis although we have not been able to address these quantitatively.

[7] Based on an average FCAS cost of $2-4/MWh in international markets including Australia and the USA (e.g., https://engagedscholarship.csuohio.edu/cgi/viewcontent.cgi?article=2270&context=urban_facpub)

coupling may in fact free up additional reserve as a byproduct and may add to the benefits rather than reduce it.

This is, however, a significant empirical issue that requires careful analysis and should be considered as a high priority starting with an estimate of reserve deficit MWs, % of time they occur, opportunity cost of provision of reserve, etc.

In the long run, market coupling should actually facilitate the creation of an integrated spinning reserve market including co-optimization of frequency control ancillary services (FCAS) over a larger control area including the ISGS generators, those who participate in the PXs, and potentially state generators who may also get eventually connected to the coupled market through SCED. As the European market coupling experience has demonstrated, the availability of FCAS may vastly improve over a larger system and lead to a lower price.[8] Put differently, efforts should be made to take advantage of coupling to create a market-based mechanism for spinning reserve.

RAMPING AND MINIMUM LOADING CONSTRAINTS:

The present SCED-RTM analysis also ignored constraints around ramping and minimum loading although the SCED optimization process operated by NLDC does account for it for the real-time dispatch. Similar to the reserve constraint, ramp up and down rates and min loading may prevent some of the transfers from ISGS to PX system or in the reverse direction because generators may not be able to ramp up fast enough to support demand in the PX, or ramp down fast enough to be replaced by generation from the PX (including the possibility that some of them are already sitting at the minimum load).

It is hard to tell again if this might seriously eat into the social welfare increase estimates that we have seen, and it is another issue that needs to be tested empirically by reconstructing the analysis more in line with what SCED does with a full dataset. Our analysis of SCUC-DAM does include these constraints and the fact that those benefits remain very significant over Rs 2,100 crores for the year in a way proves that these constraints (even if set conservatively at 1% ramp rate for some of the coal generators, etc) are unlikely to overly restrictive.

A few comments are in order to develop some insights as to why these constraints are unlikely to have a materially significant impact:

1. As Figure 5 shows even for a relatively high demand in SCED, there is around 15 GW of generation capacity that is under Rs 6000/MWh. If part of this capacity is committed to provide reserve or other system security purposes or due to contractual obligations – it should be possible to ramp these generators up as they should have plenty of operating capability to support up to 5 GW of transfer that we have assumed in our analysis;
2. Ramp rates for thermal generators can be in the 1%-3% per minute range and at least at the low end may mean ramping several GWs up may take 2 or 3 time blocks. Since high price events

[8] The 2018 CERC Discussion Paper on re-designing ancillary services had envisaged similar market based FCAS mechanism: https://cercind.gov.in/2018/draft_reg/DP.pdf

historically have spanned across multiple TBs at least for the year we have studied, the ramp up limits should not remain a limiting factor after three TBs at most if not after 1-2 blocks depending on the level of transfer needed or the ramping capability of the generators; and

3. The reverse transfer from PX to SCED during low load conditions with multiple generators sitting at the minimum load may be a material issue. These reverse transfers may typically happen at a lower difference in SMP and MCP (see Figure 8 – right hand side of the curve). The extent to which ramp down rate or minimum loading prevents the Coupled MCP to be lifted, the loss of benefits may not necessarily be as significant as the SCED→PX transfer. This is, however, a valid concern that must be tested especially as part of the DAM analysis (using DA SCED and SCUC). As noted, our preliminary analysis of SCUC-DAM shows the benefits remain very significant but it needs further probing to run the analysis for a full year with a greater level scrutiny on the data and assumptions by the stakeholders.

RESOURCE ADEQUACY ISSUES:

Sustained high prices and high price volatility in an energy-only market is not necessarily a "bad" thing as high prices are in fact essential to signal to the investors and asset owners to build new capacity, new technology like battery storage and use expensive fuel including imported coal that would not happen otherwise. As Coupled prices would reduce PX prices, there is a legitimate concern if coupling may lower incentives for entry and usage of expensive options, that are needed for system adequacy. However, it is important to note that coupling would effectively make cheaper resources that are in fact available in another segment, and it is simply facilitating access of the ISGS generators to market, or cheaper generation from the market to supplant for expensive ISGS resources. It is overcoming one of the key inefficiencies of a fragmented market and in the process providing a market-based mechanism to enhance adequacy. These market segments are fragmented at the moment and stress encountered in one does not allow the other to respond. Coupling connects these segments facilitating such response. Such mechanisms may also potentially include power traders if the Market Coupling Operator is allowed to accept their bids during the coupling process including supply-only or demand-only bids for which there is no platform available at the moment. The PMR 2021 has also introduced OTC platform besides Market coupling and CERC has already given the approval for OTC platforms.

If prices during off-peak in PX increases, it may also encourage addition of firm baseload generation capacity as well as resources like wind. Although peak prices may drop, access to firm baseload ISGS generation capacity actually helps to improve adequacy and eliminate unnecessarily volatile prices that are only there because the market is fragmented. It does not mean coupling will resolve resource adequacy issues, but it should help and would certainly not hurt.

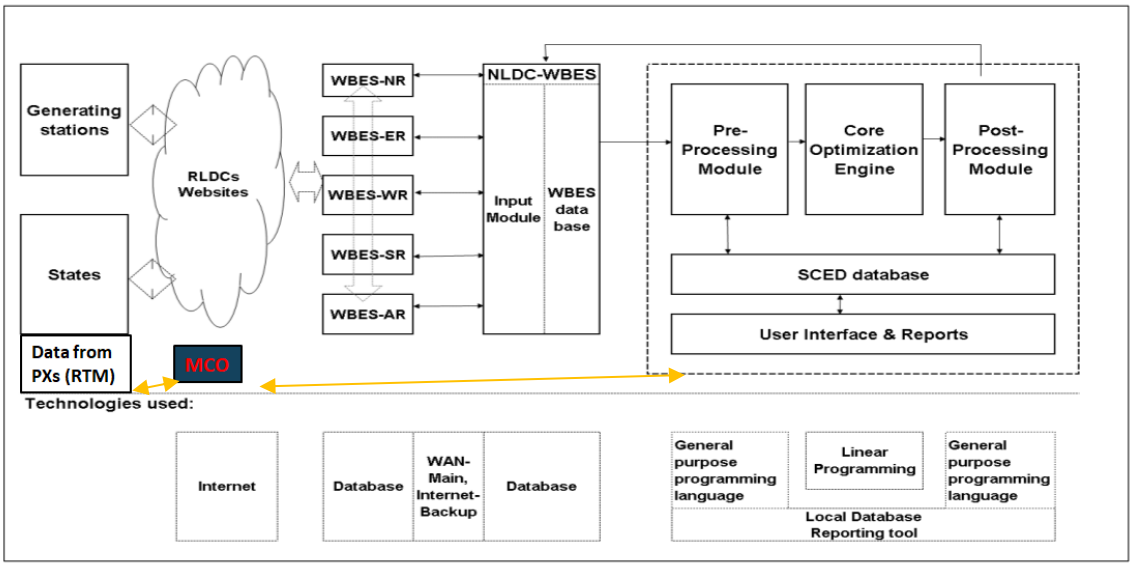
IMPLEMENTATION ISSUES:

As the MCO role adds an extra layer, there are additional data transfer links, computational issues/concerns as the entire process needs to finish well within the 15-minute interval and sequencing of the activity in the current market and SCED processes. The current analysis, although done in an

offline environment using simplified models, gives some confidence that the modeling is straightforward, resembles the SCED/SCUC model closely and hence can be a natural extension of the same model architecture and the solution time in the order of seconds should fit comfortably in the timeline. Our initial thinking is that the Grid-India ,NLDC which runs the current SCED process is best placed to take on the role of the MCO instead of one of the PX taking this role and have presented some ideas on how the additional steps for MCO can be accommodated. The core requirement for a MCO needs to be fairness, capacity and neutrality. Figure 10 shows the additional data links and the sequencing of MCO step is shown in Figure 14 (figures are sourced from the SCED reports).

This clearly needs further discussions with Grid India and PXs to develop a concrete set of steps to get to the stage of piloting the MCO role. However, both the PXs and Grid-India have the requisite intrinsic capability, be it the IT infrastructure, data transfer and exchanges, accounting and settlement and domain knowledge developed over last few years in continuous coordination amongst themselves and market participants and regulatory bodies.

