Security and Emissions Constrained Economic Dispatch (SECED)

Relevance for Carbon Emissions Trading

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CONTEXT

- ✓ NLDC implemented Security Constrained Economic Dispatch (SCED) in 2019
  - Substantial production cost savings through SCED at the National Level
- ✓ India introduced the Carbon market in 2022 (Energy Conservation (Amendment) Act of 2022)
- ✓ BEE has compiled a detailed procedure for a compensation mechanism
- ✓ CERC's Regulation RA-14026(13)/1/2024-CERC for Carbon Credit Certificate trading scheme
- ✓ Time to consider an extension of the SCED framework to include emissions as constraints
  –A cheaper option through dispatch adjustments before other capital intensives are used.
  - ✓ Security and Emissions Constrained Economic Dispatch (SECED) tool to analyze how emissions reductions can be achieved during daily generation dispatch – prepare for the carbon market
  - ✓ Power generators and DISCOMs can use SECED to buy/sell Carbon Credit Certificates (CCC) when participation in the market is allowed; and couple SECED with the carbon market

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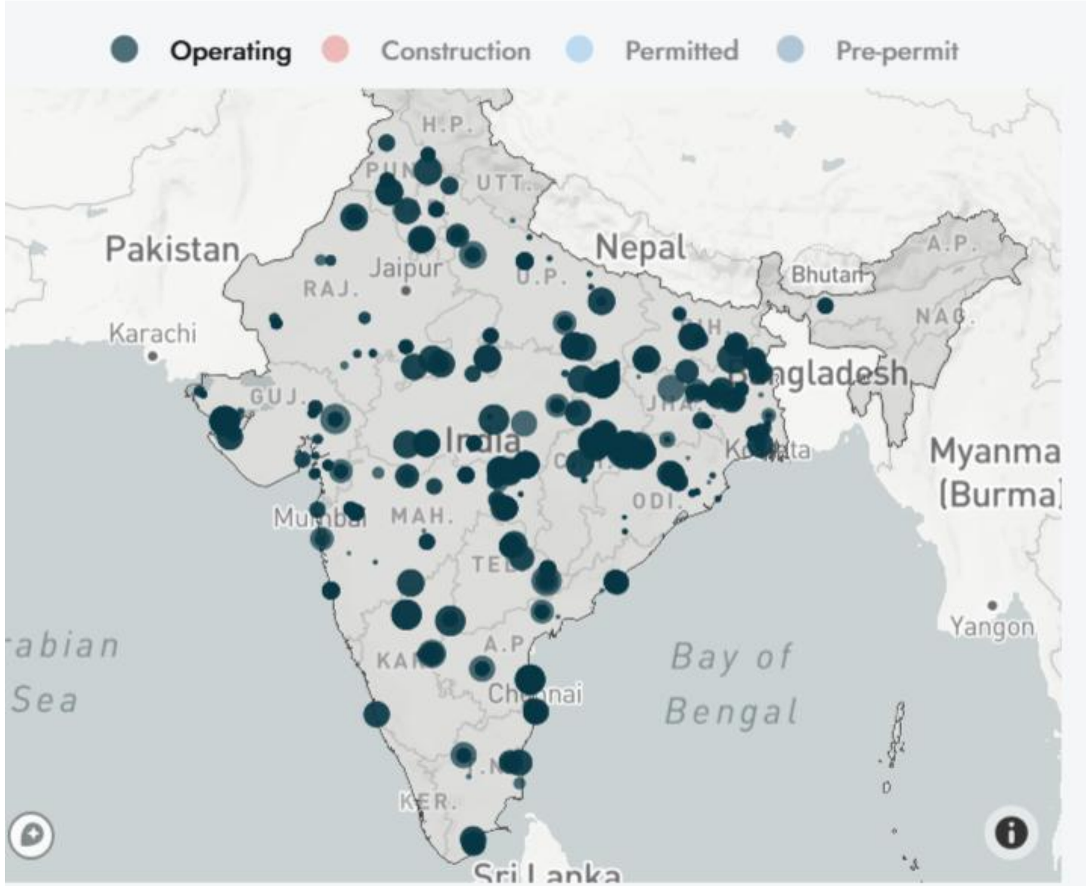
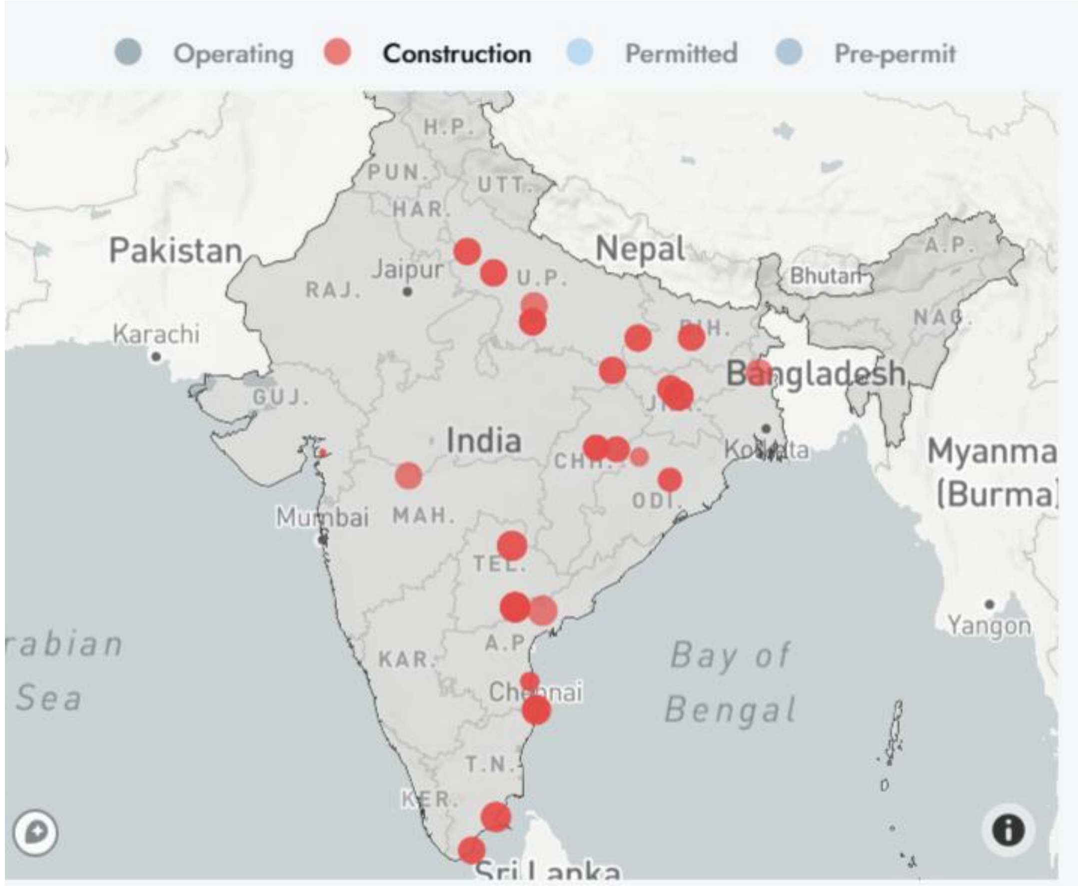
CONTEXT



Spread of Operating Coal Plant

Generation: 1380 TWh



Spread of Under-Construction Coal Plant

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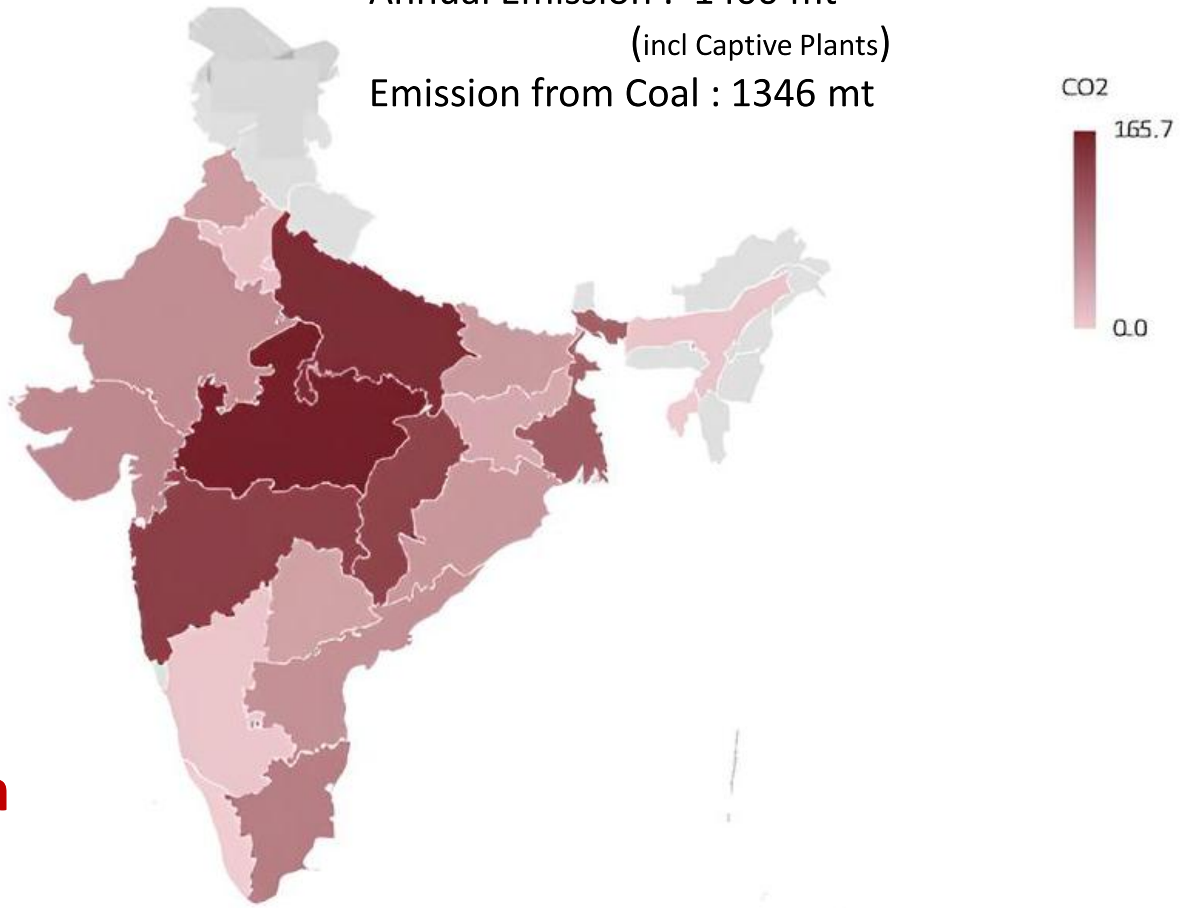
CONTEXT

1. Since 2000, Coal generation-related emissions have increased 3.7 fold
2. With average emissions growth in 43 mt pa
3. Recent years increase by around 60 mt pa
4. **RE generation reduces emission growth.**
5. Efforts needed to reduce CO2 emission
6. Carbon market is likely from 2026
7. **SECED a framework for emission reduction**

Distribution of Power Sector Emission

Year : 2023
Annual Emission : 1400 mt
(incl Captive Plants)
Emission from Coal : 1346 mt

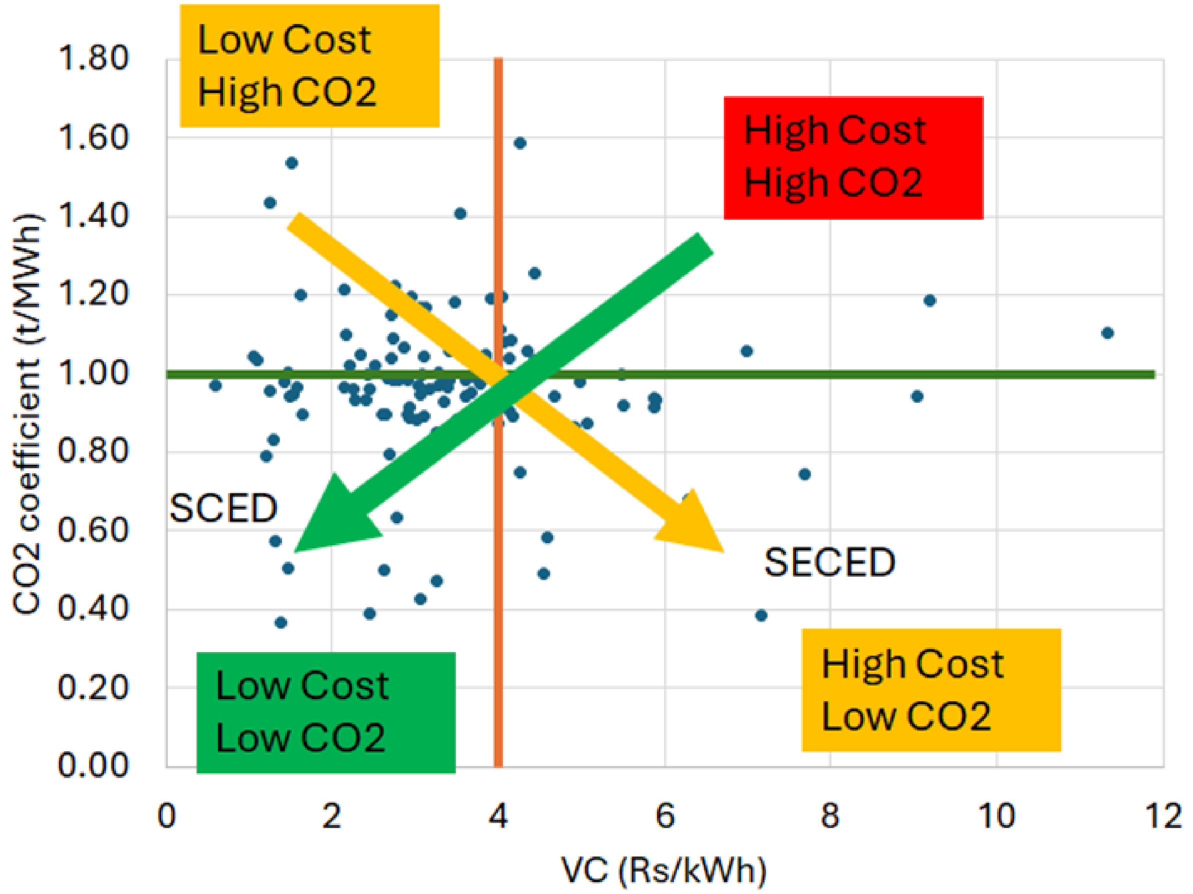


Objective of SECED

- SECED includes key aspects like variable costs (VC), emission and other parameters
- The shadow price of carbon will naturally emerge, and facilitate interventions
- Power plants will be implicitly incentivized to improve emission performance
- Data-intensive reports analysis of SECED —similar to the SCED
- No major structural disruption
- Advancements can be achieved within a regulated framework
- **Ensures that market mechanisms complement the regulated system**

SCED vs SECED – Trade -off

SCED will try to move the dispatch “horizontally” from high to low-cost units, while SECED will move them vertically.



