SECURITY AND EMISSIONS CONSTRAINED ECONOMIC DISPATCH: Relevance for Carbon Emissions Trading

Submission to:

CERC on Purchase and Sale of Carbon Credit Certificates Regulations, 2024

World Bank Energy and Extractives Practice

December, 2024

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EXECUTIVE SUMMARY

The introduction of Security Constrained Economic Dispatch (SCED) by the National Load Despatch Center (NLDC) in 2019 has yielded significant economic savings as well as smoother operation of interstate/central sector generators. As India embarks the Indian Carbon Market (ICM), it is time to consider extension of the SCED framework to include emission constraints in order to identify the most economic sources of emissions reduction opportunities within the power sector. Although the timing of inclusion of the power sector in ICM is not yet determined, development of a Security *and Emissions* Constrained Economic Dispatch (**SECED**) tool to analyze how emissions reductions can be achieved, will help to provide signals to power generation and distribution companies to buy/sell Carbon Credit Certificates (CCC).

SECED can be useful in enhancing short term (namely, real-time and day-ahead) dispatch for NLDC as well as the State Load Despatch Centers (SLDC). A medium-term planning function for SECED can also be a useful aid to planning bodies like the Central Electricity Authority and state level planning and regulatory agencies. SECED can include emissions constraints on CO_2 as well as local pollutants to comprehensively analyze the trade-off between system (variable) costs and emissions levels of all pollutants. It will produce System Marginal Price (SMP) for electricity as well as marginal and average cost of each pollutant including CO_2. It will also produce information on the emissions levels for each generation company including who can contribute how much to the emissions reduction target by adjusting their dispatch (in the short term), importing from other states/countries (if applicable), and other measures such as flexibilization of coal plants, fuel switching and diversification to cleaner generation options (in the long term). It can also enable DISCOMs to assess strategies to reduce their burden through demand side measures. SECED may be used by the system operators as well as gencos and DISCOMs (against their own portfolio) to work out their best strategy and marginal/average cost of CO_2 reduction to bid into the market.

Although the ICM is deemed to work by setting plant-wise targets and then allowing trading, SECED represents a complementary more centralized composite framework. In this model, implicit swapping among plants occurs while maintaining the same total system-wide MW output. The pool effectively consolidates CCC trades, generating earnings while ensuring that all plants benefit collectively. This bundled approach prioritizes carbon reduction, implicit trading, and creates shared gains, which are then distributed equitably. This method can be implemented around the incumbent SCED process and introduces indirect competition, fosters transparency, and enhances the accountability of the power system. It fulfills the fundamental requirements of reducing carbon emissions and in many ways circumvents the challenges associated with some of the other mechanisms like Renewable Energy Certificates (REC) around enforcement. SECED complements ICM because the latter casts the net more widely outside the power sector to secure carbon permits part of which may be cheaper than doing adjustments within the power sector. Generators that hold such permits (or free allocations if this forms part of the scheme) do not necessarily need to adjust their dispatch. On the other hand, where cheaper dispatch adjustment opportunities exist on certain days/months/seasons, requirement for permits can be avoided (or they can be banked for future usage depending on the design of the ICM). SECED will diligently perform the day-to-day dispatch process to present these opportunities and complement CCC trading.

Preliminary analysis at a national level using a very basic set of dispatch data and assumptions for Jan-Dec 2023 from publicly available sources reveals that there is a reasonable opportunity to adjust dispatch to potentially reduce 5% of the power sector emissions (approximately 60 million tons) at a (national) average cost of CO_2 of Rs 2,287/ton. There is significant variability in costs across the days of the month and over the months depending on demand and renewable (hydro, wind and solar) variability. At a state level, a similar analysis is conducted for Maharashtra for a single month (Aug 9 – Sep 8, 2023) that also shows 4.6% emissions reduction prospect at a cost of Rs 1,408/t. While these CO_2 reduction costs are significant to, they are in the range of US$20-26/t compared to European Emissions Trading System (EU ETS) permit prices that has averaged around €68/t (US$71/t), i.e., around 3 times as high. When the ICM embraces the power sector, CO_2 prices may rise significantly, and dispatch adjustment may provide a limited but cost-effective and easily implementable option in the short-term to achieve the initial few percent of reduction. It will also set a benchmark for other initiatives and also provide a pathway for decarbonization of the power sector over the next few decades.