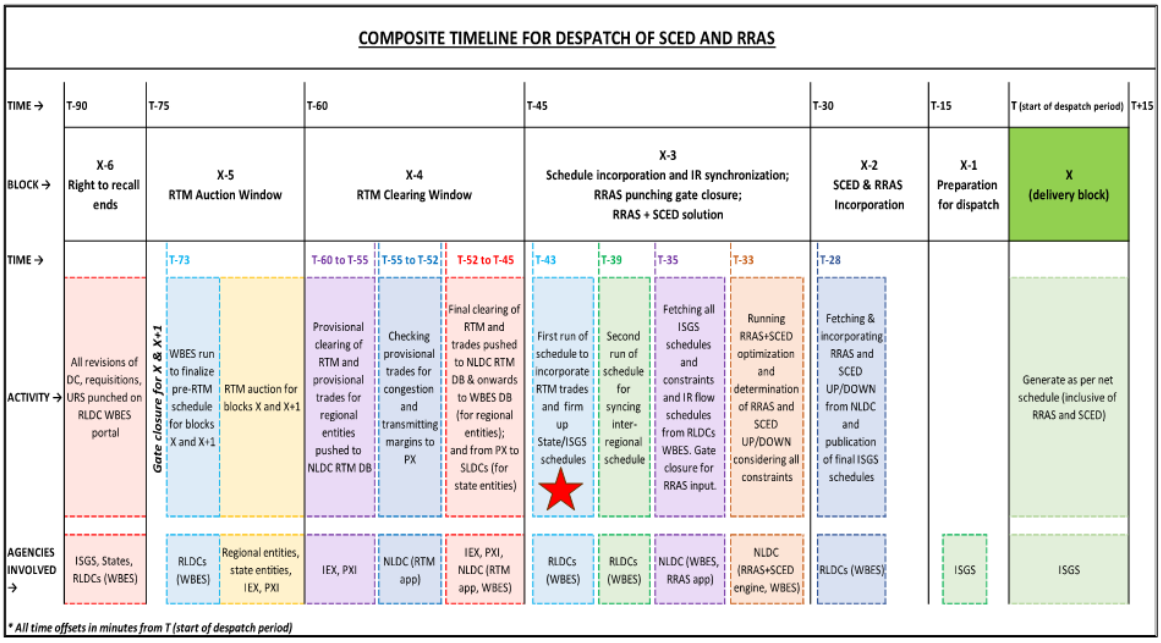
Figure 14 Integration of MCO in SCED: Data link



Source: SCED Report, Figure 8 (Architecture of Information Flow in SCED)

Figure 15 Integration of MCO in SCED: Timeline

★ Insertion of Market coupling exercise in the composite timeline subject to details.



ECONOMIC AND REGULATORY ISSUES

Coupling also opens up potentially a plethora of economic and regulatory issues especially if it connects a dispatch mechanism intended for regulated ISGS stations and PXs. We merely list some of these that have been levelled in various discussions fora to date recognizing that these are difficult issues for which in most cases there is no "right answer", and a policy decision will need to be made in view of potential significant benefits of coupling.

SCOPE AND INTERPRETATION OF THE CURRENT CERC REGULATIONS:

To begin with, it is worth asking the question – are there explicit or implicit restrictions on participation by generators in various segments of the market (namely, regulated generators such as ISGS participating in PX, or non-ISGS generators participating in the SCED, or DISCOMs for that matter effectively trading state owned generation in the PX?). Our review of the IEGC suggests there is a wide degree of freedom for cross-participation in the current IEGC 2023 and it has in fact existed going as far back as the IEGC 2010. The latter for instance already allowed for regulated (Section 62) generators to

participate in the PXs. The updated Grid Code 2023 explicitly states this (Section 49(1)(l)).[9] Following these provisions in the Grid Code, NTPC, NHPC power plants already regularly trade in DAM and RTM. Of the total RTM transactions at power exchanges, top five regional entities/states sold 51.77% of the volume, and these were Bihar, Odisha, West Bengal, Uttar Pradesh and NTPC Stations (Eastern Region).[10] These states, too, sell power that is generated in either state-owned power plants, whose energy charge rates (variable costs) are determined/ approved by the state electricity regulatory commissions, or is generated in power plants that have a PPA with the state. Therefore, both "regulated" and "merchant" power *are* currently traded on the power exchanges, and hence coupling SCUC/SCED with DAM/RTM will only formalize and incentivize the process to enhance the efficiency of power system operation.

SUPPORT FROM INTERNATIONAL REGULATORY PRACTICES:

These regulations are in fact quite well aligned with the international best practices. US markets following the Californian debacle in the summer of 2000 when market power allegations were rife in the middle of supply scarcity and persistent high prices, moved to ex-ante mitigation measures of market power to price cap-based regulation that arguably led to the crisis.[11] FERC (2002) explicitly stated that "*Effective ex ante mitigation is preferable to retroactive price changes*" and bid caps were introduced to curb market power. The proposed coupling of regulated generators and market may also be seen in the light of the former effectively putting an implicit cap on how far prices can go in the PX.

The second set of measures on monitoring of market power introduced around the same time to use cost-based dispatch models to check on bids also resonate well with our proposal. US markets use production cost modeling as part of market monitoring and there is a high degree of alignment of prices and marginal costs. All PJM resources, for instance, are required to submit at least one cost-based offer based on unit specific parameter limits (except nuclear, solar, wind and hydro are exempted from the parameter limits). [12] Bid prices are compared with the cost based offers as part of market power tests. The (Grid India) SCED process is essentially a cost-based simulation akin to the default energy bids (DEBs) set according to the variable costs in the US market.

The closest alignment between the process followed in SCED and that in a market setting is perhaps the Cost Based Pools (CBP) that have been operational in Latin America for over three decades and South Korea also implemented its pool (initially as a transition measure) in 2001. CBPs are at their heart a dispatch engine that calculates the system marginal cost/price (SMC/SMP) much the same way as SCED does for ISGS. In the South Korean CBP (see Figure 16) there is an administered capacity pricing

[9] "*The generating station whose tariff is determined under Section 62 of the Act, may sell its unrequisitioned surplus as available at 9.45 AM in the day ahead market, unless the consent is withheld by the beneficiary or buyer in writing. The sharing of net savings shall be as per provisions of Tariff Regulations and until a provision is made in the Tariff Regulations, in accordance with the detailed procedure to be prepared by NLDC and approved by the Commission"*

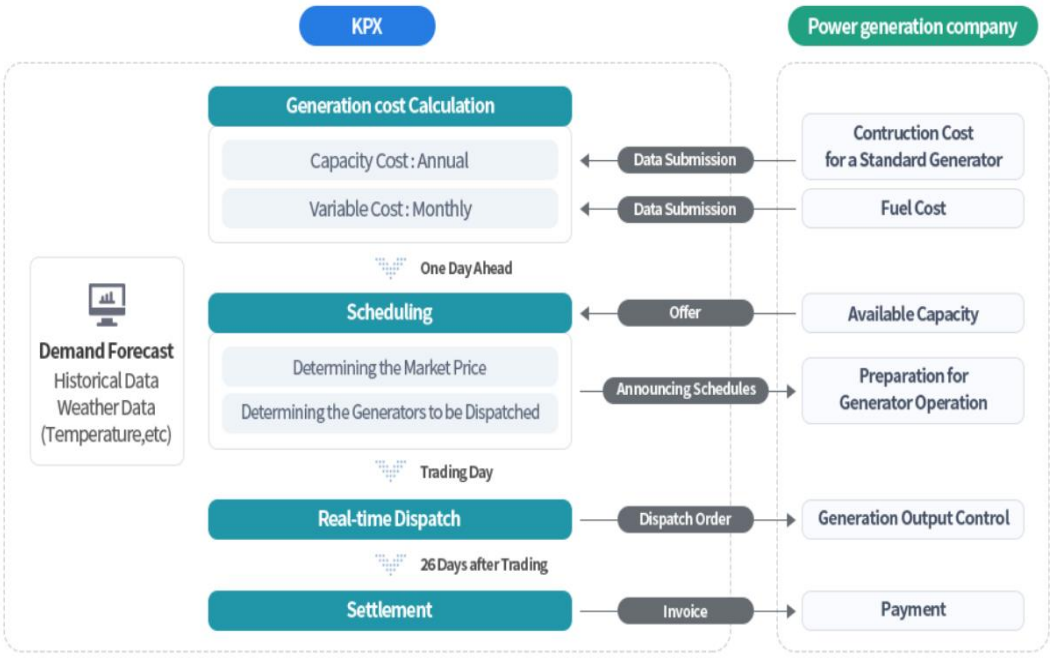
[10] Please refer to: https://cercind.gov.in/2023/market_monitoring/MMC%20Report%20Feb%202023.pdf.

[11] See for example the NBER article that cites Professor Paul Joskow's views. https://www.nber.org/digest/dec01/californias-failed-electric-power-industry-reforms

[12] Please refer to: https://www.monitoringanalytics.com/home/index.shtml and the relevant State of the Market Reports for PJM.

regime which is similar to the fixed cost payments. Unlike the Korean CBP or the capacity markets in PJM, etc., however, there is a difference with regard to the setting of fixed costs in that these costs are periodically adjusted either through a regulatory process (as in South Korea), or still better through a dynamic market-based mechanism (in the US). We discuss this issue in the next point. However, the core dispatch and participation of regulated generators in a market seem to find good support within the current CERC regulation itself, as well as internationally.