Variable cost vs emission trade-off: SCED vs SECED

The dots on this scatter plot indicate specific plants based on the VC and CO_2 cost coefficient of plants all over India.

SECED – Probable Users - Benefits

Can be used by System and Market Operator, GenCos, DisComs, Policy makers, Planners, Regulators & Environmentalist

Short-Term Use:

- ✓ **Enhancing Dispatch with lower emission**
- ✓ **Enable GenCos to assess their emission level – A target could be set for further reduction**
- ✓ **Enable DisComs to assess their strategies**

Medium-Term Use:

- ✓ **Planners & Regulators - can decide to phase out generators with high emissions.**
- ✓ **Operational planning including fuel allocation, maintenance planning and resource adequacy studies**
- ✓ **Can include constraints on CO_2 as well as local pollutants**

Produce System Marginal Price (SMP) and Marginals & Average price of each pollutant

SECED Framework and Carbon Market

- Power Sector will be included the Indian Carbon Market (ICM) in future
- A pilot study could be done for insights
- A centralized approach by Load despatchers to reduce emission
- Reduces burden on carbon markets
- Implicit swapping of plant generation based on emission maintaining MW demand
- Compliments Carbon Credit Certificate (CCC) trades
- Implicit efficient trading among generators with high and low emissions
- Introduces
  - ✓ Indirect competition
  - ✓ Fosters transparency
  - ✓ Enhance accountability
  - ✓ Market-led reduction of emissions

Plant-wise measurement of emissions mandatory

- GenCos having permits need not change the dispatch
- (CCC vis-à-vis REC)
- Cheaper option for dispatch adjustment should be used

Objectives of SECED – Daily Dispatch

Daily Dispatch by NLDC and SLDCs

- ➢ Can be built on the existing SCED tool
  - ✓ Add emission variables that are linear functions of generation
  - ✓ Add emission constraints for each pollutant
  - ✓ Carefully cluster the plants producing high-emission
  - ✓ Place limits(Constraints) for this group of plants
- ➢ Emission-constrained dispatch is a very cost-effective way to reduce emission
- ➢ Avail the feasible emission reduction first by re-dispatching
- ➢ Find out Marginals cost (Shadow Price) for emission constraints
- ➢ Compare the levelized cost of investment for the proposed equipment
- ➢ Shadow price also pinpoints the generators for possible reduction

Objectives of SECED – Multi-year Planning

Planning function:

- ✓ **Development of Tool for up to one year or more for Operational Planning**
- ✓ **Off-line tool for multi-year study**
- ✓ **Planning to decide on retirement of units in next 5 – 10 years**
- ✓ **Adjustments of plant maintenance schedule to utilize renewable resources optimally**
- ✓ **Adjustment of PPAs with high cost & high emission implications**
- ✓ **Possible to form a priority list for Resource Adequacy options to meet peak demand**
- ✓ **Provide year-ahead SMPs – could be useful as a benchmark to wholesale market price**

SECED Model Implementation: Key Features of the prototype model used for the analysis

1. SECED model: All-India single-node demand-supply balance with CO_2, SO_x, NO_x, SPM & SCED constraints (ramp, min-gen, capacity).
2. Hourly resolution, solved as a single LP for 8,760 hours.
3. 265 thermal plants: Includes variable costs & emission coefficients.
4. Demand: Based on NITI Aayog 2023 data.
5. Non-thermal generation (hydro, RE) netted off using actual CEA data for RE profiles; model dispatches thermal plants only.
6. Scenarios: Includes new hydro, solar, wind, nuclear for emissions limits(planning function).
7. Emissions constraints: Daily, monthly, annual limits;
8. Enables carbon shadow pricing trading.

SECED Model Implementation: Key Features of the prototype model used for the analysis

8. Carbon permits (exogenous price) used to meet CO_2 limits, treated as a slack variable in dispatch & capacity optimization.
9. Emissions-constrained dispatch analyzed for Maharashtra or pan-India to assess system cost & redispatch under tighter constraints.
10. Minimum CO_2 solution obtained to determine the maximum possible reduction in thermal generation & cost vs. emissions trade-off.
11. Carbon permits (\$10-\$100/ton) were tested to analyze the impact on dispatch costs & permit trading decisions (links to ICM coupling).
12. SECED planning evaluates clean energy capacity as a cost-effective CO_2 reduction strategy, especially under high permit prices & strict limits.

Appendix includes a formulation of the SECED model

Emission Price and Revenue

SECED could be used in two ways

With Emission Cap:

- **SECED will re-dispatch generation to honour the Emission Cap**
- **Emission Cap is used as constraints**

With CO_2 permit price:

- **Permit price (multiplied by Emission coef.) is added to VC**
- **No change in SCED formulation**

	Capacity (MW)	Cost (₹/MWh)	Emission coef. (t/MWh)
Sugen CC	1147	8800	0.37
Kudgi	2400	5040	0.84
Surat Lignite	500	2140	1.16

Demand: **2500 MW**

Emission Cap:

- **Scenario 1: 2500 ton**
- **Scenario 2: 2000 ton**

Note: Switching 1 MWh from Kudgi→Sugen CC implies a cost of CO2 = (8800-5040)/(0.84-0.37) = Rs 8000/t. This is lower than a switch from Surat to Sugen at Rs 8430 or Surat to Kudgi at Rs 9062/t. Therefore, CO2 reductions will follow dispatch adjustment in that order…

Emission Price and Revenue

Scenario – 1 (Emission Cap: 2500 Ton)

	Dispatch (MW)	CO_2 (t)	Shadow Price (Power) (₹/MWh)	Shadow Price (CO_2) (₹/t)	Shadow Price Cap limit) (₹/MW)	Revenue (₹) '000
Sugen	0	0	5040	0	0	0
Kudgi	2000	1680	5040	0	0	10080
Surat	500	580	5040	0	2900	1070
	2500	2260				11150

Output 1:

- **Only Surat Cap hit**
  Shadow Price: ₹2900
- **SMP : ₹5040**
- **No CO_2 constraints**
- **Total Revenue: ₹11150000**

Revenue Calculation: (Kudgi = 2000*5040)/1000+ (Surat = 500*5040 -500*2900)/1000 = 11150

Scenario – 2 (Emission Cap: 2000 Ton)

	Dispatch (MW)	CO_2 (t)	Shadow Price (Power) (₹/MWh)	Shadow Price (CO_2) (₹/t)	Shadow Price Cap limit) (₹/MW)	Revenue (₹) '000
Sugen	553.2	204.7	11760	8000	0	4868.1
Kudgi	1446.8	1215.3	11760	8000	0	7291.9
Surat	500	580.0	11760	8000	340	1070
	2500	2000				13230

Output 2:

- **Only Surat Cap hit**
  Shadow Price: ₹340
- **SMP: ₹11760**
- **CO_2 constraints hit**
- **Shadow Price: ₹8000***
- **Total Revenue: ₹13230000**

Revenue Calculation: (Sugen = 553.2*11760 – 204.7*8000) /1000+ (Kudgi = 1446.8*11760 – 1215.3*8000)/1000 + (Surat= 500*11760 - 580*8000 -340*500) /1000= ₹13230

Preliminary Results from SECED Simulations

Cost of CO2 Reduction from the Power Sector

Adjust dispatch to meet specified emissions targets

(CO2, Sox, Nox, SPM) at a daily, monthly, quarterly or annual level

SIMULATION RUN – ALL INDIA (DAILY CO2 LIMITS APPLIED) 2023

Comparison of CO_2 emissions reduction scenarios: All India

	Unconstrained	1150 MT	1100 MT	1050 MT	1000 MT
System Cost ₹ millon	3,197,123	3,280,854	3,577,762	3,899,523	4,229,638
Thermal Generation TWh	1,230	1,230	1,185	1,136	1,086
CO_2 mt	1,200	1,150	1,100	1,050	1,000
Marginal CO_2 Price (₹/t)		4,689	6,224	6,508	6,647
Avg Cost of CO_2 (₹/t)		1,673	3,805	4,682	5,162
Average generation cost (₹/MWh)	2,600	2,668	3,020	3,434	3,894

Planning Model :

All India run for 8760 hrs

Unconstrained CO_2 : 1200mt

Price increases with lower Cap

Avg CO2 Price Range: ₹1673 - ₹5162

Daily Model :

CO_2 reduction per day: 5% (60 mtpa)

All India run for 8760 hrs

Price varies hourly and daily

Avg Price : ₹ 2287/t

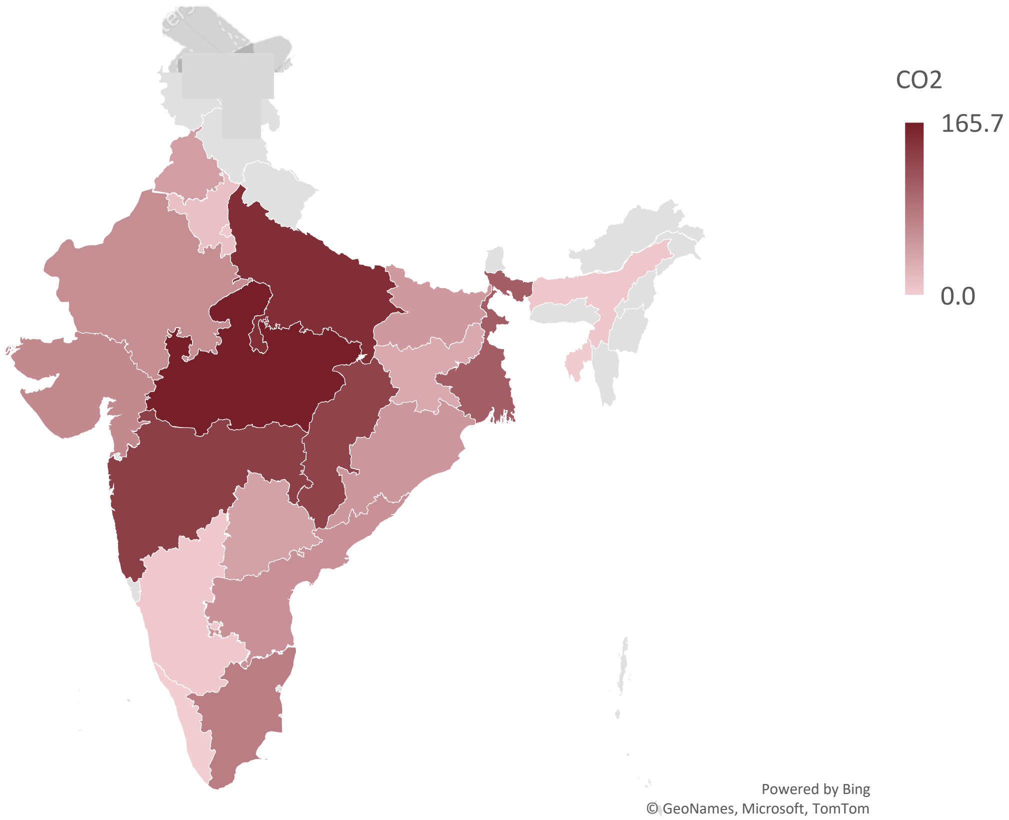
Price Range: ₹ 1731/t to ₹ 3191/t

Trade-off among COST and CO2 (Daily CO2 Limits Applied)