As a way forward, it is important to pilot SECED in NLDC/SLDC to develop necessary data and insights into CO_2 reduction measures, marginal/average costs, how dispatch and interstate flows will change. SECED planning function can also be a useful aid for other purposes including medium-term resource adequacy studies and maintenance decisions to complement the incumbent Load Generation Balance Reporting. In summary, SECED presents a natural extension to SCED which augurs well with the objectives of the ICM. It is a mechanism that can be piloted even before the ICM starts. It will provide a good understanding of how reduction in CO_2 level may be achieved within the power sector including a useful benchmark CO_2 price that can be generated through the SECED model.

1. SECURITY AND EMISSIONS CONSTRAINED ECONOMIC DISPATCH (SECED)

1.1 CONTEXT

CERC's regulation RA-14026(13)/1/2024-CERC (CERC 2024) to create framework for the exchange of Carbon Credit Certificates (CCC) on Power Exchanges in India is a welcome development that gives shape to the creation of carbon market that was under discussion for a few years. CERC's announcement builds on the design of the Indian Carbon Market (ICM) that the Bureau of Energy Efficiency has put together (BEEE 2023, BEE 2024) including the detailed procedure for compensation mechanism under the carbon credit trading scheme (CCTS) (BEE, 2024a). The ICM initiative has been lauded on all fronts (e.g., Bari, 2024, Jennifer 2024, Phillip 2024). There is, however, also a concern that the CCTS "*excludes major polluting sectors like electricity and agriculture, limiting its impact on national emissions. Experts involved in the scheme's rollout predict minimal improvements in air quality until 2031, as the system only covers about 30% of the country's emissions, leaving a large portion unregulated."* (Policy Circle, 2024).

Although nearly half of the CO_2 emissions in India, or over 1.2 billion tons (bt) come from the power sector, it needs great care to bring power generation under the fold of CCTS. The current expectation from BEE is that CCC prices will be relatively low around $10/t unlike EU ETS regime where prices have increased steeply to $70/t and beyond. However, as Tekin et al (2024) has discussed guessing a price level or trend can be tricky as expectation of low prices may lead to underinvestment and hence higher emissions, while high price expectation may lead to overinvestment and higher cost. There needs to be significant level of analysis done to form reasonable expectation of CCC prices (see e.g., Anke et al, 2020). Options for emissions reduction from power generation can range from relatively cheap adjustment of dispatch to expensive measures like fuel switching and/or renewables (plus storage), to very expensive options around carbon capture and storage. Dispatch adjustment may offer limited (e.g., below 10% of reduction from power generation) but it can potentially be lower cost than other options and relatively easy to implement through changes in dispatch protocols. These dispatch adjustments need to be analyzed and built into existing dispatch and market arrangements in real-time/day-ahead mode, as well as annual operational planning practices. For instance, medium term issues such as maintenance of generators should be considered as these hold significant implications for resource adequacy. This note focuses mainly on the cheaper end of dispatch adjustment options and also propose an analytical framework around which other options may also be evaluated. The note, in particular, proposes development and piloting of a dispatch and planning tool based on the incumbent Security Constrained Economic Dispatch (SCED) (POSOCO, 2020) used by the National Load Despatch Center (NLDC). SCED has been successfully implemented for over five years now since 2019 and also be trialed in some of the states. The proposed analytical model is termed Security **and Emissions** Constrained Dispatch (SECED) which incorporates emissions constraints in SCED and also undertakes medium term generation/price projection, maintenance decisions and allocation of generation from limited energy plants (such as storage hydro and plants with limited supply of coal/gas).

The remainder of this note provides a description of the proposed tool and also early results from a dispatch analysis to show the potential range of CO_2 reduction volume and costs.