Figure 16 Example of a cost based pool arrangement (Korean Power Exchange)



Source: Korea Power Exchange website: https://new.kpx.or.kr/menu.es?mid=a20201000000

TREATMENT OF FIXED COSTS:

The PX market is an energy-only market wherein generator bids need to cover all costs on a per MWh basis, whereas the ISGS generators are paid a fixed cost (FC) and the SCED mechanism dispatches and remunerates generators on the basis of variable costs (VC) only.[13] Therefore, if we connect the two segments and let ISGS to effectively compete on the basis of VC alone, this is not quite a level playing field. This will particularly be the case for a pure "merchant generator" that sells all of its outputs in the PX spot market. Given the dominance of the PPAs in the Indian market that accounts for ~90% of the generation share, vast majority of the generators will have a FC payment secured. There is also the issue of generators with assets that are heavily/fully depreciated. The fixed cost issue remains and the proposal for a Market Based Economic Dispatch did not quite address potential inefficiencies around

[13] Again, this is a process that broadly resembles the KPX mechanism where the capacity payments are also regulated/administered prices that are periodically adjusted.

incumbent PPAs and FCs.[14] Coupling will not resolve this issue at all, but the social welfare increase is a real benefit that will need to be traded off against any disbenefits for unfair competition. It may be handled through the benefits sharing mechanism to offset PX generators that lose dispatch which may be still an improvement over the fragmented state of the market.

INTERFERENCE WITH THE MARKET:

A related criticism of mixing a regulated mechanism with market is that it may be seen as an interference of a process run by the system operator with the market. It is certainly not the ideal solution given the fixed cost issue we have just discussed, but there is no such "ideal" solution unless there is a holistic reform of the PPAs that has not happened for more than 30 years. Any efficiency gain that can be achieved in the short term without an extensive reform is worth doing. SCED, in itself, is a good example of such a process that has saved over Rs 2500 crores over the past 4+ years. The Coupling mechanism is a natural extension of it that should be easy to implement building on that experience and as the analysis suggests can be potentially more beneficial. Coupling will **not** dissuade ISGS generators from going to the market. On the contrary, this will be a more direct way for these generators to get access to the market. As the MBED process has been continually delayed for over three years now, coupling is a good alternative to bring some semblance of market exposure which is less disruptive. There will be changes needed to encourage ISGS generators to participate e.g., increase limits of trading margin.

COAL ALLOCATION AND IMPORT:

As the dispatch changes, there may be higher utilization of cheaper domestic coal in low variable cost plants, and a commensurate reduction in dispatch from the more expensive ones including plants running on expensive imported coal. If this shift is significant, there may also be a need to revisit the coal allocation within allowable provisions in the current policy. These changes including reduced reliance on imported coal should however be seen in positive light as an efficient and integrated market should strive to reduce reliance on expensive resources.

NEED FOR MARKET MONITORING:

As the market size grows, the addition of a potentially dominant player with significant baseload capacity will reinforce the need for market monitoring, the responsibility for which will need to be separated from the MCO. This is, however, not a new concern. High incidence of prices sitting at price cap, highly inelastic demand etc. should already require an examination of bids to see if there are

[14] See for instance the discussion in: https://www.sciencedirect.com/science/article/pii/S1040619023000064 and also the following article: https://jaiveeru.substack.com/p/5-cutting-the-clutter-the-jumla-of

market power concerns in the current market. Coupling should bring additional liquidity, additional players and hence a natural check on the extent to which market power may be exercised by the incumbent dominant generators.

POTENTIAL EXPANSION OF THE MARKET THROUGH MCO:

This MCO framework permits clearance of unbalanced supply offers and demand bids on some power exchanges in India. Currently, supply offers and demand bids, that are not completely matched go unserved on power exchanges even when the "larger" power system has avenues (through other power exchanges or SCED) to serve them. As an extension to the coupling of PXs and SCED, the framework allows coupling of supply offers and demand from regular traders, and day ahead and intraday continuous trading products available on power exchanges.

BENEFITS SHARING:

As we have alluded to this point, the flow of money through the MCO and sharing of benefits will require careful attention. There are usually quite a few different ways to share benefits, and in this instance, a treatment of FCs across different ownerships and vintage of plants, may open up numerous such possibilities. This clearly requires some work to lay out the key options, and trade-offs therein. CERC has issued orders for sharing of the benefits in case of SCED and therefore has set a precedence. We have not attempted to do this as our initial focus is to check if there are enough benefits to warrant exploring these additional layers of complexities around benefits sharing. The findings so far indicate such benefits can indeed be very significant and therefore the exploration on benefits sharing mechanism options should be considered as a priority issue.

MISCELLANEOUS OTHER ISSUES

IS COUPLING RELEVANT IN A SYSTEM WHERE ALL EXCHANGES AND SEGMENTS ARE NATIONAL?

Market coupling in Europe has its genesis in markets across different countries getting coupled. The situation in India is different in that the geographical scope of the Power Exchanges as well as SCED is already nationwide. It therefore raises a pertinent question as to the relevance of coupling multiple 'national' markets/segments.[15] The short answer is that coupling, and integration is always the

[15] It is worth noting here that Great Britain, in fact, has two national power exchanges – EPEX and NP – that were setup as Nominated Electricity Market Operators (NEMO). These were established as 'regulated persons' in the

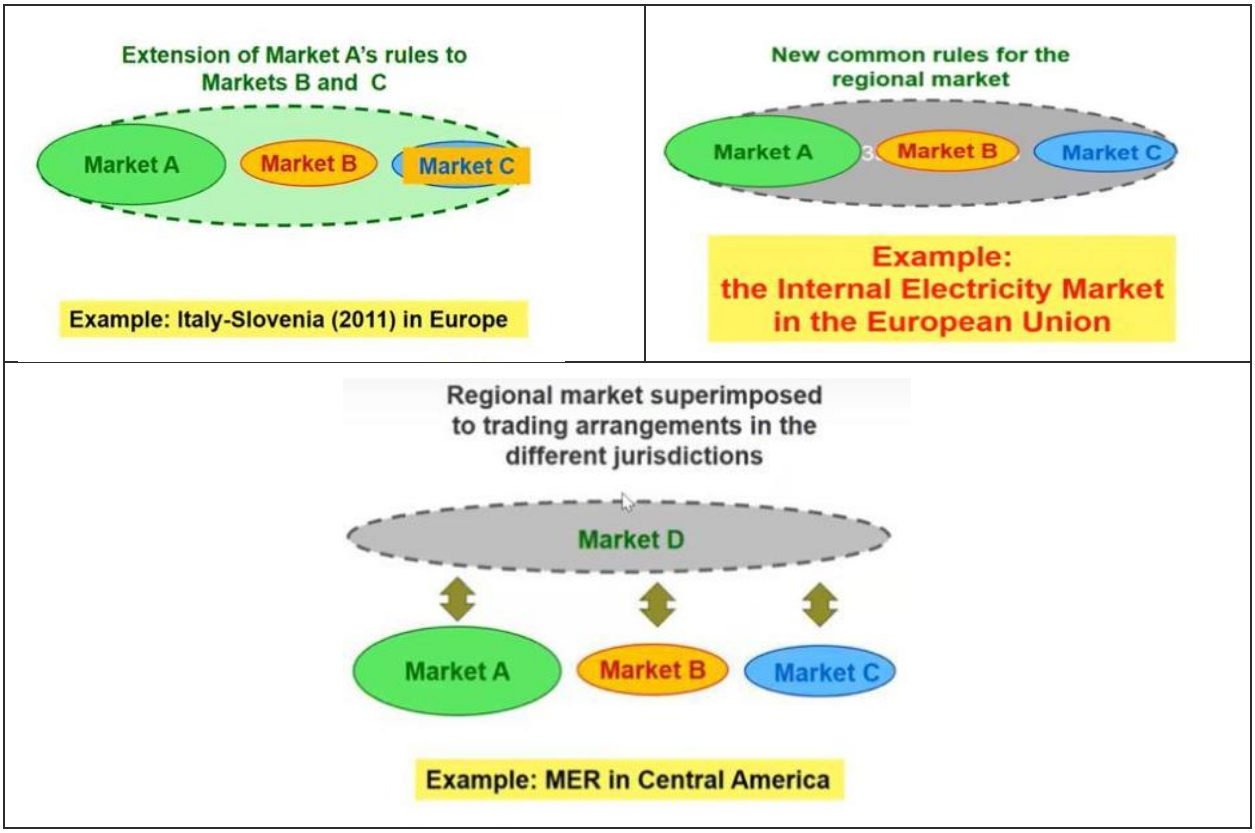
preferred outcome over fragmented segments. The geographical scope is to a large extent irrelevant. If there are social welfare gains to be made, prices become stable, ad-hoc transmission corridor allocation is avoided, and in due course system security can be enhanced through spinning reserve co-optimization in bigger control areas – there are obviously many things going in support of coupling. Our analysis amply demonstrates the first two points on significant social welfare increase and reduction in prices and price volatility. There was at least Rs 1,000 crores in RTM, and over Rs 2,100 crores in the DAM, left on the table last year and if high/volatile prices continue, there are crores more being lost every day. This is a nationally important issue for inculcating good economics and system security that calls for immediate action through a pilot.