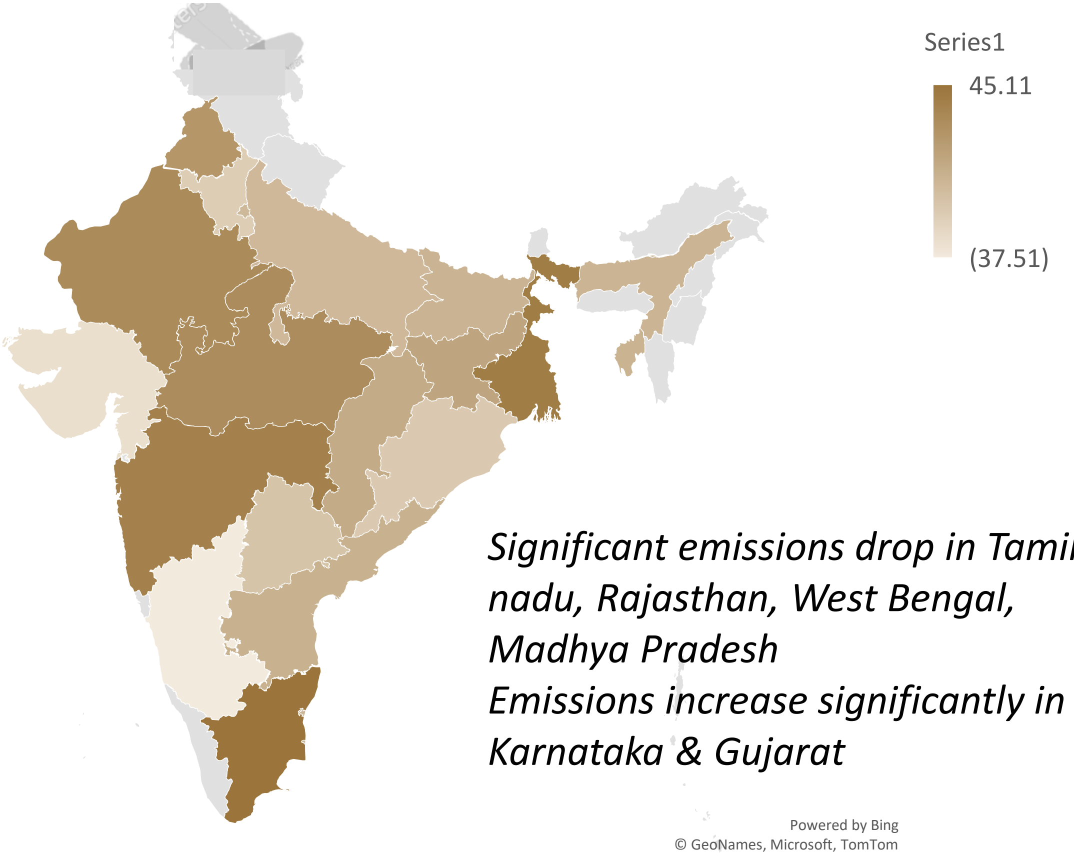
Description	Unconstrained	"CO2" Constrained (1% Reduction)	"CO2" Constrained (3% Reduction)	"CO2" Constrained (5% Reduction)	"CO2" Constrained (5.5% Reduction)	"CO2" only Optimised
System Cost (Rs mill)	3436403	3441608	3485470	3578800	3614615	4279405
Thermal Generation (TWh)	1230	1230	1230	1230	1230	1230
CO2 mt	1209	1197	1172	1148	1142	1105
SO2 m kg	6915	6834	6718	6615	6585	6516
NOx m kg	2954	2956	2954	2950	2950	2851
SPM m kg	458	454	441	426	423	395
Unit Cost (₹/MWh)	2794	2799	2834	2910	2939	3480
CO2 Shadow price (₹/t)	N/A	1267	3180	5445	5630	N/A

ANNUAL CO2 EMISSIONS BY STATE (MILLION TONS)

Unconstrained **Total Emission** (mt)

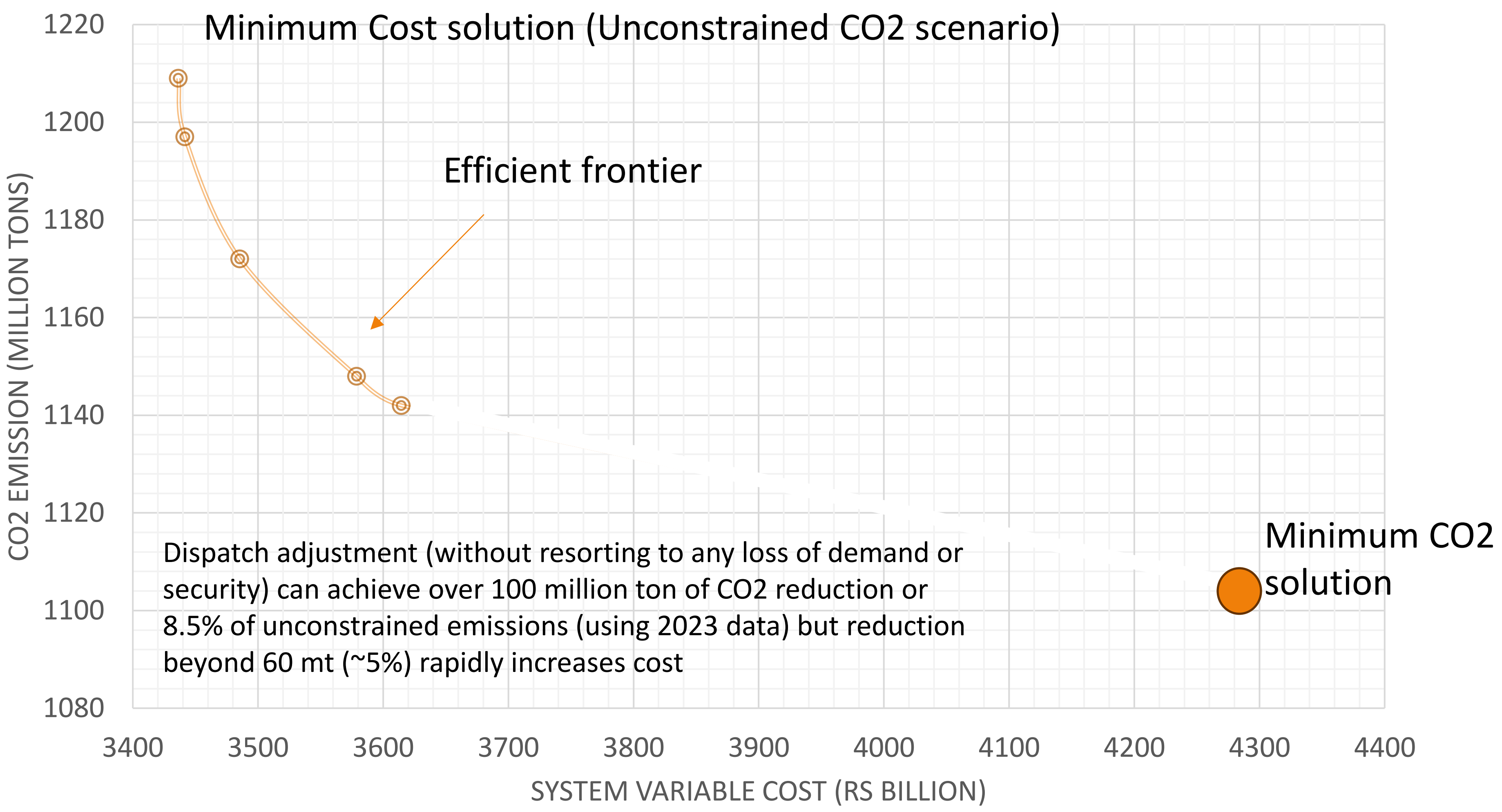


Difference in state emissions between Unconstrained and 10% Emission Reduction



Significant emissions drop in Tamil nadu, Rajasthan, West Bengal, Madhya Pradesh
Emissions increase significantly in Karnataka & Gujarat

Trade-off among COST and CO2 (Daily CO2 Limits Applied)



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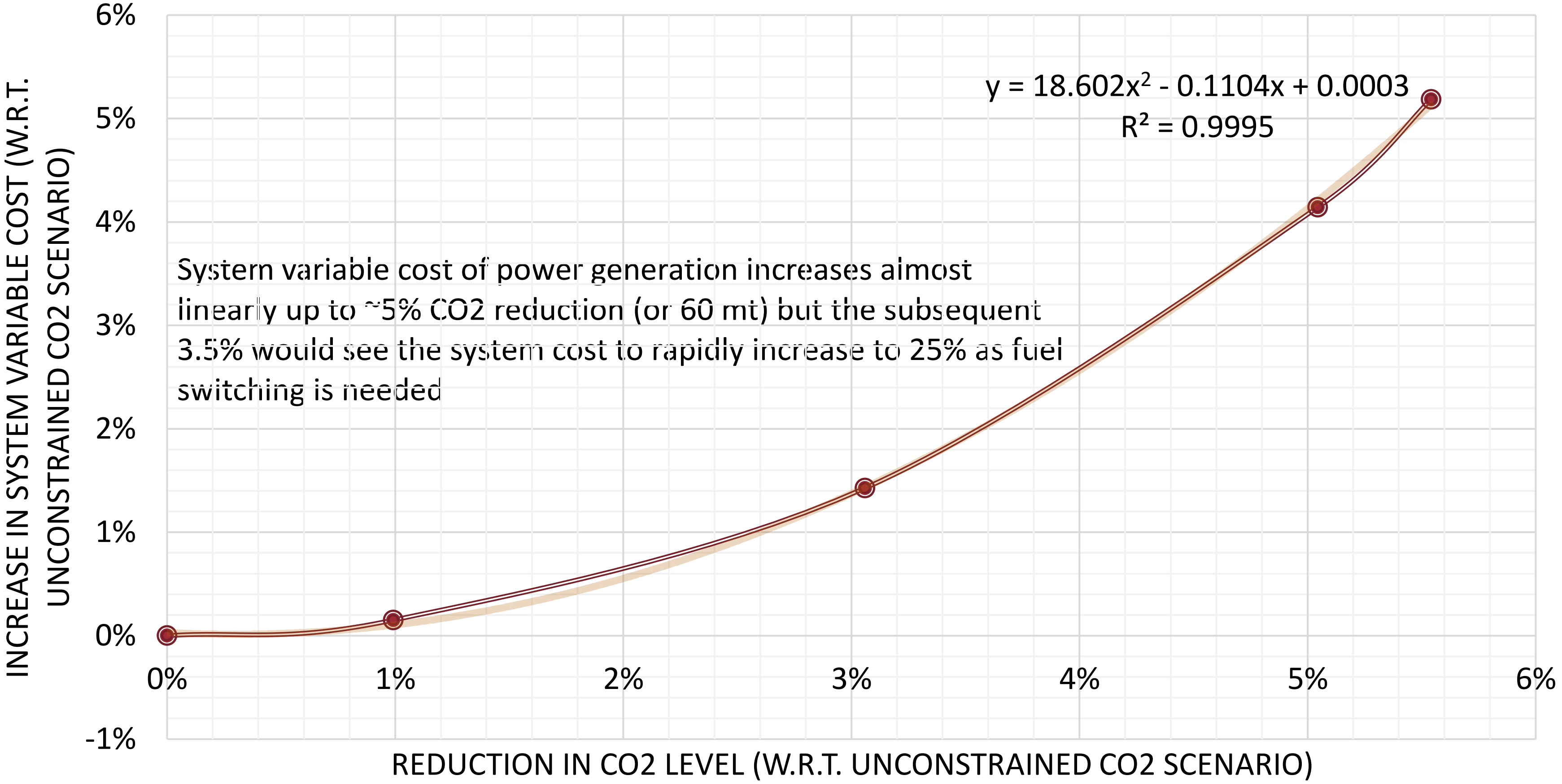
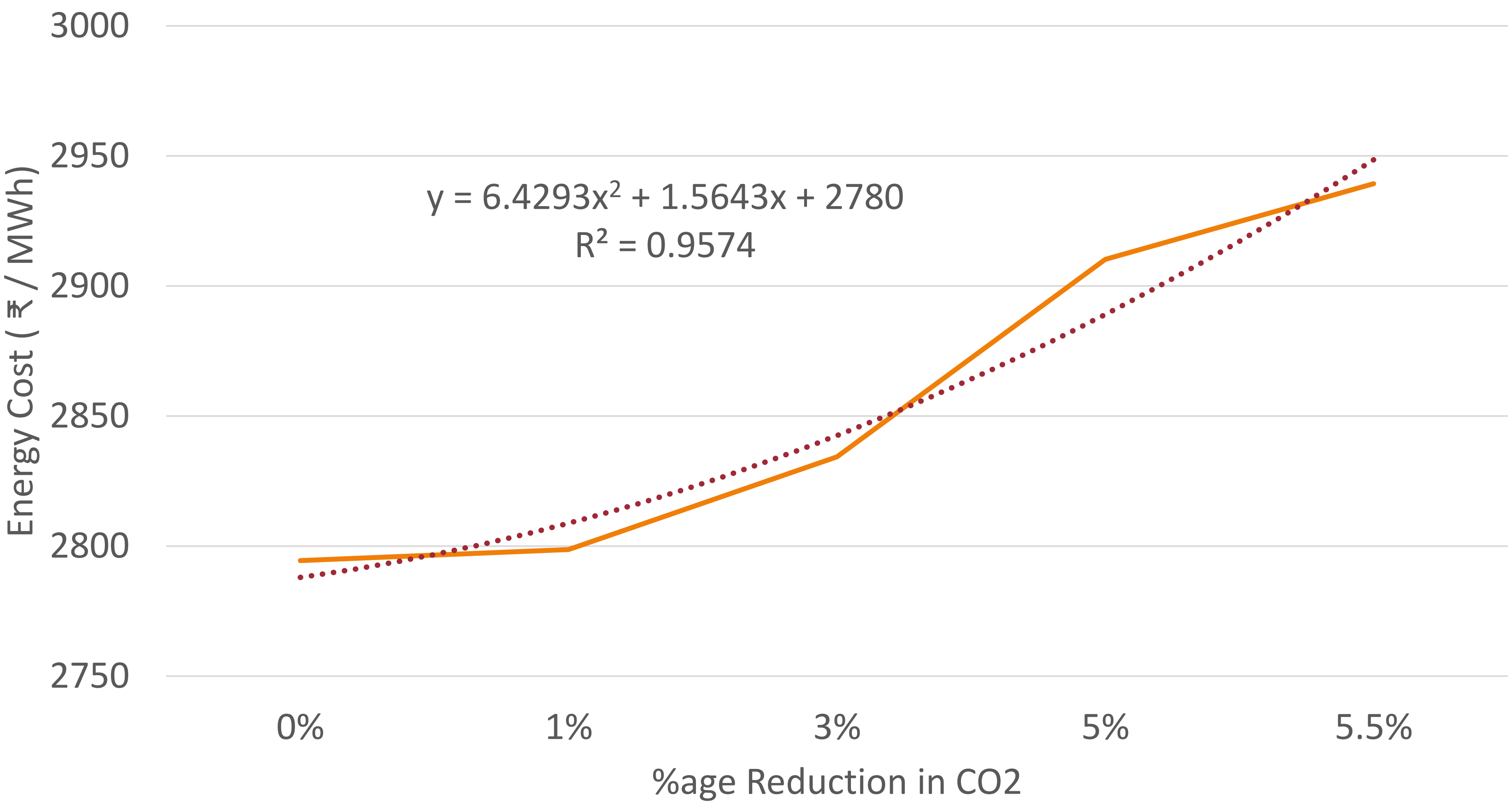
TRADE-OFF AMONG COST AND CO2 (DAILY CO2 LIMITS APPLIED)