1.2 OVERVIEW OF SECED

SECED is a tool that system operators, regulators and planners can use to (a) dispatch the system to minimize the cost while honoring security constraints and keeping a tab on emissions; and (b) also identify medium to long term operational and policy decisions on resource adequacy (RA) needs, check if the system needs additional flexible resources, decide on the optimal maintenance policy, test the efficacy of power purchase agreements, identify cost-effective emissions reduction opportunities without breaching RA standards, and derive shadow price of carbon and system marginal costs. SECED can be a very useful aid for organizations like the Load Despatch Centers (NLDC, SLDCs) and CEA to further enhance the dispatch and planning. It can for instance provide inputs to RA analysis, develop local pollutant reduction strategies as the model can indicate the plants/units where reductions are most economical and also provide guidance on economic CO_2 reduction opportunities to claim significant climate finance.

SECED will require new development in the same vein as SCED developed by NLDC and currently being explored for Maharashtra, Gujarat etc. among other states. This can be done cost-effectively using General Algebraic Modeling System (GAMS) platform that will enable keeping the structure fully compatible with SCED functionality and data. This can be developed collaboratively with the academic institutions, members from CEA/MoP/state planning bodies, NLDC, senior experts who have overseen development of SCED, and institutions like the World Bank that have supported such developments including GAMS licenses. A tool that is compliant with the IEGC 2023 requirements and customized for available data from CEA and other state agencies, is expected to be a low-cost, transparent, and flexible tool to develop insights into the RA issues, maintenance policies, emissions reduction strategies, among other strategic priorities.

1.3 SECED DISPATCH FUNCTION: OBJECTIVE

Dispatch [Part (a)] functionality of SECED will be in real-time and day-ahead dispatch mode that system operators can use including real-time system operation connected to SCADA/EMS as mandated under the IEGC 2023. System operators use some dispatch planning (day-ahead) or real-time tool but those typically lack the ability to balance emissions. SECED will provide the added ability to put in an emissions constraint and help operators to identify opportunities to re-optimize dispatch and reduce emissions in the most cost-effective manner. This is going to be an extremely effective way to monitor emissions reduction initiatives effectively breaking the process down to daily and hourly dispatch regimes.

SECED may, for instance, be set up for NLDC or intra-SCED building on the existing SCED tool as follows:

- Add emissions variables (Particulate Matters PM2.5 and PM10, SOx, NOx, CO_2) that are a linear (or piecewise linear) function of generation.

- Add emissions constraints for each pollutant noting that the local pollutants (PM, SOx, NOx) constraints will need to be set carefully for clusters of plants that contribute significantly to air pollution in highly populated areas considering how these pollutants disperse in the atmosphere depending on wind speed and other ambient conditions (which may be seasonal). In other words, these limits will be placed on groups of plants in specific locations and they may vary across the seasons.[1] Constraints on different pollutants can interact and in particular a stringent emission limit (e.g., a deep cut on CO_2) may dominate others, i.e., if that constraint is met then it automatically means meeting all other constraints. While CO_2 may or may not be an immediate focus in India, the point is valid for other combinations of pollutants too and illustrates the fact that an integrated assessment of all pollutants through a dispatch tool is an important task that has rarely received any attention.

- It may not be necessary, for instance, to install Flue Gas Desulfurization (FGD) units for SOx if CO_2 or PM2.5 requires actions that automatically caps SOx below the required limit. Emissions constrained dispatch may typically provide a very cost-effective way to reduce both local pollutants as well as CO_2 although there may be a limit on how much emissions reduction is feasible through dispatch adjustment before installation of abatement equipment are necessary. Nevertheless, it will definitely save costs if not obviate the need for a significant part of the investments in FGD, low NOx burners, switching to gas generation, etc. The shadow prices on the emissions constraints in fact would indicate the marginal cost of emissions reduction which can be compared with the levelized cost of investments in abatement equipment like FGD. It has been shown in the past that the cost of SOx could be as low as less than Rs 10/kg (Chattopadhyay, 1995) which is a fraction of what it would take for a FGD unit to do such reductions (even ignoring the operating cost and heat rate penalties associated with FGDs). In fact, the levelized cost of abatement equipment could be set as penalties on the relevant local pollutant costs (and international CO_2 permit may in the same vein act as a penalty for CO_2 limits) to indicate that if the cost of emissions adjustment reaches such a value, it is better to install FGDs, etc. (or buy CO_2 permit).