ALTERNATIVE MODELS FOR COUPLING:

A related issue is how different markets or market segments are integrated. There is no unique model. As we have noted before, UK previously had two national Power Exchanges that were both coupled with (and through) EU markets to create a common price for Great Britain, that have since been decoupled and there are new arrangements under discussion on coupling them domestically. There have been other models in the past with one set of market rules being applied to other markets integrating into it which was/is quite common with Eastern European countries integrating into an existing market. Over the years these markets may form a common set of rules as has been the case with the EU Internal Electricity Market. There are still other models like a regional electricity market superimposed for trading arrangements among the subsystems/countries maintaining the sovereignty of the individual jurisdictions. This has been the case with the Southern African Power Pool (SAPP), SIEPAC/MER in Latin America, and a similar system is evolving in Eastern Africa, and also has been under discussion for the South Asian regional electricity market. Dr Pototsnchig's recent presentation nicely illustrates the three generic models of market coupling shown in Figure 17.

Electricity Act 1989 with Ofgem overseeing their compliance with the national electricity rules. Both EPEX and NP were connected to the European market before BREXIT and hence were indirectly coupled with each other. As a BEIS report puts it: "*The two NEMOs cooperated to establish arrangements whereby the EU market coupling process matched bids and offers from across the EU taking into account that trades could be completed between these two exchanges without physical network constraint, resulting in the same day-ahead price determined for both NEMOs in the EU day-ahead auction – **creating a single GB clearing price**.*" The gains of trade of EU-wide interconnection in 2015 was estimated by Newbery et al (2015) at €3.3 billions majority of which was achieved through coupling of day ahead and balancing markets over key interconnectors. As Great Britain leaves the EU Single Market, it leaves the two NEMOs operating independently. Geske et al (2019) projects the loss of gains of trade (measured as an increase in generation costs) at €560 million annually (for 2030) of which €300 million losses are incurred by Great Britain. The Great Britain electricity market arrangements are currently under a review (REMA).

Figure 17 Three possible models of regional electricity market



'Source: Presentation by Dr Alberto Pototschnig, Florence School of Regulation.

In the Indian context, there needs to be a discussion on the broader coupling involving how ISGS, most RE (including solar/wind/hydro) and bulk of the state generation capacity that do not currently participate in the PXs. The current scope of work considers coupling across ISGS and PXs only and shows there are enough reasons to make this happen and in terms of the model this seems relatively straightforward. It should be possible to create a MCO role in NLDC/GCIL or one of the PXs and add a thin layer of optimization on top in a matter of a few months. As the scope broadens to states, there are more choices, namely, (a) if the SCED system for ISGS should be extended to states and they should integrate among themselves (b) which then couples further with the PXs, or (c) if the individual states should couple with PXs, etc. This needs some focused analysis and discussion to develop a roadmap. Glachant (2010) is noteworthy who had foreseen multiple possibilities for the European market to evolve from a centralized market for all down to layered price coupling. In the past 13 years, Europe has seen the evolution of both regimes in different parts, as well as the decoupling of the Great Britain! Coupling has by and large benefited as there is significant literature (e.g., Haluzan et al, 2022 and Parisan and Pelagatti, 2019 among the more recent articles) and market data on it. That said, there is already a foregone conclusion - the process of coupling must start sooner rather than pontification or worse further fragmentation as has been the past trend.

BLOCK BIDS:

While the SCED-RTM in the near term is a bigger priority, there needs to be some consideration for all of the complexities in the DAM including the presence of block bids. We have not dealt with DAM modeling at this stage, but this together with unit commitment, minimum loading, ramping and reserve issues that we discussed before; all need to be brought under the fold of SCUC-DAM integration. While we have included a preliminary SCUC-DAM analysis as part of this work, we note its limitations including reliance on representative days and limited data. As such, we strongly recommend a follow-up should be taken up as a next step by concerned authorities considering the fact that the volume in DAM is 3-4 times as high offering potentially benefits that are also significantly higher (e.g., at least double according to our first-cut estimate). Such a framework would also bring significant opportunities to optimize commitment of ISGS generators, smother operation of the system including more stable and predictable dispatch pattern over the entire day, co-optimize and price FCAS, etc.

If the state generators can also implement SCED *and* link through the incumbent ISGS SCED eventually as we envisage the Phase 2 of the coupling process, it would further widen the scope of optimization bringing further savings, liquidity, price stability and stable system operation.

LINK WITH THE DEVIATION SETTLEMENT MECHANISM AND DERIVATIVE PRICES:

There are two important connotations of changes in DAM/RTM price level and volatility, namely:

1. **As the Deviation Settlement Mechanism (DSM) prices in India are closely linked to the spot price, robust spot price that should result from market coupling gains special importance.** Volatility in the DAM/RTM prices pose high risk for generators, especially wind and solar generators, especially for under-injection during high price events. As coupling can cause a drastic reduction in extreme price events, it should come as a major blessing to renewable generators; and
2. **The reduction in volatility as well as average price reduction (e.g., 9.2% reduction in DAM prices) will also have a major impact on prices for derivatives**. The premium on financial products that help retailers/DISCOMs to protect against high price events can rise disproportionately in a high volatility regime like the one that has been observed recently. DISCOMs may be either forced to bid excessive demand at the cap, or buy a peak product like a cap contract, or have physical hedge (e.g., build/contract energy storage). If market coupling can obviate the need for any of these, it is a major relief. The stability around the off-peak prices, on the other hand, provides significant revenue certainty to baseload generators and it would in turn stabilize baseload products which is also useful to bring in baseload generation without necessarily having to write long term PPAs.

RENEWABLE ENERGY INTEGRATION AND SYSTEM OPERATION ISSUES:

As the share of solar and wind generation are on the rise, the need for spinning reserve, spot price stability, efficient congestion management etc., are also fast becoming critically important issues. As coupling helps to create a bigger pool of generation and reserve resources and avoids pro-rating of

transmission allocation keeping a bigger fleet of generators visible to the MCO, it should facilitate a smoother, technically and economically efficient way to run the system.

CONGESTION AND TRANSMISSION ISSUES:

While congestion has not been a major issue in the recent past, it had surfaced many times over a longer stretch of market operation over the past 15 years. It may be observed that market splitting on the exchanges before 2015 was led to 72% curtailment on PXIL 20-27% on IEX and India had lost 3.1 BU due to congestion.[16] As India strives to integrate over 300 GW of additional solar and wind over the next seven years with large quantum of new solar/wind generation concentrated in a few states, both spinning reserve allocation and transmission corridor utilization are going to be paramount. Grid India (August 2023) is currently contemplating a significant increase in number of bid areas and this is another consideration where coupling will be helpful. Market coupling and greater participation of RE generation in the market including coupling/integrating the Green DAM will all gain importance over the coming years. It is important to pilot coupling of markets and SCED/SCUC from this perspective too.[17]

WOULD INCREASING THE PRICE CAP OBVIATE THE NEED FOR COUPLING?

As some of the views expressed in various fora have rightly suggested sustained high prices and high price volatility over the last few months are in part caused by the recent lowering of price cap from Rs 20,000/MWh to Rs 12,000/MWh and further to Rs 10,000/MWh. As the World Bank Submission to CERC in August 2022 noted (World Bank, 2022), lowering price cap arbitrarily, further fragmentation of the market through HP-DAM, GDAM etc. can lead to inefficient outcomes. [18] There should clearly be a proper change process to assess the price cap to avoid such outcomes. However, the question arises if raising the price cap back to Rs 20,000/MWh or whatever the right price cap ought to be[19] would obviate the need for market coupling? There is probably some logic in it as the current tightness of supply eases and hence the nervousness on the demand side would go away leading to a more normal price pattern that preceded the months of low-price cap. However, while a high price cap in theory

[16] CERC order: https://cercind.gov.in/2015/orders/SO158.pdf and also please refer to the article in the Economic Times: https://energy.economictimes.indiatimes.com/amp/news/power/india-lost-3-1-billion-units-of-electricity-to-transmission-congestion-in-2014-15/47878431

[17] It should be noted that due to extensive development of transmission system in India, congestion and market splitting is rare in the Inter State Transmission System in India now. However, recent transmission expansion planning studies indicate balancing resources from over large balancing areas need to be brought together for RE integration with minimal curtailment. Market coupling, by bringing together diverse capacities from various regions enables better utilization of transmission system, reduced congestion (by minimizing loop flows), and better RE integration.

[18] World Bank, COMMENTS ON THE PROPOSAL FOR A HIGH PRICE SEGMENT OF DAY AHEAD MARKET (HP-DAM), Submission to CERC, August 2022. Available on request.