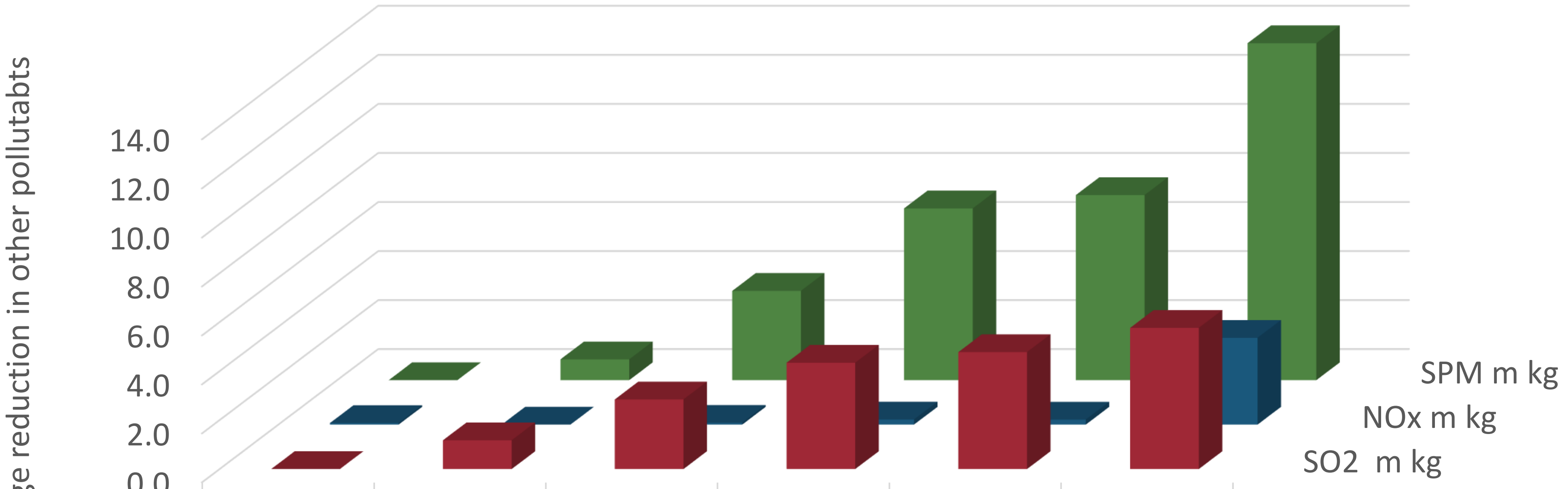


Increase in Energy Price with restriction in Emission



(Daily CO2 Limits Applied)

CO-RELATION OF OTHER POLLUTANTS WITH CO2

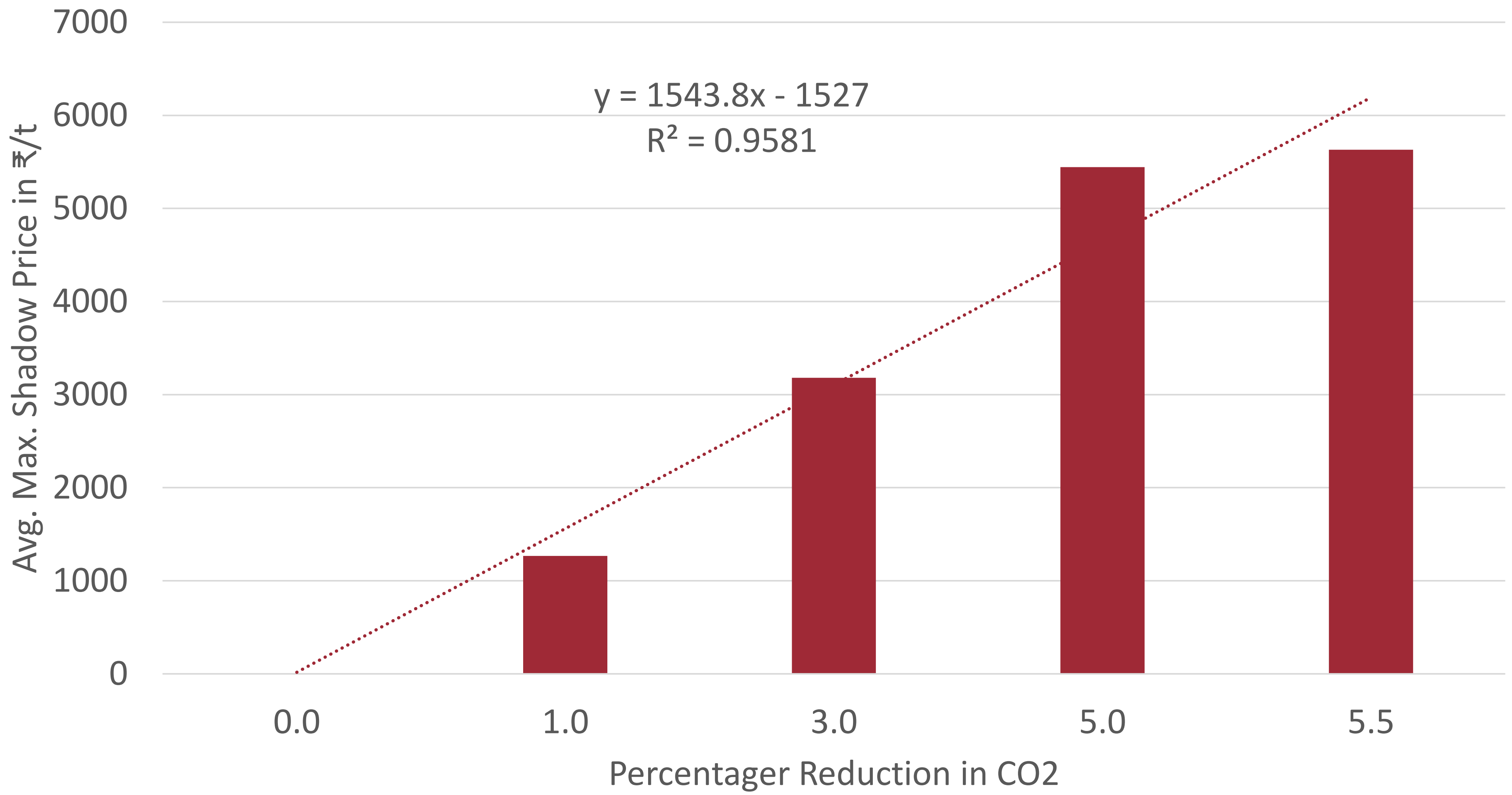


	0%	1%	3%	5%	5.5%	8.5%
SO2 m kg	0.0	1.2	2.8	4.3	4.8	5.8
NOx m kg	0.1	0.0	0.1	0.2	0.2	3.5
SPM m kg	0.0	0.8	3.6	7.0	7.6	13.7

%age reduction in CO2

(Daily CO2 Limits Applied)

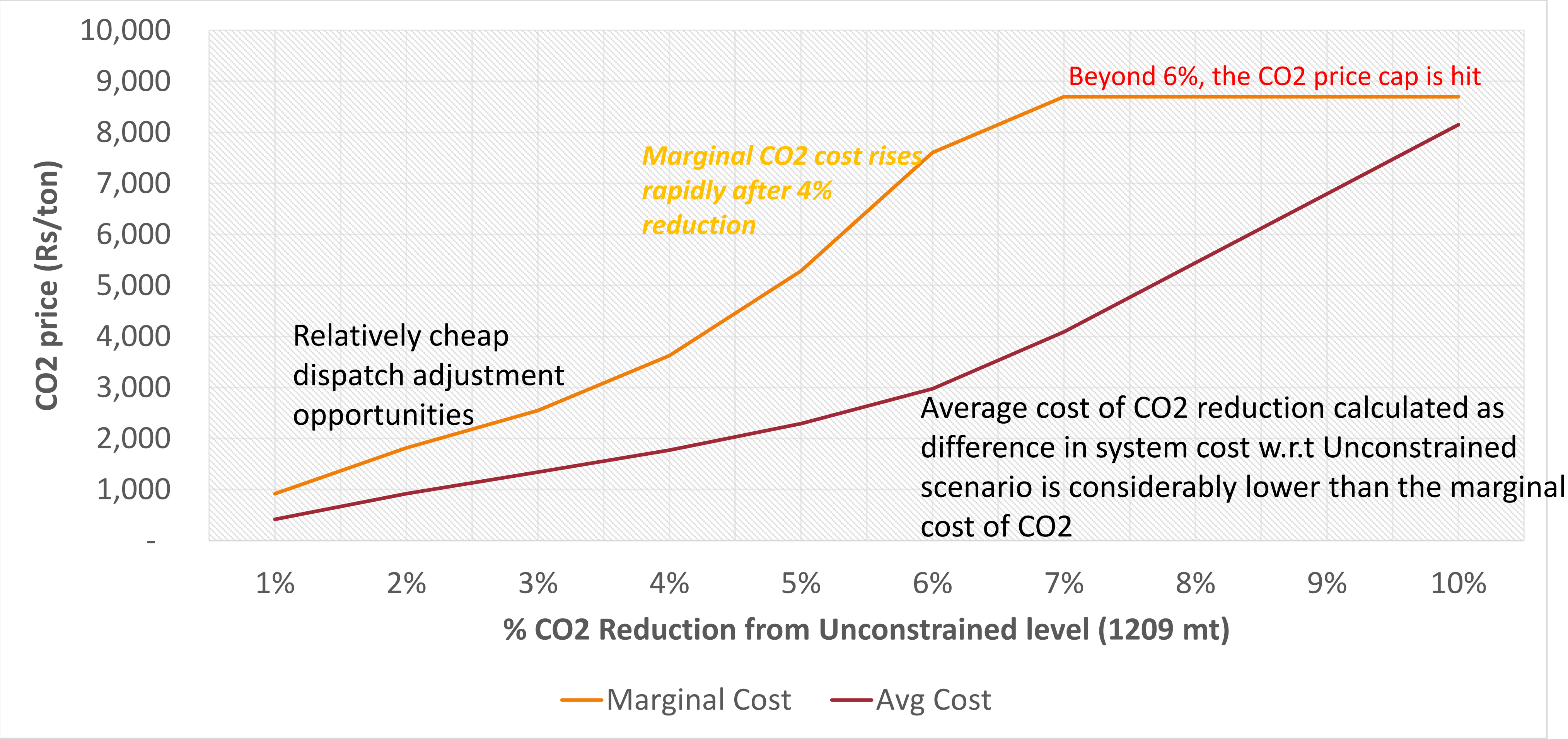
Shadow Price of CO2



(Daily CO2 Limits Applied)

Avg vs Marginal Cost of CO2 (Annual CO2 Limits Applied)

We also analyzed a case with annual CO2 limits (rather than daily CO2 limits which are more restrictive) and also used a high Rs 8700/t ($100/t) price cap for CO2 to avoid infeasibility : **73 mt of 6% of Unconstrained CO2 level can be reduced through dispatch adjustment for a total cost increase of Rs 215 billion.**