The value of doing a SECED dispatch function is potentially significant as it would enable the system operators to provide useful guidance on where to reduce emissions, how much and at what cost and at what point capital investments in FGDs are needed. If SECED is also used to decide on CO_2 reduction, there are valuable emissions credits and climate financing available to reward such emissions reductions. One of the features of an emissions constrained dispatch is that it will pinpoint the most cost-effective units where reductions can take place and this may usually mean these units lose utilization over the years. The polluting units where emissions reductions are most cost effective may, for instance, sit at minimum load frequently or shut down more frequently than they would otherwise run. Again, the shadow prices for the minimum loading constraints would be a useful signal to identify these units for shutting down or repurposing in the long run. As more data on dispatch adjustment and shadow prices

[1] A potential data source is NASA website: https://fluid.nccs.nasa.gov/wxmaps/chem2d/?stream=G5FPFC&field=pm25sfc&level=0&fcst=20241118T120000&region=sevseas&tau=048

are gathered, it could provide highly accurate pointers to investments in abatement equipment, fuel switching and eventual shutdown of older and inefficient coal units.

1.4 SECED PLANNING FUNCTION: OBJECTIVE

SECED planning Part (b) function will be more relevant for organizations like CEA and state planning bodies to develop/refine a tool for medium term (up to one or more years) operational planning. SECD planning function will help the planning bodies to strike a balance among system cost, reliability and resource adequacy and emissions. The ability to have a standardized tool that also performs SCED function on a daily basis is helpful to understand the implication of medium-term decisions on dispatch and System Marginal Prices (SMP). Part (b) is effectively offline/planning mode that may include up to a year of operations planning as well multi-year planning to decide retirements over say the next 5-10 years. This will also be useful for a range of decision makers including policy makers in ministries, regulatory bodies, utility planners, international agencies including development banks. SECED planning function will be effective to these stakeholders to form a priority list of RA options to meet peak demand if the supply projections entail periods of low reserve margin with high expected unserved energy.

On the other hand, SECED will also be useful to identify old/inefficient/expensive plants that can be gradually in phases safely retired without jeopardizing system security (e.g., if SECED dispatch function shows units that are not running much at all, or sitting persistently at minimum load for a significant number of days in a year), how to best adjust maintenance of units to take advantage of renewable resources (including hydro and VRE), if there are inflexible PPAs that have significant cost and emission implications, a projection of PM, SOx, NOx and CO_2 marginal costs. SECED can also provide a year-ahead projection of SMPs that will be extremely useful as a benchmark to wholesale market prices from IEX/PXIL and in fact regulators in other countries use such projections as part of market monitoring, tariff benchmarks and other functions.

1.5 SECED FUNCTIONALITY

SECED dispatch function will find a way to balance between cost, emissions and system security. It should lead to an open-source, flexible, low-cost dispatch and planning tool that operators and planners can use for short and medium-term operations planning with a special emphasis on decarbonization of the system.

1.5.1 SECED DISPATCH: FUNCTIONALITY

1. SECED should meet the minimum requirements of SCED as implemented for the national system operator in India, namely, it should do hourly/sub-hourly dispatch in real-time mode to minimize variable cost subject to meeting demand, ramping constraint, etc.[2]

2. In addition, it should co-optimize ancillary services to hold raise and lower frequency control ancillary services.

3. Day-ahead SECED should consider unit commitment decisions including units that may need to be turned on to provide ancillary service duty. Day-ahead SECED also consider energy constrained units like hydro energy limits, optimal charging/pumping and discharging/generation of BESS/pumped-hydro storage.

4. Emissions constraints that may be specified in a variety of way including a longer term carbon budget broken down to annual→monthly→weekly→daily→hourly limits. This in itself will be a task that may be done through SECED planning function.

5. The interaction between (2) and (3) is important to capture as emissions constraints would typically free up capacity at expensive and high-emission coal generators some of which may participate in provision of ancillary services (subject to meeting technical requirements).

1.5.2 SECED PLANNING: FUNCTIONALITY

1. SECED planning function can be seen as an equivalent to production simulation tools like GE-MAPS, PROMOD, PLEXOS MT etc. as a way to complement long term capacity expansion modeling tools like PLEXOS LT, ORDENA, World Bank's EPM, etc. It can also have useful interplay with SCED for short-term decisions, e.g., maintenance plans, hydro energy allocations for individual days/weeks, emissions limits, etc. can be fed from SECED Planning to SECED Dispatch module to understand the impacts of medium-term decisions on short term dispatch and SMPs.