[19] See for instance, Reisz, 2013 who argues price caps in excess of Australian $100,000/MWh or Rs 6,000,000/MWh. Australian price cap has over the past 25 years increased from A$5000/MWh to over A$13,000/MWh.

addresses the concerns of "missing money"[20] incentivizing new capacity to come in, it also significantly increases the risk of dominant generators exercising market power. A price cap needs to be judiciously determined (Chattopadhyay, 2018) and by and large all markets have one, although internationally even Rs 20,000/MWh is deemed to be very low.

Regardless of the level, a price cap – high or low or just right – does not address the issue of market fragmentation. If there are ISGS or state generators sitting idle that the incumbent PXs do not "see" – there is no way to achieve the optimal dispatch. This is in fact why we see significant benefits when the price cap was set at Rs 12,000/MWh as well as Rs 10,000/MWh in our analysis. Chances are that if we run the analysis for another year when the cap was Rs 20,000/MWh, we will still see benefits. These benefits will not be realized unless the fragmented segments are connected as there is no sensible pathway for all of these transactions to find their way to the optimal dispatch and entry decisions.

[20] Missing money is a term coined by William Hogan, see for example, his concerns on peaking generators not being able to recover its fixed cost in presence of a binding price cap: https://scholar.harvard.edu/whogan/files/hogan_energy_only_092305.pdf

CONCLUDING REMARKS AND RECOMMENDATIONS

In order to conclude this note, we revisited a few pertinent questions that were posed in the CERC Staff Paper on market coupling (CERC, August 2023) followed by a short summary of the findings and recommendations that we elicited based on these.

OUR RESPONSES TO THE KEY QUESTIONS POSED IN THE CERC STAFF PAPER

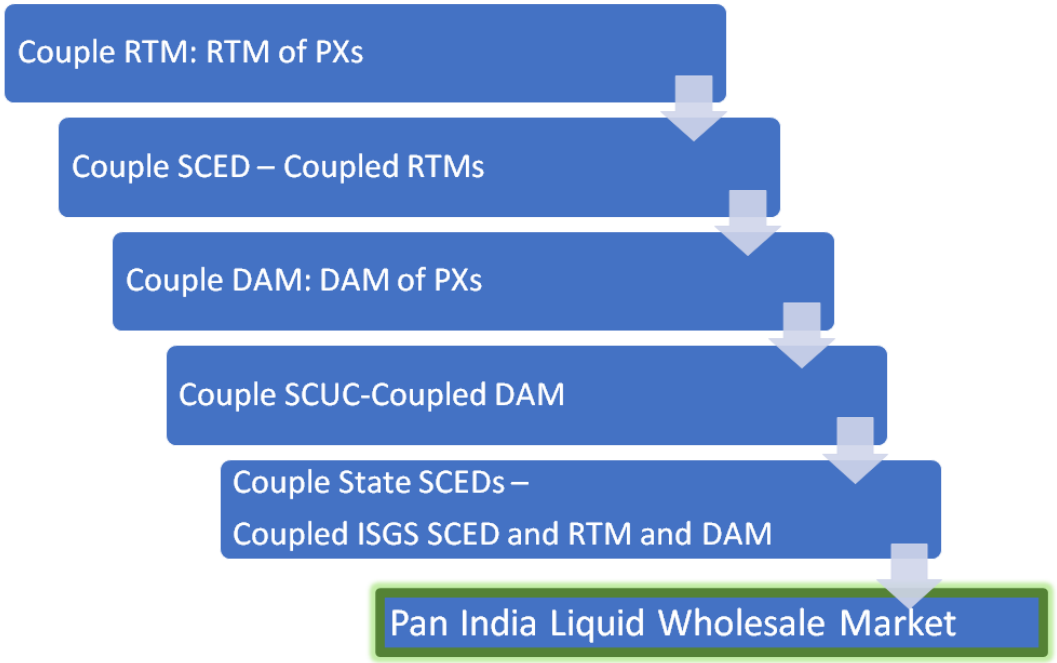
DOES THE CURRENT INDIAN POWER MARKET SCENARIO FORM A COMPELLING CASE FOR MARKET COUPLING?

There definitely is a compelling case for market coupling which marks a step in the right direction to form an efficient and liquid wholesale market. Multiple PXs and too many segments therein (GDAM, HP-DAM) have created a fragmented and confusing marketplace with too many prices, mutual inconsistencies, siloed investment signals, and unnecessary price volatility that can only be managed through inefficient market interventions such as lowering of price cap, forming a separate High Price DAM segment, ad-hoc transmission corridor allocations, etc. Coupling will help to reduce the fragmentation, consolidate and stabilize price signals. It is also a great opportunity to orient dispatch to market participation in other segments starting with that of the ISGS generators followed by state generators, until such time a pan-India liquid market becomes a reality. The process can start with connecting SCED (Security Constrained Economic Dispatch) mechanism to RTMs (Real Time Markets) of coupled PXs. A preliminary simplified analysis of SCED-RTM for Aug 22 – Jul 23 suggests a savings to the tune of Rs 1000 crores would have accrued had a Market Clearing Operator (MCO) tried to expand the scope of optimization. Adding DAM should considerably enhance these savings – our preliminary estimates suggest it can potentially more than double the savings from SCED-RTM coupling.

IN WHICH MARKET SEGMENT SHOULD THE COUPLING BE INTRODUCED FIRST?

Figure 18 shows a sequence of coupling activities that may start with coupling of PX RTMs, followed by connecting the RTMs with SCED, and then the process moves onto the DAM segments of PX, and so on. It is important to bring the integration with the SCED component through an MCO early in the process as the MCO can be the binding force in bringing together the PXs as well. The process needs to be managed carefully with rigorous analysis, pilots and active monitoring following implementation. It is envisaged that this sequence of activities will yield significant additional benefits with progressive coupling of various segments to create a pan-India liquid wholesale market with robust price signals *and* ensure efficient transmission allocation and secure system operation.

Figure 18 Sequence of coupling



WHO SHALL BE THE MARKET COUPLING OPERATOR?

This needs careful thinking keeping in view the entire roadmap (ENTSOE, 2016). The MCO attributes include fairness, neutrality, market capability, and system operation capability. If the intent is to stop at the PX level (RTM and DAM) – perhaps the leading PX operator with sufficient capacity could do the job. However, if there is intent to go beyond that to elicit significant additional economic and technical efficiencies, thoughts should be given to institutional engineering, namely, a national level nodal entity like Grid India who can competently integrate SCEDs (including state level SCEDs), transmission and ancillary services management capabilities. No single PX is possibly going to be able to manage all of these functions which are critical especially as India embarks on a much deeper penetration of solar and wind. The MCO role presents a great opportunity to assimilate the features of advanced Market Management Systems that are capable of integrating SCUC and SCED features in a market environment, support a full range of flexible resources including demand response and allow coordination with neighboring systems.[21] This would also improve the governance aspect by introducing a layer of check and balance. Lehtonen et al (2014) provides an excellent account of the evolution of the governance process in the Europe and how the responsibilities were demarcated across

[21] Please refer to the presentation by Dr. Deepak Sagi (General Electric) in the webinar organized by IEEMA where he presents the full range of features of an MMS:
https://www.linkedin.com/feed/update/urn:li:activity:7116383358728728576/

the MCO/TSO and PXs.[22] ENTSOE (2016) also provides a great summary of the governance issues from a transmission system operator perspective.

WHICH ALGORITHM SHOULD BE ADOPTED FOR A COUPLED MARKET?

As PXs have invested in their algorithms connected to their own set of products, it may not be a good idea to try and harmonize them by moving to a common PX design. The MCO role needs to find a common denominator to find market segments that can be profitably integrated and functionalities that enhance technical efficiency. If SCED(s) are integrated, it would seem like a natural move to an algorithm that brings together a few common features like block bids (in DAM in all PXs), ramp rate, minimum generation (in SCED) together with additional functions like co-optimization of frequency control ancillary services (that was envisaged by CERC and POSOCO but have not been implemented fully yet). It will ensure that the independence and innovations of PX remain in place, preserve the value and yet and the process moves upwards and onwards to a system wherein prices converge across different segments, transmission allocation is internalized and reserve is allocated over a much broader control area optimally.

HOW WILL THE CLEARING & SETTLEMENT BE CARRIED OUT?

The market clearing and settlement functions can be decoupled to some extent. The MCO can clear the market, arrive at a coupled price and cleared bids and offers, send it back to each segment (PXs, ISGS, state generators) who continue to use their own settlement process within the bounds of the incumbent rules and bylaws. The recent IEGC 2023 has detailed provision of various Pools like DSM, SCED Pool etc. and similarly a MCO Pool can also be added for smooth clearing and settlement. There are enough processes and systems have evolved and are in place encompassing all the stakeholders. There is enough intrinsic IT and other faculty capability developed amongst PXs and NLDC to handle clearing and settlement at the MCO level.

SUMMARY AND RECOMMENDATIONS

In summary,

1. Our view is that the CERC Staff Paper has articulated the issues around PX coupling well, but we also see significant scope for coupling PXs further with the current SCED process for the ISGS fleet as it has almost 10 times capacity of the largest PX. Further, currently smaller exchanges that have only supply offers or demand bids in certain time blocks and hence are not

[22] In particular Figure 3 of the paper by Lehtonen et al (2014) is noteworthy as it lays out the outline of a guideline on governance that will likely be need to be developed for India.

able to serve such members/clients, may also get an opportunity when SCED with all the generators and demand is coupled with PXs.