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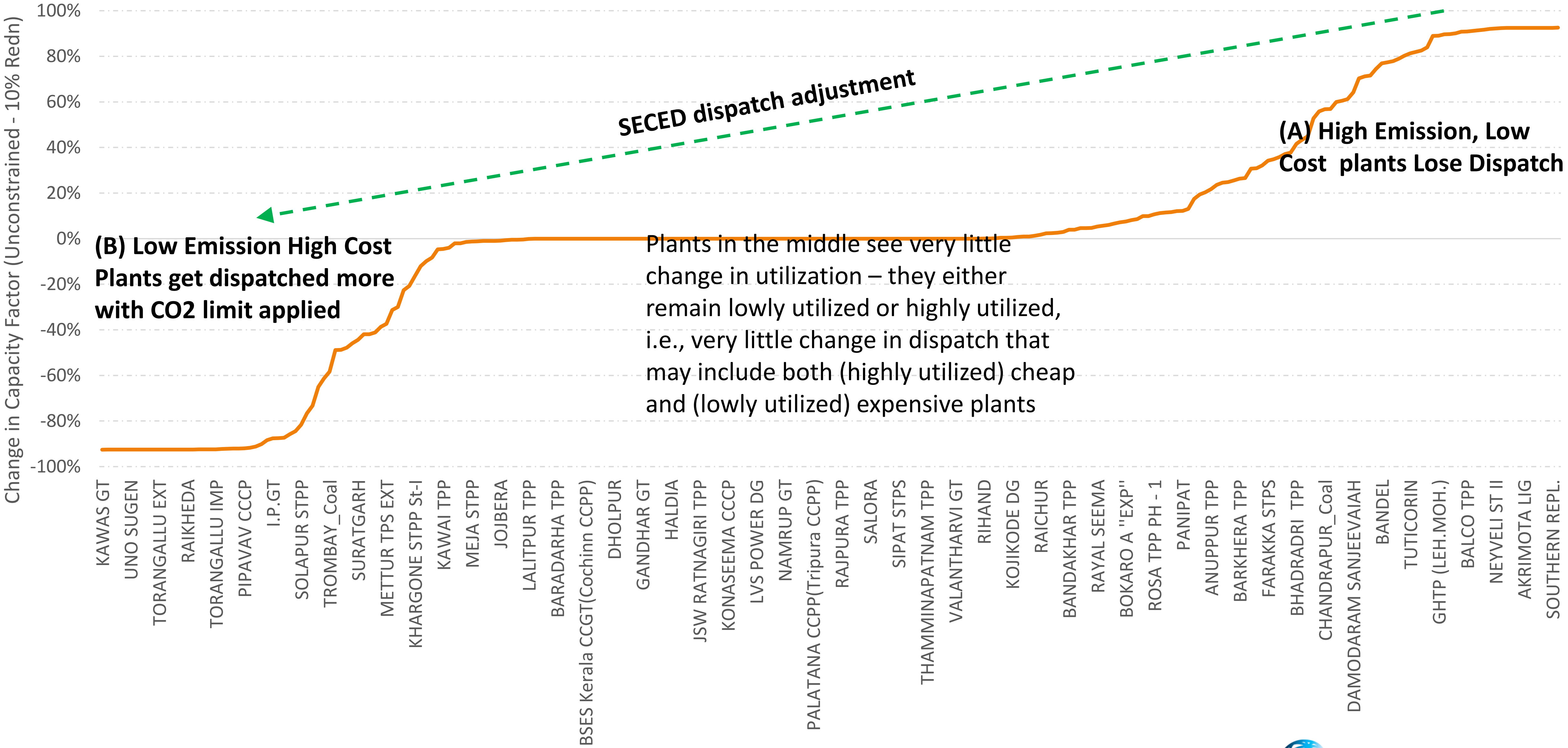
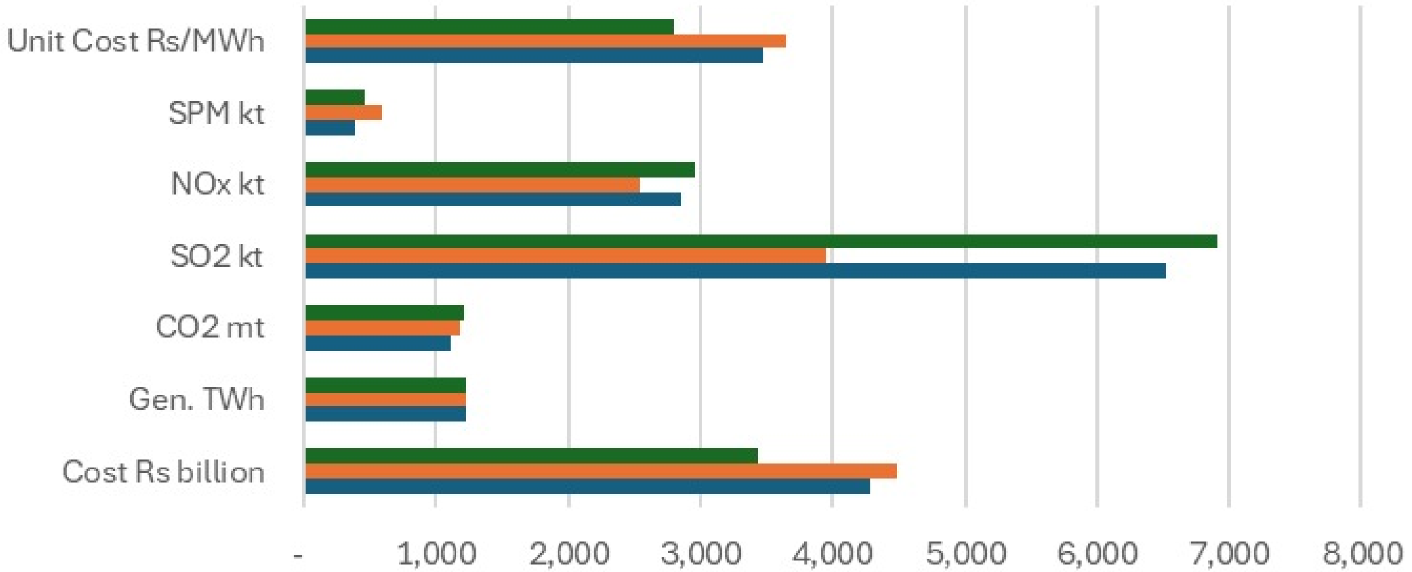


Change in Capacity Factor (Unconstrained - 10% Redn)
100%
80%
60%
40%
20%
0%
-20%
-40%
-60%
-80%
-100%
SECED dispatch adjustment
(A) High Emission, Low Cost plants Lose Dispatch
(B) Low Emission High Cost Plants get dispatched more with CO2 limit applied
Plants in the middle see very little change in utilization – they either remain lowly utilized or highly utilized, i.e., very little change in dispatch that may include both (highly utilized) cheap and (lowly utilized) expensive plants
KAWAS GT
UNO SUGEN
TORANGALLU EXT
RAIKHEDA
TORANGALLU IMP
PIPAVAV CCCP
I.P.GT
SOLAPUR STPP
TROMBAY_Coal
SURATGARH
METTUR TPS EXT
KHARGONE STPP St-I
KAWAI TPP
MEJA STPP
JOJBERA
LALITPUR TPP
BARADARHA TPP
BSES Kerala CCGT(Cochinn CCPP)
DHOLPUR
GANDHAR GT
HALDIA
JSW RATNAGIRI TPP
KONASEEMA CCCP
LVS POWER DG
NAMRUP GT
PALATANA CCPP(Tripura CCPP)
RAJPURA TPP
SALORA
SIPAT STPS
THAMMINAPATNAM TPP
VALANTHARVI GT
RIHAND
KOJIKODE DG
RAICHUR
BANDAKHAR TPP
RAYAL SEEMA
BOKARO A "EXP"
ROSA TPP PH - 1
PANIPAT
ANUPPUR TPP
BARKHERA TPP
FARAKKA STPS
BHADRADRI TPP
CHANDRAPUR_Coal
DAMODARAM SANJEEVAIAH
BANDEL
TUTICORIN
GHTP (LEH.MOH.)
BALCO TPP
NEYVELI ST II
AKRIMOTA LIG
SOUTHERN REPL.

Cost for SO_2 and CO_2 comparison

Comparison of Min Cost, SO2 and CO2 solutions



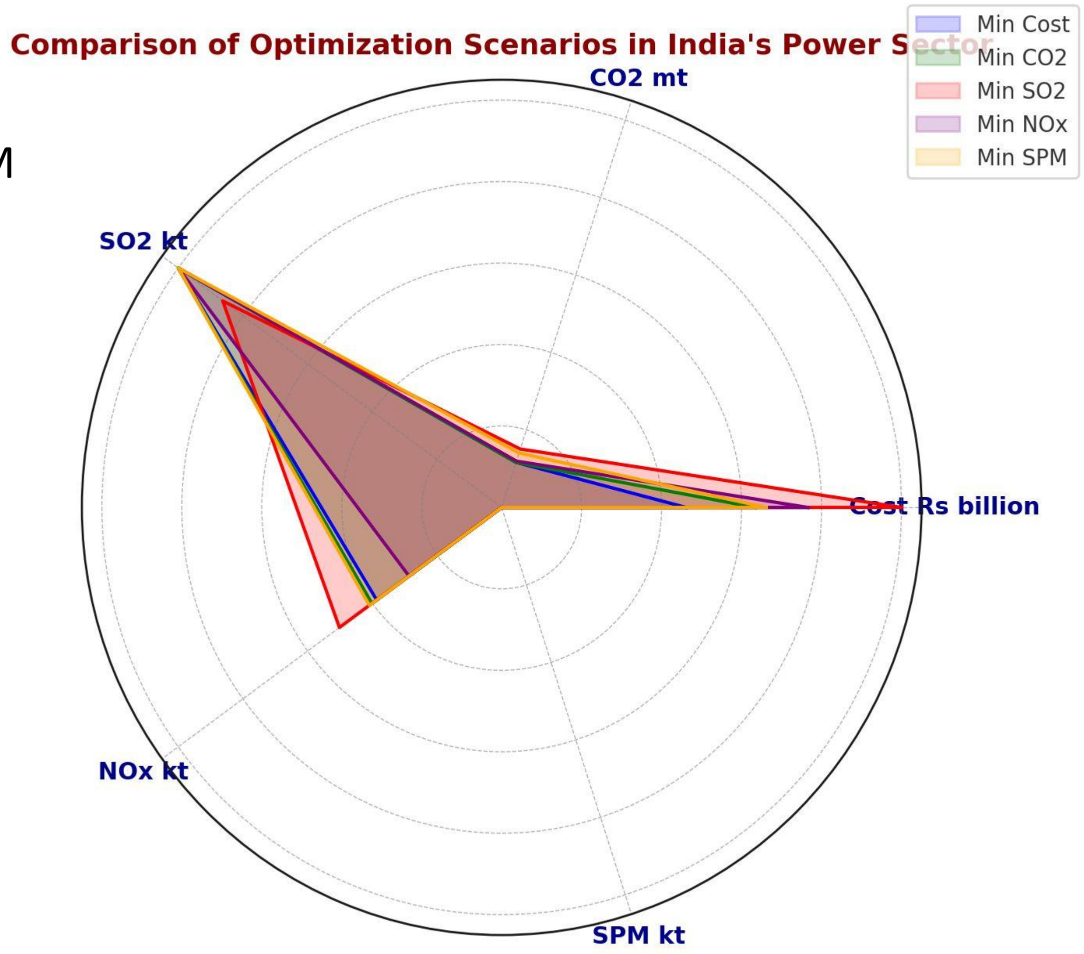
	Cost Rs billion	Gen. TWh	CO2 mt	SO2 kt	NOx kt	SPM kt	Unit Cost Rs/MWh
Min Cost	3,436	1,230	1,209	6,915	2,954	458	2,793
Min SO2	4,490	1,230	1,177	3,954	2,546	588	3,651
Min CO2	4,279	1,230	1,105	6,516	2,851	395	3,479

Min Cost Min SO2 Min CO2

MINIMIZATION OF SO_2, NO_X AND SPM

- ✓ Reduction of one pollutant leads to reduction of others except SPM
- ✓ Separate optimization runs possible to minimize specific pollutants
- ✓ Reduction of specific pollutants at specified area possible

	Min Cost	Min CO2	Min SO2	Min Nox	Min SPM
Cost Rs billion	**3,436**	4,279	4,490	4,565	4,235
CO2 mt	1,209	**1,105**	1,177	1,175	1,174
SO2 kt	6,915	6,516	**3,954**	5,794	6,223
NOx kt	2,954	2,851	2,546	**2,052**	2,752
SPM kt	458	395	588	548	**349**
Unit Cost Rs/MWh	2,793	3,479	3,651	3,712	3,444
Gen. TWh	1,230	1,230	1,230	1,230	1,230



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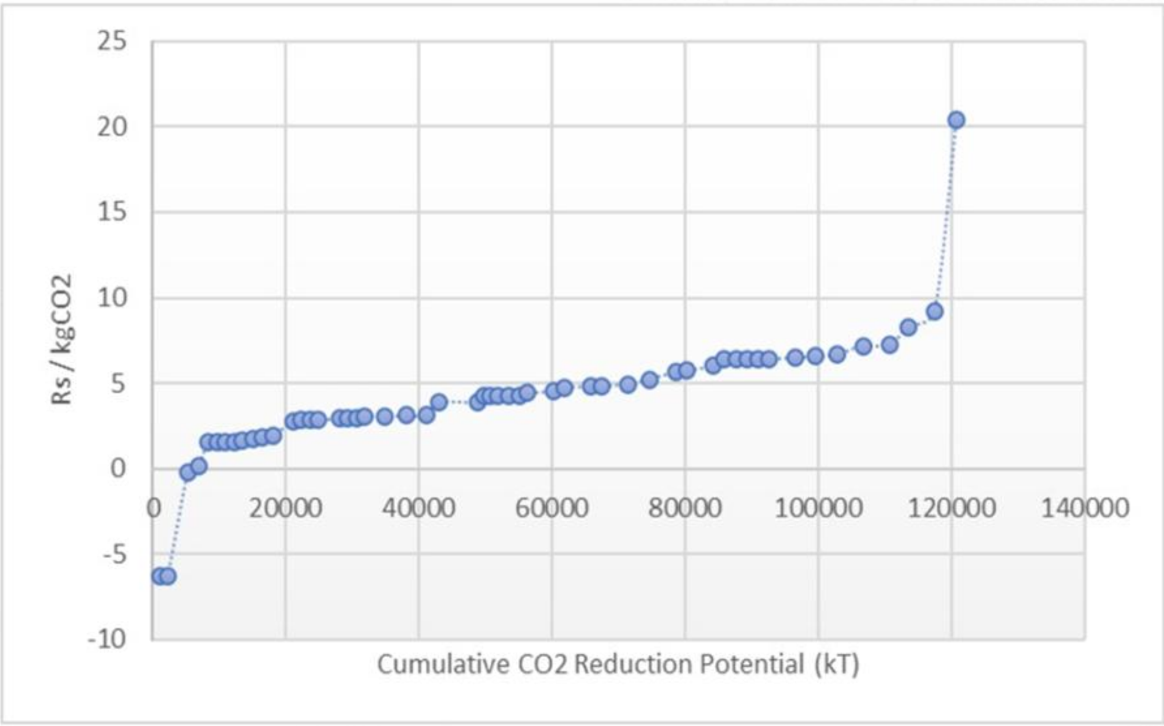
Cost of CO_2 Reduction - Maharashtra

(5.8 – VC of coal/gas plant)/(CO2 coefficient of coal/gas plant – 0.6) [these values are plotted for all plants in ascending order]



Cost vs Emission trade-off for Maharashtra (Aug 9 – Sep 9, 2024)

	Variable Cost (Million Rs)	Emission (kT)
Minimum cost	27375	8392
Minimum emission	32352	7430
Minimum cost subject to 250 kT/day max limit	27927	8000

Marginal CO_2 abatement curve for Maharashtra

Note: the negative values at the left represent gas plants that are more expensive than Rs 5.8/kWh, or have emissions coefficients below 0.6

STATE AND NATIONAL-LEVEL OPTIMIZATION

	State Level Cons	National
System Cost Rs mill	3,665	3,579
Total Generation TWh	1,230	1,230
CO2 mt	1,148	1,148
SO2 kg	5,839	6,615
NOx kg	2,760	2,950
SPM kg	515	426
Unit Price Rs/MWh	2,980	2,910
Avg Cost of CO2 Rs/t	3,918	2,505

National Level optimization will be economical compared to the State-level

More granular study required at the State level and need to check availability of transmission

Key Points from SECED Analysis So far...