2. Two variants: (a) multi-year planning that may have quarterly/monthly steps each with representative days for each quarter/month and model retirement decisions; and (b) annual model with monthly/weekly steps that consider maintenance decisions; These models will inform each other, namely, retirement decisions should inform the annual model which in turn should inform the daily model including allocation of emissions targets, hydro energy, maintenance schedule, etc.

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[2] Indian SCED implementation details are available on POSOCO website: https://posoco.in/wp-content/uploads/2020/02/POSOCO_SCED_Pilot_Detailed_Feedback_Report_Jan_2020.pdf

3. SECED planning model should be a longer term version of dispatch, albeit with approximations wherever possible, e.g., model representative days per months (say 3 days – peak, average and low demand) in hourly rather than sub-hourly resolution.

4. Model generator maintenance decisions so that these can be optimized to also contribute to lower system cost taking into account the emissions cap among other things.

5. Model retirement decisions so that expensive and high-emission units often with zero or negative stranded cost, can shut down making room for cheaper and cleaner generation to displace their generation.

SECED Planning function can effectively be a complement to the incumbent Load Generation Balance Report (LGBR) and similar processes followed by states with an optimized maintenance schedule and resource adequacy measures for the next 6 months to a year. As renewable penetration and significant seasonal variability in hydro, solar, wind and demand already saw adverse impacts on supply reliability, it is important to have a tool that can help the planning and regulatory bodies to provide useful directions on when generators can or cannot be taken out for maintenance, flag potential low reserve periods so that any power outages and mitigation measures can be planned ahead of time.

SECED can also provide a way to indicate when emissions can be reduced cost-effectively and set the projections for CO_2 prices over the coming months/year. It will help to plan the thermal generation fleet owners not only to maintain their units but also plan for fuel allocation and, even partial shutdown of the expensive and high emissions plants (for part of the year). As the cost of power generation goes up with the ETS, these decisions are going to be critically important for generators as well as DISCOMs to minimize their cost burden. As an example, if a high emitting plant (say at 1.2 t/MWh) operates at 60% PLF, a CO_2 permit price of Rs 2000/t would entail incurring an additional cost of Rs 12 million per year. If the genco could purchase power from another plant that has an emission factor of 0.9/t, it will save them Rs 600/t (or, Rs 500/MWh). If this implies, the plant is better off operating only part of the high demand months, planning ahead of its partial closure would be beneficial.

In summary, SECED dispatch and planning function would provide a comprehensive framework to:

1. Provide a way to understand the trade-off between cost, emissions and resource adequacy which will be important from a policy perspective to set the thresholds for emissions, tariff setting, resource adequacy standards and necessary mitigation measures for low reserve days/weeks;
2. A projection of CO_2 certificate prices for generators and DISCOMs to plan their carbon budget for the year(s) ahead, participate in auction processes using the price guide, and set the necessary shorter term CO_2 reduction targets.
3. It will also be a useful aid to the LGBR process including a guide for maintenance of thermal generators in the system, generators that should be on partial shutdown mode and potential candidates for closure and repurposing; and
4. Daily and real-time dispatch that in turn can use the shorter term CO_2 reduction targets to develop dispatch and prices to participate in the daily trading.

1.6 UNDERSTANDING THE EMISSION PRICES AND REVENUE CALCULATION

An issue that may benefit from some additional clarification relates to treatment of CO_2emission in SECED through permit prices vis-à-vis an emissions cap. SECED may work either with an emissions caps for the system, or generators may specify a price of the permits they possess (along with any free allocations they may have received). The former approach will determine a shadow price of the CO_2 cap reflective of a power sector specific cost of adjusting dispatch (and any other measure included in the model). The latter approach will provide the market price of the permit as an input. Both approaches are workable with their pros and cons as follows:

1. **SECED with emissions cap**: Using an emissions cap in the SECED dispatch process would provide a direct incentive to reduce emissions by reducing dispatch in an optimal way. The allocation of benefits of the original SCED process remains unchanged with a minor adjustment to consider the shadow price of CO_2. There is no reason why SECED cannot be used this way, especially if the internal adjustments within the power sector has an implied (shadow) price of CO_2 that is attractive. NLDC, for instance, may retain its current dispatch mechanism for the interstate generators, at least for part of the emissions reduction; and

2. **SCED with CO_2 permit prices**: If, on the other hand, generators find the permit prices attractive alongside any free permits, SECED may run with the permit price (multiplied by the emissions coefficient) added to the variable cost of the generators. There is no explicit cap applied and the SCED engine needs no change.