2. **It is important to bring the integration with the SCED component through an MCO early in the process as the MCO can be the binding force in bringing together the PXs as well.**

3. Coupling obviates the need of arbitrary allocation of transmission corridors. Coupling will facilitate allocation of transmission corridors in a manner that contributes to maximization of social welfare at the national level.

4. A simplified analysis with conservative assumptions puts the social welfare benefits of coupling SCED with IEX at Rs ~1000 crores for August 2022 – July 23 and there are other significant benefits of lowering average price, price volatility and price cap incidences.

5. This analysis is also extended to include a preliminary version of Security Constrained Unit Commitment (SCUC) and DAM – this has the potential to double the savings to over Rs 2,100 crores for the same year. However, this study needs refinement and validation of inputs – **we strongly recommend an extension of the study by CERC**.

6. The process of running the analysis also reveals it is reasonably easy to construct the coupling optimization and it should also be easy to embed it in the current NLDC processes around SCED/SCED as an additional layer of optimization. Grid India is a natural fit for the Market Coupling Operator given that they run SCED and allocate transmission and as the system operator is endowed with the necessary knowledge, capacity, fairness and neutrality needed for the task.

7. **A piloting and sandboxing of the SCED-RTM (and eventually SCUC-DAM) of all PXs seem to us as a useful next step to calculate the benefits more accurately using the SCED and full PX demand-supply bid data in real-time.** This will give a much better feel on the extent of savings, changes to the dispatch, prices, etc., as well as practical challenges that may be encountered. As we have demonstrated in the examples, volume of transfers can be capped and for piloting purposes, it may be set at a relatively low volume initially (e.g., 1 GW) and increased incrementally (say by 500 MW) over time to develop insights into incremental gains of trade.

8. Further thoughts and analysis will be needed for SCUC-DAM integration including consideration of frequency control ancillary services, ramping, minimum loading etc. There are many complex issues around how many start/stop decisions are practically feasible on a monthly/quarterly/annual basis even if frequent switching on/off of generators prove to be profitable. While our preliminary analysis has covered some of the issues around basic unit commitment constraints, a more comprehensive study on this topic is timely to assess potentially much higher benefits from SCUC-DAM coupling. **A pilot on this will also form a natural extension of the SCED-RTM counterpart.**

9. The data that is accumulated through the pilots with suitable confidentiality measures and masking should also be made publicly available for a broader set of analyses to fine tune the model and processes around it.

10. Last but not the least, there needs to be concerted effort to build capacity in this area to form the MCO role and supporting R&D activities to sustain and enhance the scope of optimization over the years including capacity that will need to be built in the states.

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ANNEXURE 1: GAMS CODE USED FOR THE ANALYSIS

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eObjectiveSCED.. vObjectiveSCED =e= Sum((m,t,SB)$(iter(m) = i),vSCED_Buy(SB,m,t)*SCED_BuyerPrice(SB,m)) - Sum((m,t,SS)$(iter(m) = i),vSCED_Sell(SS,m,t)*SCED_SellerPrice(SS,m));
eObjectiveIEX.. vObjectiveIEX =e= Sum((m,t,IB)$(iter(m) = i),vIEX_Buy(IB,m,t)*IEX_BuyerPrice(IB,m,t)) - Sum((m,t,IS)$(iter(m) = i),vIEX_Sell(IS,m,t)*IEX_SellerPrice(IS,m,t));
eObjectiveCoupled.. vObjectiveCoupled =e= Sum((m,t,SB)$(iter(m) = i),vCoupled_SCED_Buy(SB,m,t)*SCED_BuyerPrice(SB,m)) - Sum((m,t,SS)$(iter(m) = i),vCoupled_SCED_Sell(SS,m,t)*SCED_SellerPrice(SS,m))
                                        + Sum((m,t,IB)$(iter(m) = i),vCoupled_IEX_Buy(IB,m,t)*IEX_BuyerPrice(IB,m,t)) - Sum((m,t,IS)$(iter(m) = i),vCoupled_IEX_Sell(IS,m,t)*IEX_SellerPrice(IS,m,t));

eDemandSupplySCED(t).. Sum((m,SB)$(iter(m) = i),vSCED_Buy(SB,m,t)) =e= Sum((m,SS)$(iter(m) = i),vSCED_Sell(SS,m,t));
eDemandSupplyIEX(t).. Sum((m,IB)$(iter(m) = i),vIEX_Buy(IB,m,t)) =e= Sum((m,IS)$(iter(m) = i),vIEX_Sell(IS,m,t));
eDemandSupplyCoupled(t).. Sum((m,SB)$(iter(m) = i),vCoupled_SCED_Buy(SB,m,t))  + Sum((m,IB)$(iter(m) = i),vCoupled_IEX_Buy(IB,m,t)) =e= Sum((m,IS)$(iter(m) = i),vCoupled_IEX_Sell(IS,m,t))


eSCED_Sell_Limit(SS,m,t)$(iter(m) = i).. vSCED_Sell(SS,m,t) =l= SCED_SellerQuantum(SS,m);
eSCED_Buy_Limit(SB,m,t)$(iter(m) = i).. vSCED_Buy(SB,m,t) =l= SCED_BuyerQuantum(SB,m,t);

eIEX_Sell_Limit(IS,m,t)$(iter(m) = i).. vIEX_Sell(IS,m,t) =l= IEX_SellerQuantum(IS,m,t);
eIEX_Buy_Limit(IB,m,t)$(iter(m) = i).. vIEX_Buy(IB,m,t) =l= IEX_BuyerQuantum(IB,m,t);

eCoupled_SCED_Sell_Limit(SS,m,t)$(iter(m) = i).. vCoupled_SCED_Sell(SS,m,t) =l= SCED_SellerQuantum(SS,m);
eCoupled_SCED_Buy_Limit(SB,m,t)$(iter(m) = i).. vCoupled_SCED_Buy(SB,m,t) =l= SCED_BuyerQuantum(SB,m,t);
eCoupled_IEX_Sell_Limit(IS,m,t)$(iter(m) = i).. vCoupled_IEX_Sell(IS,m,t) =l= IEX_SellerQuantum(IS,m,t);
eCoupled_IEX_Buy_Limit(IB,m,t)$(iter(m) = i).. vCoupled_IEX_Buy(IB,m,t) =l= IEX_BuyerQuantum(IB,m,t);

eObjectiveSCED.. vObjectiveSCED =e= Sum((m,t,SB)$(iter(m) = i),vSCED_Buy(SB,m,t));
eObjectiveIEX.. vObjectiveIEX =e= Sum((m,t,IB)$(iter(m) = i),vIEX_Buy(IB,m,t));
eObjectiveCoupled.. vObjectiveCoupled =e= Sum((m,t,SB)$(iter(m) = i),vCoupled_SCED_Buy(SB,m,t)) + Sum((m,t,IB)$(iter(m) = i),vCoupled_IEX_Buy(IB,m,t));

eDemandSupplySCED(t).. Sum((m,SB)$(iter(m) = i),vSCED_Buy(SB,m,t)) =e= Sum((m,SS)$(iter(m) = i),vSCED_Sell(SS,m,t));
eDemandSupplyIEX(t).. Sum((m,IB)$(iter(m) = i),vIEX_Buy(IB,m,t)) =e= Sum((m,IS)$(iter(m) = i),vIEX_Sell(IS,m,t));
eDemandSupplyCoupled(t).. Sum((m,SB)$(iter(m) = i),vCoupled_SCED_Buy(SB,m,t))  + Sum((m,IB)$(iter(m) = i),vCoupled_IEX_Buy(IB,m,t)) =e= Sum((m,IS)$(iter(m) = i),vCoupled_IEX_Sell(IS,m,t))
                                                + Sum((m,SS)$(iter(m) = i),vCoupled_SCED_Sell(SS,m,t));

eSCED_Sell_Limit(SS,m,t)$(iter(m) = i).. vSCED_Sell(SS,m,t) =l= SCED_SellerQuantum(SS,m);
eSCED_Buy_Limit(SB,m,t)$(iter(m) = i).. vSCED_Buy(SB,m,t) =l= SCED_BuyerQuantum(SB,m,t);

eIEX_Sell_Limit(IS,m,t)$(iter(m) = i).. vIEX_Sell(IS,m,t) =l= IEX_SellerQuantum(IS,m,t);
eIEX_Buy_Limit(IB,m,t)$(iter(m) = i).. vIEX_Buy(IB,m,t) =l= IEX_BuyerQuantum(IB,m,t);