1. CO_2 reduction potential: 5%-6% (61-73 mt annually) at ~Rs 3000/t.

   - Equivalent to one year's emission increase from the past five years.

2. Dispatch adjustment cost:
   - Rs 49 billion (Rs 1346/t) for 36 mt (3% below unconstrained level).
   - Rs 215 billion (Rs ~3000/t) for 73 mt (5% below unconstrained level).

3. SECED extension to SCED can enable a generation shift from high-emission to lower-emission plants (e.g., gas).

4. Marginal CO_2 reduction cost > Rs 6000/t beyond 5%-6% reduction, as costlier gas replaces coal.

5. Further reductions need cross-sector solutions, e.g., carbon permits (CCC) or long-term clean energy transition.

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Discussion

SECED: Three Key Functions

(1) **Adjust dispatch** to meet specified emissions targets (CO_2, Sox, Nox, SPM) at a daily, monthly, quarterly or annual level

(2) **Buy/sell CO2 Permits** (CCC) wherever (buying) permits can be a cheaper way to meet the CO_2 target, or selling permits to other sectors can reduce cost

(3) Test the efficacy to **add clean generation options** to the (national) portfolio if these can further help to meet the emissions targets

All three levels of analysis are useful: (1) allows to understand the fundamental cost-emission trade-off within the power sector and the extent emissions can be reduced in a standalone mode even before ICM starts (2) effectively allows the power sector to be coupled to the ICM, and (3) provides the much-needed link to clean generation options to specifically address CO2 and other emissions reduction

Adding Permits and Clean Energy Options to the SECED Analysis

(1) **<u>Adjust dispatch</u>** to meet specified emissions targets (CO2, Sox, Nox, SPM) at a daily, monthly, quarterly or annual level

↓

(2) **<u>Buy/sell CO2 Permits</u>** (CCC) wherever (buying) permits can be a cheaper way to meet the CO2 target, or selling permits to other sectors can reduce cost

↓

(3) Test the efficacy to **<u>add clean generation options</u>** to the (national) portfolio if these can further help to meet the emissions targets

PERMITS AND CLEAN ENERGY OPTIONS

- CO_2 Permits or Carbon Credit Certificates enable carbon emitters to buy allowance (from other sectors that can reduce CO_2) to generate using fossil fuels with emissions being offset elsewhere

- If permit prices are low (e.g., $10/t), dispatch adjustments up to that point (as captured by the shadow price of the emissions constraint) will be worthwhile and beyond that generators may choose to buy permits that effectively cap the CO_2 price for the power sector

- A high price of CO_2 as happens to be the case in Europe over the past 3 years, dispatch adjustment including fuel switching may be economic

- Adding clean generation options to the portfolio in the longer term may also provide a second alternative as the cost of solar, wind, hydro, nuclear may be competitive to permit prices and also hedge against the volatility of permit prices

- SECED may be used to model both in addition to dispatch adjustments – adding permit price to SECED effectively allows the dispatch mechanism to be coupled with the Indian Carbon Market in future with daily CCC prices becoming an input to the incumbent SCED process

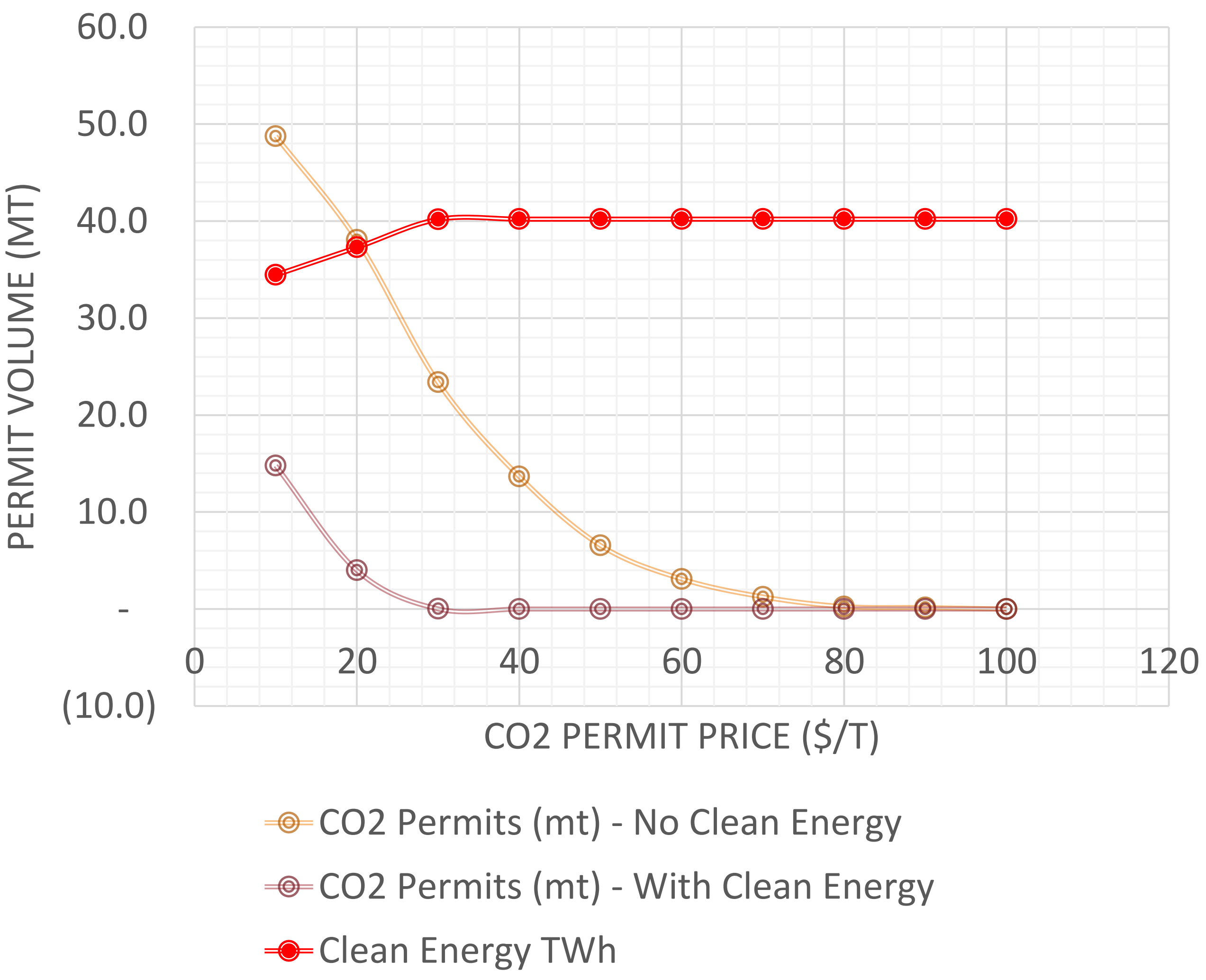
5% CO_2 Reduction Scenario with Permits Allowed

Permit price ($/t)	90	80	70	60	50	40	30	20	10
Permit Price (₹)	7,830	6,960	6,090	5,220	4,350	3,480	2,610	1,740	870
System Cost (Rs Billion)	3,579	3,578	3,578	3,576	3,572	3,564	3,548	3,522	3,483
CO2 Volume (mt)	1,148	1,148	1,149	1,151	1,155	1,162	1,172	1,186	1,197
SO2 Volume (kt)	5,916	5,916	5,924	5,928	5,937	5,967	6,055	6,131	6,199
Nox Volume (kt)	2,798	2,798	2,800	2,798	2,796	2,804	2,826	2,848	2,852
SPM Volume (kt)	487	487	487	489	493	498	500	508	514
CO2 Permit Volume (mt)	0.14	0.25	1.25	3.09	6.55	13.66	23.37	38.05	48.76

- If permit prices are high – volume of permit is quite low and at $100/t (Rs 8700/t) – no permits are used
- As permit prices are lowered, the volume grows to 48.76 mt at $10/t which has been expressed as a potential starting point of CCC price in India (and has been the experience in other markets historically albeit those cheaper carbon offsets may be limited)
- Cost faced by the power sector (variable cost of generation plus permit prices) will drop to meet the 5% emissions target

5% CO_2 Reduction Scenario with Permits and Clean Energy Options Allowed

- As noted in the last slide CO2 permit volume drops rapidly as permit prices increase
- If clean energy options (hydro, solar, wind and nuclear) – some of these options especially hydro and solar become cost effective at $20/t and reduces the need for permits in the long term
- Need for permits at $40/t is practically eliminated to meet the 5% target – clean generation requirements reach 40.2 BU (TWh)
- It shows how SECED can be used by Gencos to plan their diversification strategy to meet a carbon obligation



Comparison of 5% Reduction Scenarios

- Total reduction target of 60.4 mt is met quite differently with and without clean energy options
- Dispatch adjustment is the sole option for the power sector at high permit prices absent any clean energy option
- However, if clean energy options are presented/adopted by Gencos in the long term, it can account for 38.6 mt out of 60.4 mt reduction (or 64%)
- Savings from clean energy comes from its ability to replace expensive fossil fuel generation as well as economically meeting the emissions reduction target including avoided permits – at $30/t permit, the total savings is Rs 85.8 billion (close to $1 billion pa that includes $0.4b in avoided permit costs)

		No Clean Energy		With Clean Energy		
Permit Price	Tot Redn mt	Disp. Adj	Permits	Disp. Adj	Permit	Clean Energy
10	60.4	11.7	48.8	12.5	14.8	33.1
20	60.4	22.4	38.1	20.6	4.0	35.8
30	60.4	37.1	23.4	21.8	0.0	38.6
40	60.4	46.8	13.7	21.8	-	38.6
50	60.4	53.9	6.6	21.8	-	38.6
60	60.4	57.3	3.1	21.8	-	38.6
70	60.4	59.2	1.3	21.8	-	38.6
80	60.4	60.2	0.3	21.8	-	38.6
90	60.4	60.3	0.1	21.8	-	38.6
100	60.4	60.4	-	21.8	-	38.6

7% CO_2 Reduction Scenario with Permits and Clean Generation

- For a more stringent 7% target, permit requirements can go up to 38.9 mt at $10/t although requirements drop quickly down to 7.3 mt at $20/t and peters out below 1 mt from $30/t
- This is mostly because more and more clean energy options including nuclear followed by wind become economic as the CO_2 constraint is tightened and permit prices are high forcing the power sector to reduce CO_2
- Total new clean generation needed reaches 60 BU (TWh) in this case

Permit price ($/t)	10	20	30	40	50
Permit Price (₹)	870	1740	2610	3480	4350
System Cost (Rs Billion)	3,474	3,499	3,502	3,502	3,502
CO_2 Volume (mt)	1163	1131	1125	1124	1124
SO_2 Volume (kt)	6028	5864	5832	5826	5826
Nox Volume (kt)	2776	2725	2713	2711	2710
SPM Valume (kt)	498	482	479	479	479
CO_2 Permit (mt)	38.89	7.32	0.89	0.17	0.02
New Cap (Solar)	10,000	10,000	10,000	10,000	10,000
New Cap (Hydro)	5,000	5,000	5,000	5,000	5,000
New Cap (Wind)	-	-	658	777	797
New Cap (Nuke)	-	3,000	3,000	3,000	3,000

Concluding Remarks

1. SECED as a natural extension of the SCED model to include emissions constraints provides a useful and timely framework to eliminate generation from relatively expensive and highly polluting generators to reduce CO2 and local pollutant emissions

2. Although the volume of such reduction in % terms is less than 10% of total emissions – such dispatch adjustments can be a very cost-effective way to reduce CO2 by ~60 million tons pa (5% of total CO2 emissions from the power sector) for approx. $1.6 billion which is a very significant volume in absolutely terms that is worth $4-5 billion at the prevailing CO2 prices in Europe

3. There are important co-benefits in terms of concomitant reduction in local pollutants – most notably 5% of CO2 would also be accompanied with a similar level of reduction in SOx that could reduce the need for FGDs

4. As the Indian Carbon Market is poised for a start in 2026, SECED provides an excellent framework and a tool that the power generators, planners and regulators can start using to weigh up potential permit buy and sell opportunities, associated marginal cost of CO2 etc., to effectively start the process of trading within the power sector

Way Forward

1. A complete SECED database for all plants including local pollutant and CO_2 coefficients, variable cost, ramp rates etc. needs to be put in place – developing robust estimates of pollution coefficients in itself is a big task (see for instance, the work in the 1990s by Lamont and Obessis)

2. The SECED model with all its functionalities needs to be developed including maintenance decisions, transmission constraints, resource adequacy-related constraints and emissions constraints;

3. The model can also be useful for

   - Understanding the shadow prices (e.g., units with significant shadow price against minimum generation constraint for all years and can be shown to reduce system cost if it is taken out),
   - Coupling of the incumbent SCED and Indian Carbon Market (see the next slide),
   - installation of FGD and other emissions control equipment,
   - establish benefits of cross-border and interstate power trade through expansion of transfer capability,
   - evaluate demand-side measures, etc.;

Way Forward

1. As with the electricity market vs SCED –

   - Possible for a SECED to reduce the emissions reduction target for multiple generations
   - Coexist with the market-based trading system through auctions etc.
   - Allocation of benefits will need to consider additional factors that are currently available
   - Shadow price of emissions against the daily cap that needs to be collectively met and the resultant optimal dispatch.