Consider the following illustrative example for three generators (Gen1-Gen3):

	Capacity	Cost	Emission
Gen1	100	100	0.6
Gen2	200	30	0.9
Gen3	300	20	1.2

Note: Capacity in MW, Cost in $/MWh and emission in t/MWh

They need to collectively meet a demand of 350 MW and the emissions cap is initially set at 500 tons (which does not bind) and then lowered to 350 tons.

If SECED is solved as a linear programming optimization problem, the emissions limit can be expressed as a linear constraint: sum product of generation and emissions coefficient ≤ 500 (or 350). The LP will adjust the dispatch when the constraint binds (e.g., at 350 cap) and the shadow price produces an economically consistent price on CO_2 that reflects the revised dispatch. This follows from the duality theory that reformulates the dispatch/primal problem in terms of prices/duals including the shadow price of the emissions cap. The dispatch/primal problem minimizes total cost subject to meeting demand, emissions cap and generator capacity limits. The pricing/dual problem is an exact equivalent problem expressed as the prices that maximizes the revenue from selling 350 MW power less emissions costs at the shadow price of CO_2 and that of capacity limits subject to prices limited by costs. The primal and dual of the SCED linear programming formulation for the dispatch can be stated as follows:

Objective:

Minimize $\text{Cost} = \sum_{g \in G} \text{Gen}(g) \times \text{GenData}(g, \text{"}cost\text{"})$.

Constraints:

1. **Emission Calculation:**

$$\text{CO2}(g) = \text{Gen}(g) \times \text{GenData}(g, \text{"}Emission\text{"}) \quad \forall g.$$

2. **Meet Demand:**

$$\sum_{g \in G} \text{Gen}(g) \geq 350.$$

3. **CO2 Limit:**

$$\sum_{g \in G} \text{CO2}(g) \leq 500.$$

4. **Capacity Constraint:**

$$\text{Gen}(g) \leq \text{GenData}(g, \text{"}capacity\text{"}) \quad \forall g.$$

Dual Objective:

Maximize the total value of the shadow prices:

$$\text{Dual Objective: } 350\lambda - 500\mu + \sum_{g \in G} \text{GenData}(g, \text{"}capacity\text{"}) v_g$$

Dual Constraints:

1. For $\text{Gen}(g)$:

$$\lambda - \pi_g + v_g \leq \text{GenData}(g, \text{"}cost\text{"}).$$

2. For $\text{CO2}(g)$:

$$\mu + \pi_g \geq \text{GenData}(g, \text{"}Emission\text{"}).$$

Note:

1. *λ: Shadow price for the **Meet Demand** constraint.*
2. *μ: Shadow price for the **CO_2 Limit** constraint.*
3. *vg: Shadow price for the **Capacity Constraint** for each generator g.*
4. *πg: Dual variable for the **Emission Calculation** for each generator g.*

Decoding Shadow Prices and Dual Variables in Optimization Models: As the note to the table above shows shadow prices (or, dual variables) are critical components in optimization models, providing valuable insights into the impact of system constraints. The principle of duality is important as it connects prices to the physical realities in the system. The shadow price for the "Meet Demand constraint (λ)" represents the marginal cost of satisfying an additional unit of demand. It forms the basis for locational marginal prices (LMP) in electricity markets. Similarly, the shadow price for the CO_2 Limit constraint (μ) reflects the cost associated with relaxing the emission cap by one unit. It is a carbon price that embodies physical adjustments to dispatch among other measures that are needed to achieve emissions reduction with the power sector. For individual generators, the shadow price (vg) indicates the cost of increasing capacity for a specific generator g, while the dual variable (πg) quantifies the impact of each generator's emissions on the system-wide constraints. These metrics collectively guide decision-making in balancing economic efficiency, capacity utilization, and environmental objectives.