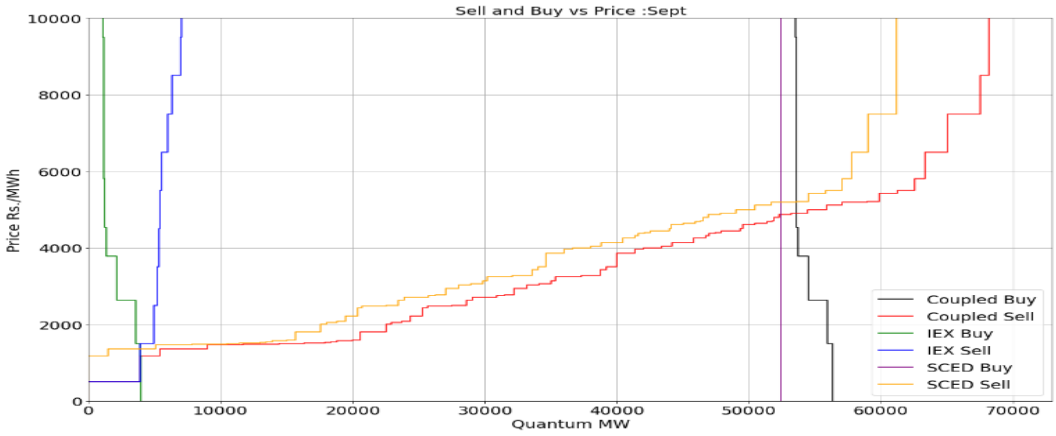
eCoupled_SCED_Sell_Limit(SS,m,t)$(iter(m) = i).. vCoupled_SCED_Sell(SS,m,t) =l= SCED_SellerQuantum(SS,m);
eCoupled_SCED_Buy_Limit(SB,m,t)$(iter(m) = i).. vCoupled_SCED_Buy(SB,m,t) =l= SCED_BuyerQuantum(SB,m,t);
eCoupled_IEX_Sell_Limit(IS,m,t)$(iter(m) = i).. vCoupled_IEX_Sell(IS,m,t) =l= IEX_SellerQuantum(IS,m,t);
eCoupled_IEX_Buy_Limit(IB,m,t)$(iter(m) = i).. vCoupled_IEX_Buy(IB,m,t) =l= IEX_BuyerQuantum(IB,m,t);