2. SECED presents a natural extension to SCED which augurs well with the objectives of the ICM.

   - A mechanism that can be piloted even before the ICM starts.
   - Will provide a good understanding of how a reduction in CO_2 level is possible
   - Set a useful benchmark CO_2 price that can be generated through the SECED model.

KEY REFERENCES

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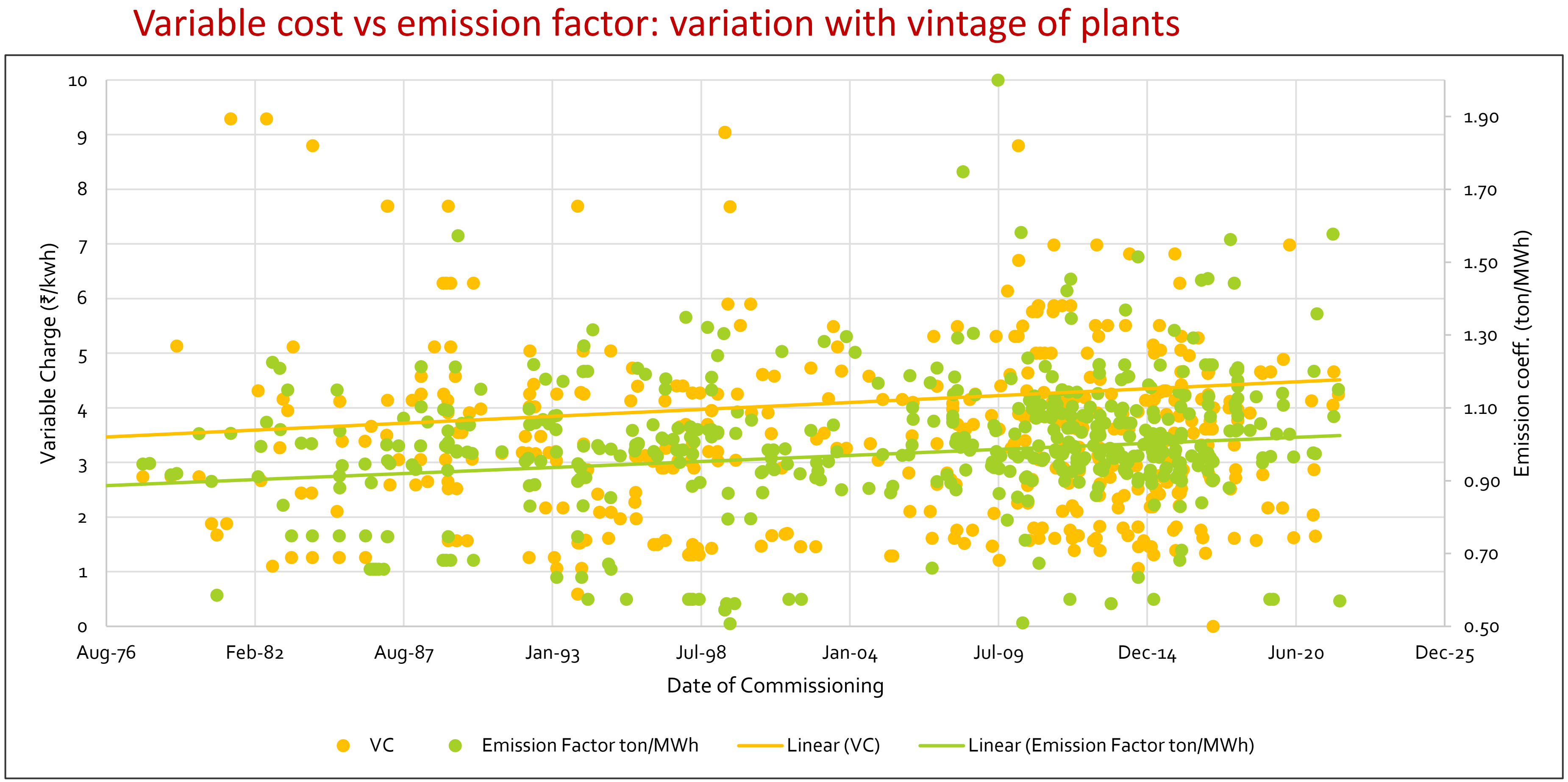
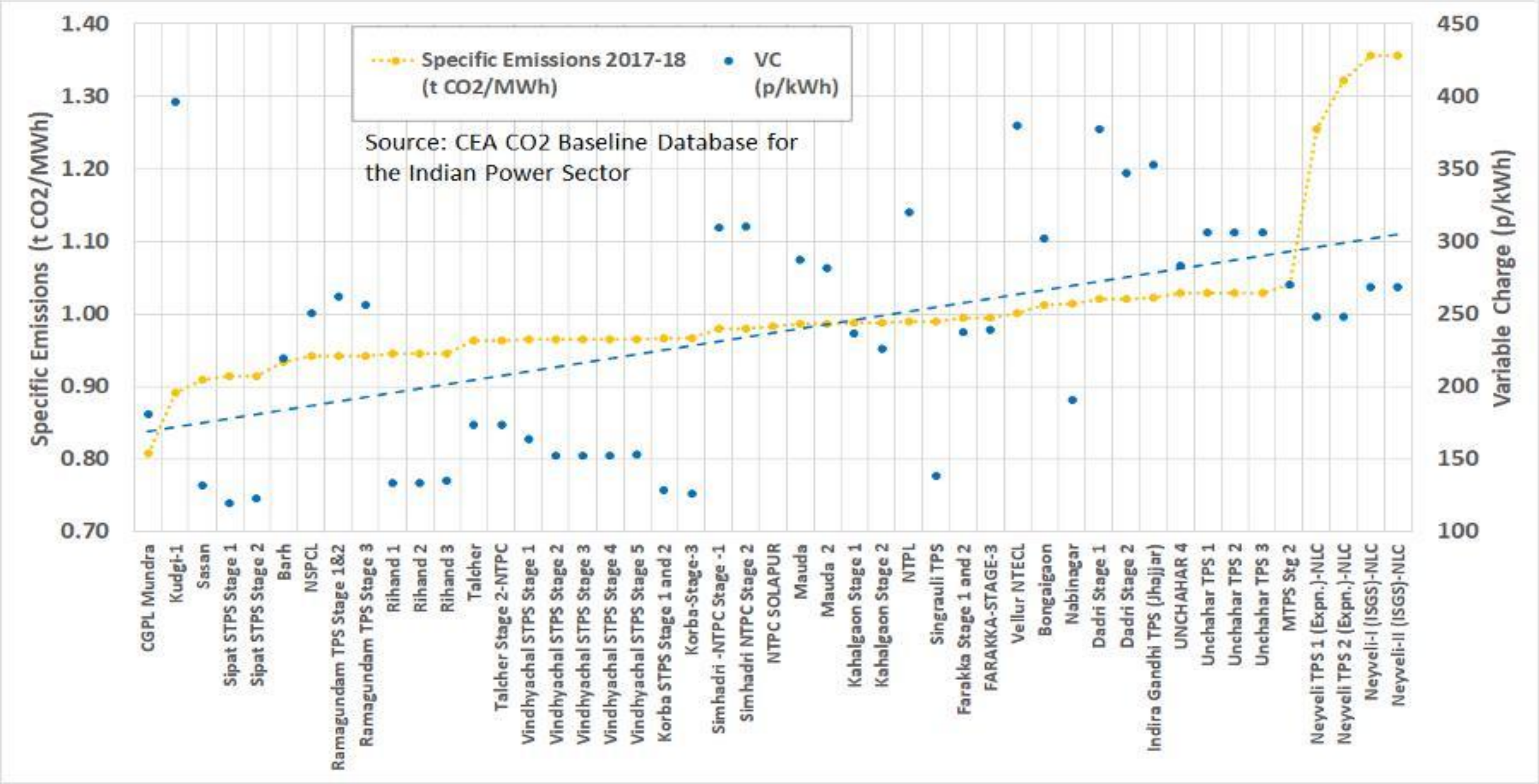
Additional Data

Emission Factor vis-à-vis VC – All India

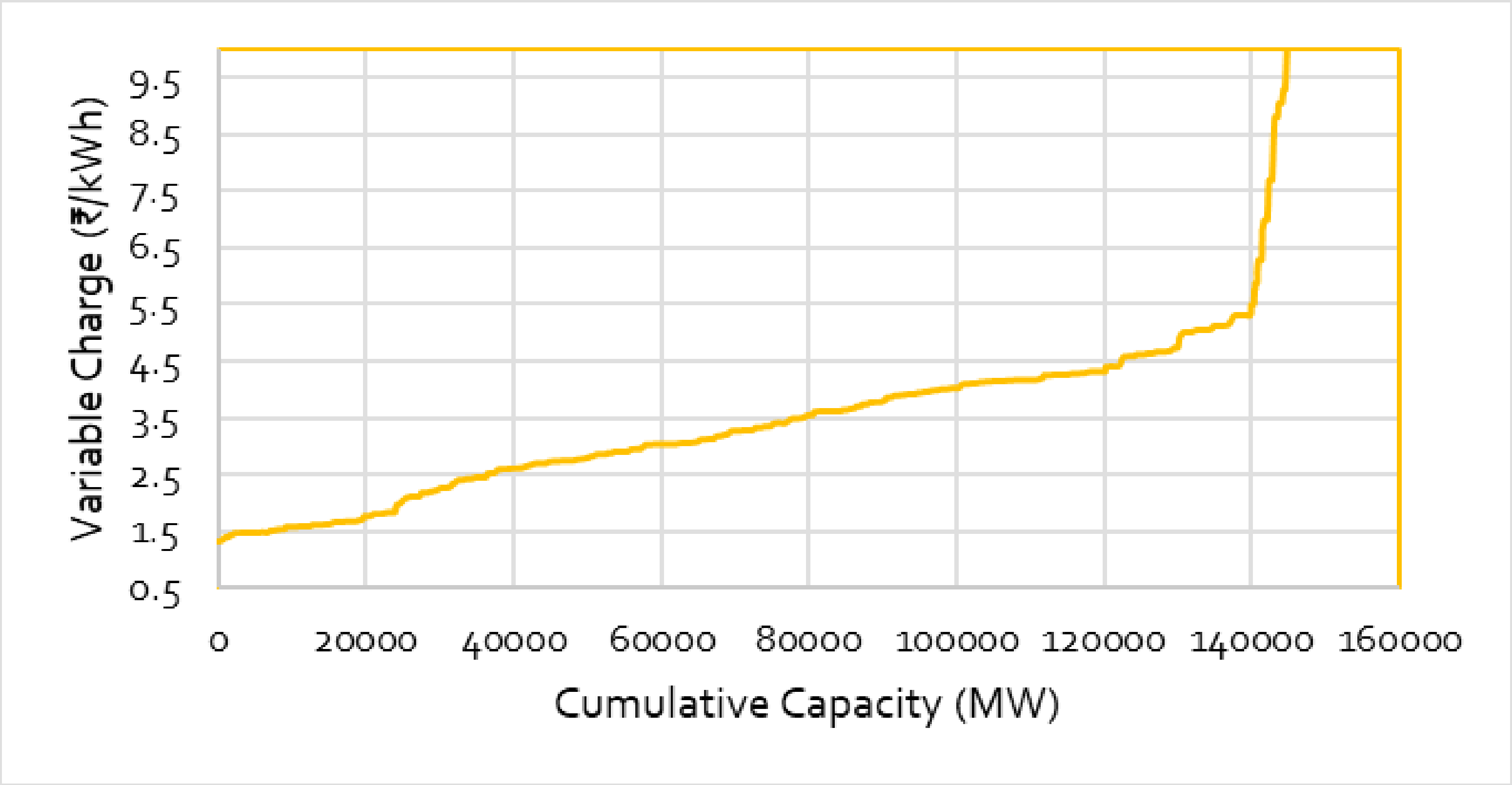


The plot shows that both the variable costs and the emission factors exhibit an increasing trend with the time

Emission Factor vis-à-vis VC – All India Thermal

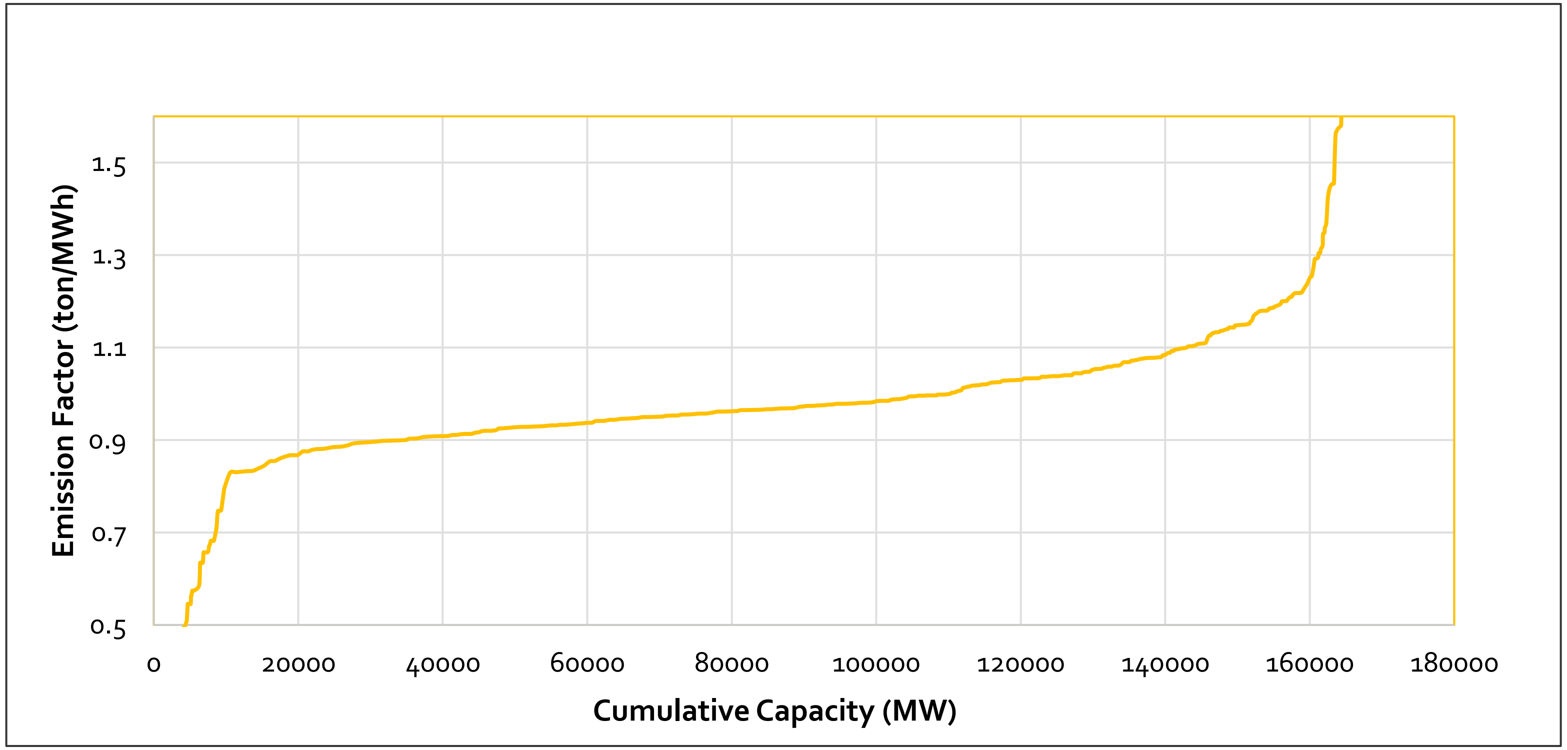


VARIABLE COST VS CUMULATIVE CAPACITY



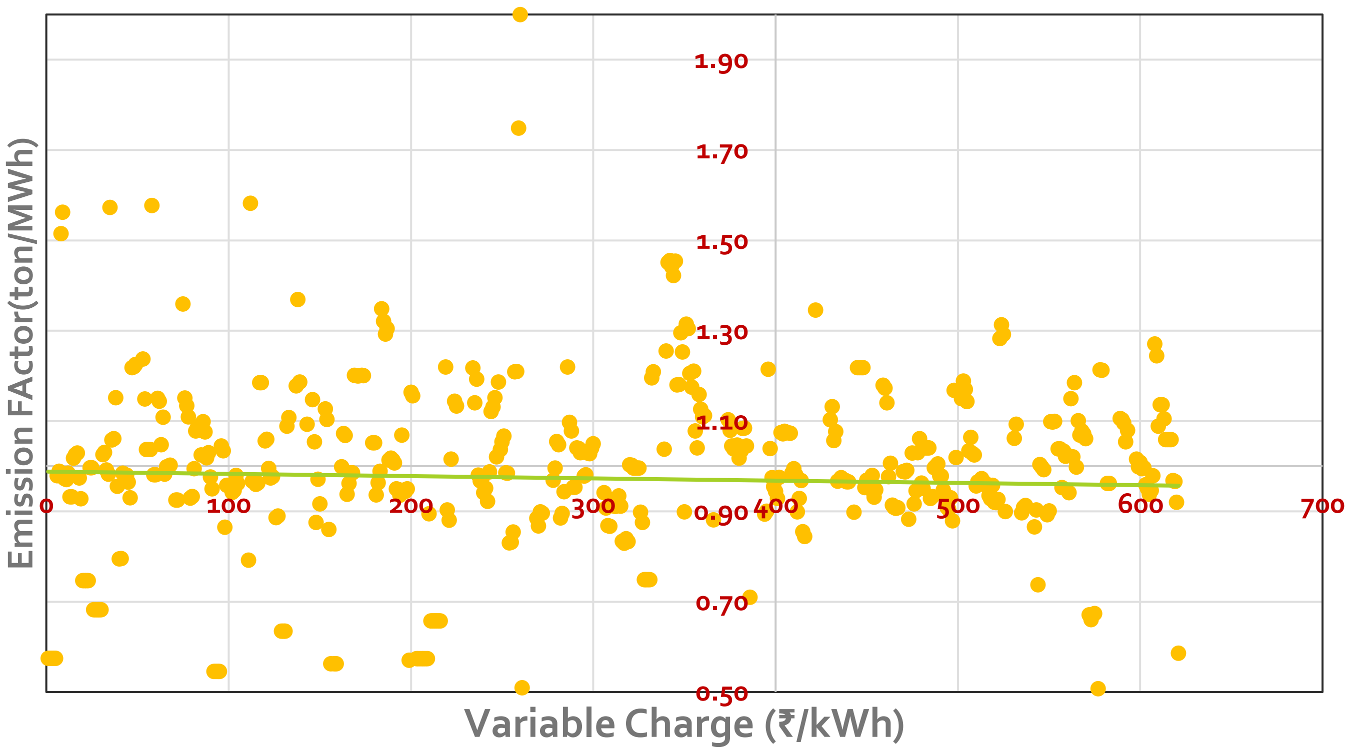
- ✓ **Variable cost varies between ₹ 1.5 to Rs 5.5 for a total capacity of around 120 GW.**
- ✓ **High variable cost i.e. between ₹ 5.5 to 9.5 is for gas-based generation (in operation) of only 10 GW.**

Emission factor vs cumulative capacity



- ✓ **Emission factor varies between 0.85 to 1.3 ton/MWh for most capacities ~ 125 GW.**
- ✓ **Lower emission factor i.e. < 0.6 is mainly of the gas-based generation.**

Variable cost vs Emission factor



The emission Factor is reducing with the increase in variable cost and hence reduction of emission will lead to a higher cost of production

SECED: Mathematical Formulation

The model is coded in GAMS with data read from Excel

SETS AND PARAMETERS

Symbols

Sets

Name	Domains	Description
g	g	generators
m	*	months
d	*	days
t	*	time
ng	g	new generation options

Parameters

Name	Domains	Description
MaxMTCO2		maximum daily limit on CO2 in kilo tons
CO2PermitPrice		CO2 permit price in Rs per ton
GenData	g, *	Generator data
Demand	m, d, t, *	Demand and RE profile
Avail	g, m, d, t	Randomized availability of generators
DailyCO2	m, d	Daily CO2 limit
AnnCapex	ng	annualized capex of new generators in Rs per kW per year

VARIABLES AND OBJECTIVE FUNCTION

Variables

Name	Domains	Description
Cap	ng	new capacity addition for new generators
Gen	g, m, d, t	dispatch
Unmet	m, d, t	load shed
Surplus	m, d, t	excess generation
Cost		Cost - objective function
Emission		Emission calculations
CO2Permit	m, d	permits bought to meet the daily CO2 limit - violation variable
Commit	g, m, d, t	Commitment decision 0 or 1

Obj

$$\text{Cost} = \sum_{g,m,d,t} (\text{Gen}_{g,m,d,t} \cdot \text{GenData}_{g,\texttt{VC}} \cdot 1000) + \sum_{m,d,t} (\text{Unmet}_{m,d,t} \cdot 10000 + \text{Surplus}_{m,d,t} \cdot 1000) + \sum_{m,d} (\text{CO2Permit}_{m,d} \cdot 1000000 \cdot \text{CO2PermitPrice}) + \sum_{ng} (\text{AnnCapex}_{ng} \cdot \text{Cap}_{ng} \cdot 1000)$$

$\text{Gen}_{g,m,d,t} \geq 0 \ \forall g, m, d, t$
$\text{Cap}_{ng} \geq 0 \ \forall ng$
$\text{CO2Permit}_{m,d} \geq 0 \ \forall m, d$
$\text{Unmet}_{m,d,t} \geq 0 \ \forall m, d, t$
$\text{Surplus}_{m,d,t} \geq 0 \ \forall m, d, t$

CONSTRAINTS...

$$\text{ProfileS}_{'New\_Solar',m,d,t}$$

$$\text{Gen}_{\texttt{New\_Solar},m,d,t} \leq \text{Cap}_{\texttt{New\_Solar}} \cdot \text{Demand}_{m,d,t,\texttt{Solar\_Avg\_N}} \qquad \forall' New\_Solar', m, d, t$$

$$\text{ProfileW}_{'New\_Wind',m,d,t}$$

$$\text{Gen}_{\texttt{New\_Wind},m,d,t} \leq \text{Cap}_{\texttt{New\_Wind}} \cdot \text{Demand}_{m,d,t,\texttt{Wind\_Avg\_N}} \qquad \forall' New\_Wind', m, d, t$$

$$\text{ProfileH}_{'New\_Hydro',m,d,t}$$

$$\text{Gen}_{\texttt{New\_Hydro},m,d,t} \leq \text{Cap}_{\texttt{New\_Hydro}} \cdot \text{Demand}_{m,d,t,\texttt{Hydro\_Avg\_N}} \qquad \forall' New\_Hydro', m, d, t$$

$$\text{ProfileN}_{'New\_Nuke',m,d,t}$$

$$\text{Gen}_{\texttt{New\_Nuke},m,d,t} \leq \text{Cap}_{\texttt{New\_Nuke}} \cdot \text{Demand}_{m,d,t,\texttt{Nuke\_Avg\_N}} \qquad \forall' New\_Nuke', m, d, t$$

$$\text{GenCap}_{g,m,d,t}$$

$$\text{Gen}_{g,m,d,t} \leq \text{GenData}_{g,\texttt{Cap}} \cdot \text{Avail}_{g,m,d,t} \cdot \text{Commit}_{g,m,d,t} \qquad \forall g, m, d, t$$

$$\text{GenCapNew}_{ng,m,d,t}$$

$$\text{Gen}_{ng,m,d,t} \leq \text{Cap}_{ng} \cdot \text{Avail}_{ng,m,d,t} \qquad \forall ng, m, d, t$$

$$\text{RampUp}_{g,m,d,t}$$

$$\text{Gen}_{g,m,d,t-1} - \text{Gen}_{g,m,d,t} \leq \text{GenData}_{g,\texttt{Cap}} \cdot 60 \cdot 0.015 \qquad \forall g, m, d, t \mid (\text{ord(t)} > 1)$$

$$\text{RampDn}_{g,m,d,t}$$

$$\text{Gen}_{g,m,d,t} - \text{Gen}_{g,m,d,t-1} \leq \text{GenData}_{g,\texttt{Cap}} \cdot 60 \cdot 0.015 \qquad \forall g, m, d, t \mid (\text{ord(t)} > 1)$$

$$\text{MinGen}_{g,m,d,t}$$

$$\text{Gen}_{g,m,d,t} \geq \text{GenData}_{g,\texttt{Cap}} \cdot 0.4 \cdot \text{Commit}_{g,m,d,t} \qquad \forall g, m, d, t$$

CONSTRAINTS...

$$\mathbf{DemandEq}_{m,d,t}$$

$$\sum_{g} \text{Gen}_{g,m,d,t} = \text{Demand}_{m,d,t,\texttt{Load}} - \text{Demand}_{m,d,t,\texttt{Solar\_Avg}} - \text{Demand}_{m,d,t,\texttt{Wind\_Avg}} - \text{Demand}_{m,d,t,\texttt{Hydro\_Avg}}$$

$$\forall m, d, t$$

$$\mathbf{EmisLimit}$$

$$\frac{\sum_{g,m,d,t} \left(\text{Gen}_{g,m,d,t} \cdot \text{GenData}_{g,\texttt{CO2}}\right)}{1000000} \leq \text{MaxMTCO2}$$

$$\mathbf{EmisLimitDaily}_{m,d}$$

$$\frac{\sum_{g,t} \left(\text{Gen}_{g,m,d,t} \cdot \text{GenData}_{g,\texttt{CO2}}\right)}{1000000} - \text{CO2Permit}_{m,d} \leq \text{DailyCO2}_{m,d} \cdot 0.93 \qquad \forall m, d$$

$$\mathbf{EmisCon}$$

$$\text{Emission} = \frac{\sum_{g,m,d,t} \left(\text{Gen}_{g,m,d,t} \cdot \text{GenData}_{g,\texttt{CO2}}\right)}{1000}$$