eSocialWelfareSCED(t).. Sum(m$(iter(m)=i),SocialWelfare("SCED",m,t)) =l= Sum((m,SB)$(iter(m) = i),vSCED_Buy(SB,m,t)*SCED_BuyerPrice(SB,m))
                                                                        - Sum((m,SS)$(iter(m) = i),vSCED_Sell(SS,m,t)*SCED_SellerPrice(SS,m));
eSocialWelfareIEX(t).. Sum(m$(iter(m)=i),SocialWelfare("IEX",m,t)) =l= Sum((m,IB)$(iter(m) = i),vIEX_Buy(IB,m,t)*IEX_BuyerPrice(IB,m,t))
                                                                        - Sum((m,IS)$(iter(m) = i),vIEX_Sell(IS,m,t)*IEX_SellerPrice(IS,m,t));
eSocialWelfareCoupled(t).. Sum(m$(iter(m)=i),SocialWelfare("Coupled",m,t)) =l= Sum((m,SB)$(iter(m) = i),vCoupled_SCED_Buy(SB,m,t)*SCED_BuyerPrice(SB,m))
                                                                        - Sum((m,SS)$(iter(m) = i),vCoupled_SCED_Sell(SS,m,t)*SCED_SellerPrice(SS,m))
                                                                        + Sum((m,IB)$(iter(m) = i),vCoupled_IEX_Buy(IB,m,t)*IEX_BuyerPrice(IB,m,t))
                                                                        - Sum((m,IS)$(iter(m) = i),vCoupled_IEX_Sell(IS,m,t)*IEX_SellerPrice(IS,m,t));
```

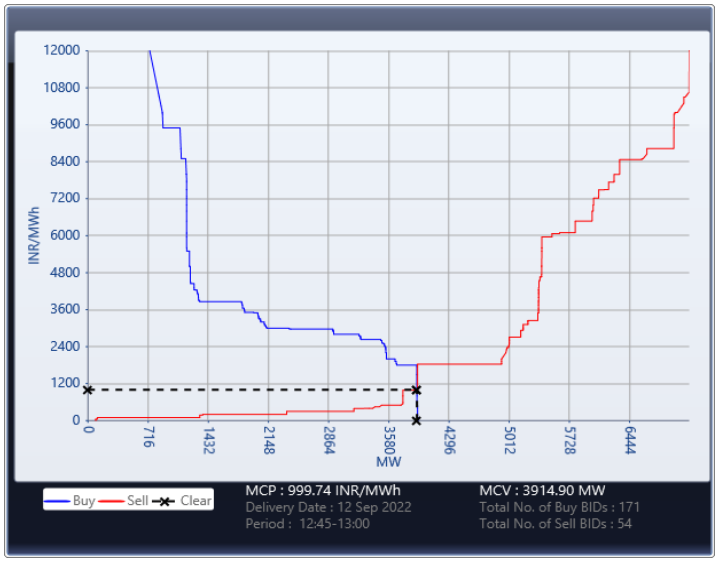
ANNEXURE 2: ADDITIONAL SAMPLE CASES

There are five sample time blocks presented in this section that illustrate transfers from SCED to IEX as well as IEX to SCED with MCP> SMP and SMP > MCP, respectively. Coupled market clearing volume (MCV) and MCP are also shown.

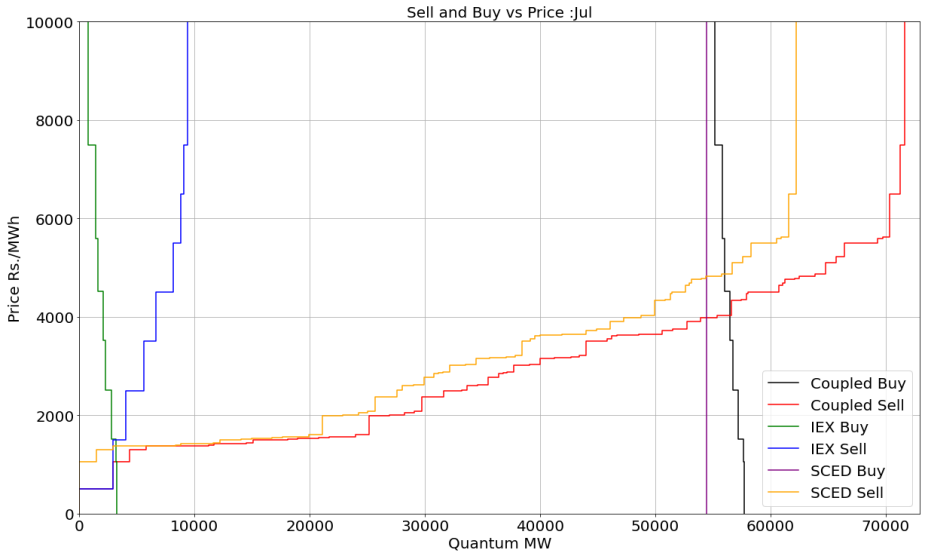
CASE 1: IEX MCP << SCED SMP : 12th September 2022 – 12:45-13:00 (Afternoon)



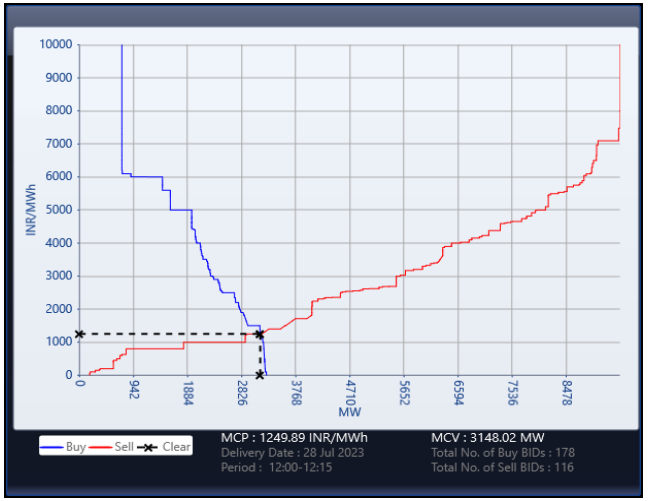
MM/DD/YYYY		
9/12/2022	12:45 (Afternoon)	
	MCV MW	**MCP Rs/MWh**
BAU IEX	3921	500
BAU SCED	52424	4994
BAU IEX+SCED	56345	
Coupled IEX+SCED	53632	4796
Coupled case: IEX SELL	5398	
Coupled case: SCED GEN	48234	
Coupled case: IEX DEMAND	1208	
Coupled case: SCED DEMAND	52424	
Coupled - IEX BAU	49711	4296
Coupled - SCED BAU	1208	-198



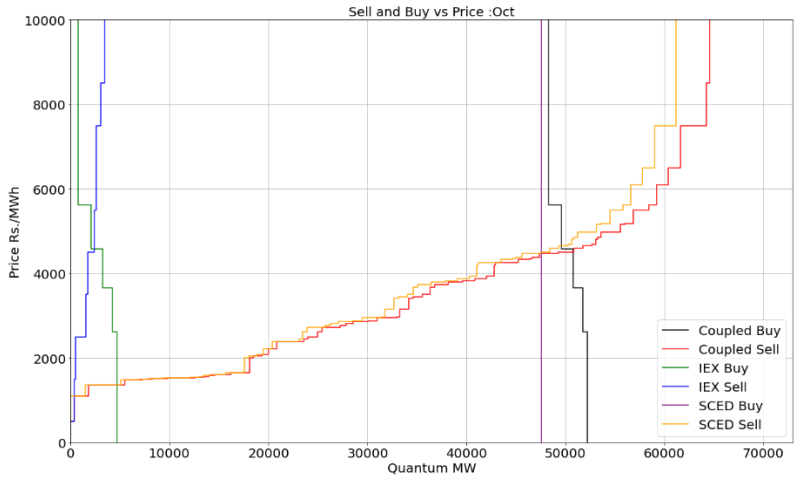
CASE 2: IEX MCP << SCED SMP – 28th July 2023 – 12:00-12:15 (Afternoon)



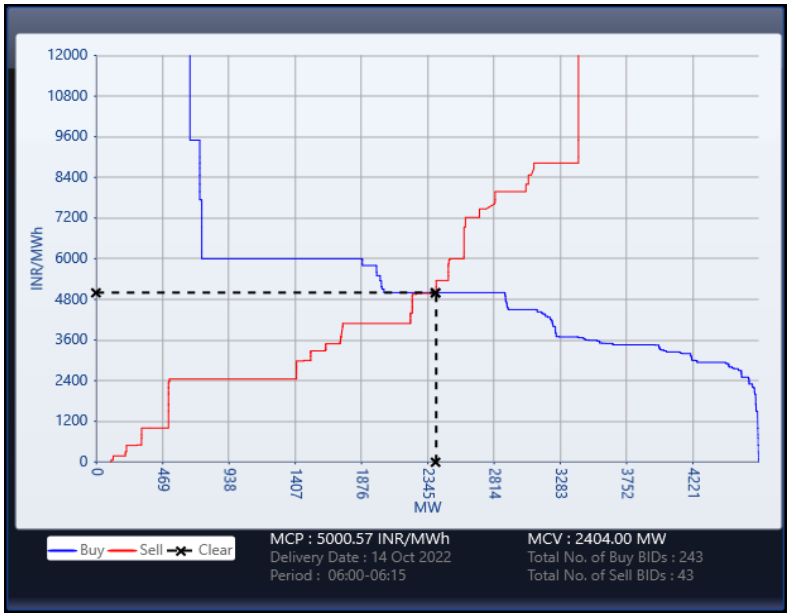
MM/D D/YYYY		
7/28/2023	12:00 (Afternoon)	
	MCV MW	**MCP Rs/MWh**
BAU IEX	3192	1500
BAU SCED	54449	4780
BAU IEX+SCED	57641	
Coupled IEX+SCED	56489	3979
Coupled case: IEX SELL	6636	
Coupled case: SCED GEN	49853	
Coupled case: IEX DEMAND	2040	
Coupled case: SCED DEMAND	54449	
Coupled - IEX BAU	53297	2479
Coupled - SCED BAU	2040	-801



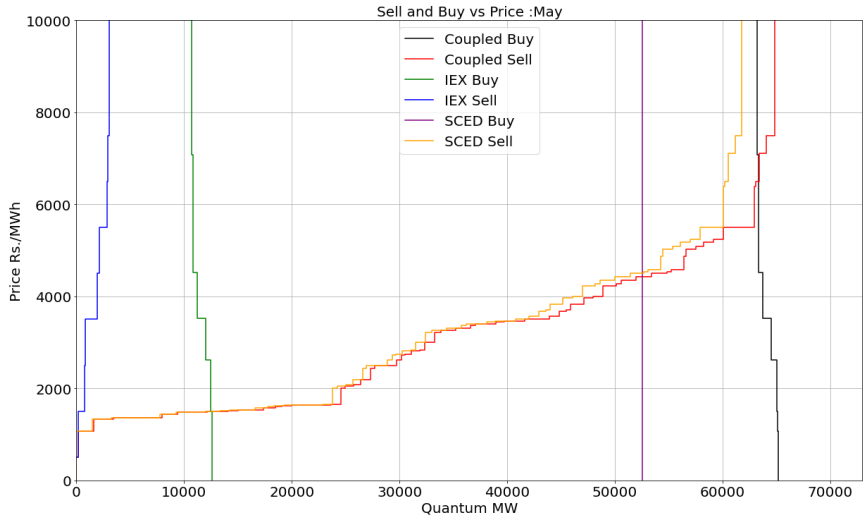
CASE 3: IEX MCP ~ SCED SMP – 14th October 2022 – 6:00-6:15 (Morning)



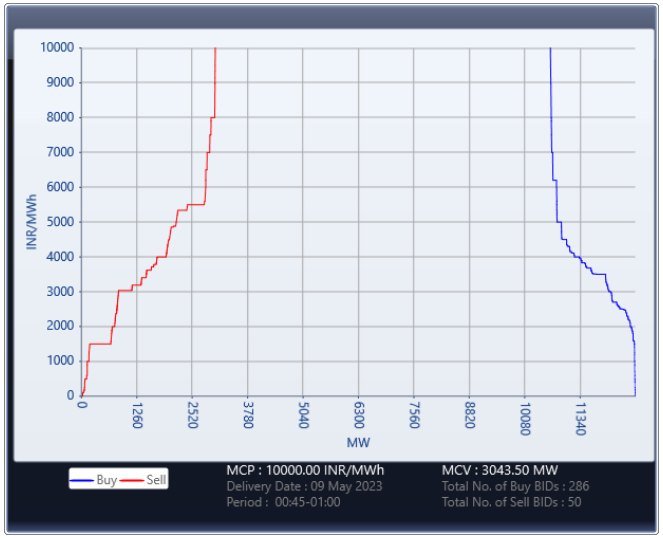
MM/DD/YYYY		
10/14/2022	06:00	
	MCV	**MCP Rs/MWh**
BAU IEX	2404	4500
BAU SCED	47576	4468
BAU IEX+SCED	49980	
Coupled IEX+SCED	50808	4500
Coupled case: IEX SELL	2348	
Coupled case: SCED GEN	48460	
Coupled case: IEX DEMAND	3232	
Coupled case: SCED DEMAND	47576	
Coupled - IEX BAU	48404	0
Coupled - SCED BAU	3232	32



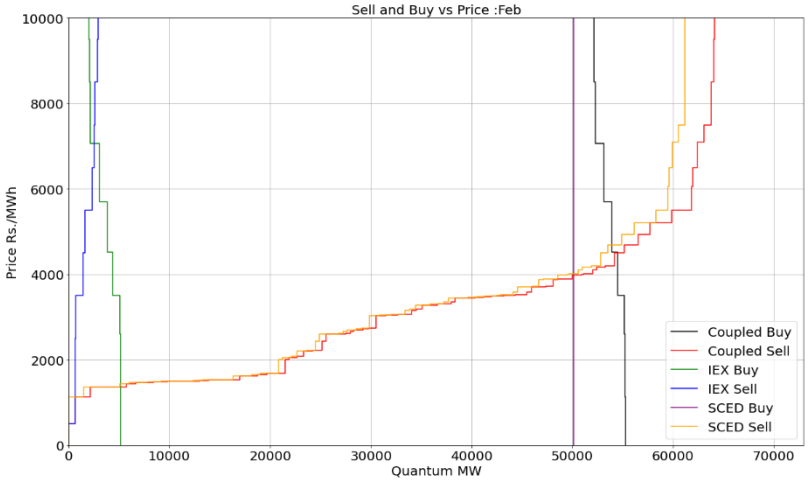
CASE 4: IEX MCP >> SCED SMP – 9th May 2023 – 00:45-01:00 (Night)



5/9/2023	00:45	
	MCV	**MCP Rs/MWh**
BAU IEX	3043	9500
BAU SCED	52560	4425
BAU IEX+SCED	55603	
Coupled IEX+SCED	63364	6500
Coupled case: IEX SELL	2838	
Coupled case: SCED GEN	60526	
Coupled case: IEX DEMAND	10804	
Coupled case: SCED DEMAND	52560	
Coupled - IEX BAU	60321	-3000
Coupled - SCED BAU	10804	2075



CASE 5: IEX MCP > SCED SMP – 9th Feb 2023 – 06:00-06:15 (Morning)



2/9/2023	06:00	
	MCV	**MCP Rs/MWh**
BAU IEX	2530	6500
BAU SCED	50140	4001
BAU IEX+SCED	52670	
Coupled IEX+SCED	54512	4197
Coupled case: IEX SELL	1417	
Coupled case: SCED GEN	53095	
Coupled case: IEX DEMAND	4372	
Coupled case: SCED DEMAND	50140	
Coupled - IEX BAU	51982	-2303
Coupled - SCED BAU	4372	196