Table 1 and Table 2 show the solutions for the emissions unconstrained (500 t cap) and constrained (350 t cap) scenarios including how the primal and dual solutions can be combined to calculate the revenue. Power price in the unconstrained scenario is $30/MWh which corresponds to the cost of the marginal generator Gen2. Emissions are 405 t which is below the 500 t limit and hence CO_2 price is zero. The cheapest generator is at the limit and the capacity limit price is $10/MWh which is the difference between price and its cost.

Table 1 Dispatch and revenue analysis: Unconstrained solution with 500 t cap

	Dispatch (MW)	CO2 (t)	Power Price (λ) ($/MWh)	CO2 Price (μ) ($/t)	Cap limit (vg) ($/MW)	Revenue ($)
Gen1	0	0	30	0	0	0
Gen2	50	45	30	0	0	1500
Gen3	300	360	30	0	10	6000
	350	405				7500

Table 2 presents a very different scenario with Gen3 pushed back to 133.33 MW to meet the 350 t cap, Gen2 goes to the limit and Gen1 has to pick up the balance 16.67 MW. Power price shots up to $180/MWh which reflects the fact each MW of incremental demand requires Gen1 to increase by 2 MW at a cost of 2X$100=$200 and back down Gen3 by 1 MW (i.e., less $20) to remain within the CO_2 cap (i.e., emissions increase is 2X0.6-1.2=0). The note to the table works out the revenue calculation that basically nets out the payment for CO_2 emissions which in turn considers the emissions factors of the generators.

Table 2 Dispatch and revenue analysis: Constrained solution with 350 t cap

	Dispatch (MW)	CO_2 (t)	Power Price (λ) ($/MWh)	CO_2 Price (μ) ($/t)	Cap limit *(vg) ($/MW)*	Revenue *($)
Gen1	16.67	10	180	133.33	0	1666.66
Gen2	**200**	180	180	133.33	**30**	6000
Gen3	133.33	160	180	133.33	0	2666.66
	350	**350**				10333.33

**Note: Revenue calculations following the dual formulation is done are:*

1. *Gen1 =16.66*180-10*133.33 = 1666.66*
2. *Gen2= 200*180-180*133.33-30*200 = 6000*
3. *Gen 3 = 133.33*180-133.33*160 = 2666.66*

As noted before, the internal economic consistency of the dispatch and emissions prices here ensures that the dispatch adjustment is optimal to meet the emissions cap at the lowest possible cost (within the power sector) and SECED can continue to use the same cost allocation processes with the minor adjustment to factor in the shadow prices of emissions.

It of course makes a significant implicit assumption that the schedules submitted by the generators to the NLDC make significant adjustments at their end for NLDC to change the dispatch incrementally and be able to meet the cap. Even if this assumption does not hold, the process still works albeit the changes to the schedule may be significant, and the cap may need to be violated at the CO_2 penalty price set under the ICM.

The second method SCED using permit price requires no change to the SCED other than adjusting the variable cost to include generator specific emission coefficient multiplied by the permit price. In fact, if the permit price is set at the shadow price of CO_2 – the dispatch will match. However, if the permit price is different, dispatch and price outcomes will be different. Revenue calculations can be done using the same approach. The objective function for this optimization will of course be higher by the cost of CO_2. Since CO_2 costs are "transfers", the cost of generation or the 'resource costs' need to be separated.

It should also be possible to use a mix of the two approaches, i.e., a combination of permit prices and a cap but this requires a careful consideration because a normal scenario should be to use one or the other. by simply adjusting the emissions cap by the permits (and free allocations) held by the utility. This will work for a setup where the optimization is performed for a single entity, e.g., NTPC plants. For a multi-utility set up, the process may be more complex with each utility declaring its own caps based on the permits/allocation it holds and the NLDC/SLDC effectively playing the role of an energy and emissions broker (Chattopadhyay, 1995a) to perform the coordination. Such an optimization still sits within the scope of a SECED framework.

1.7 ICM AND SECED: A HARMONIOUS BLEN

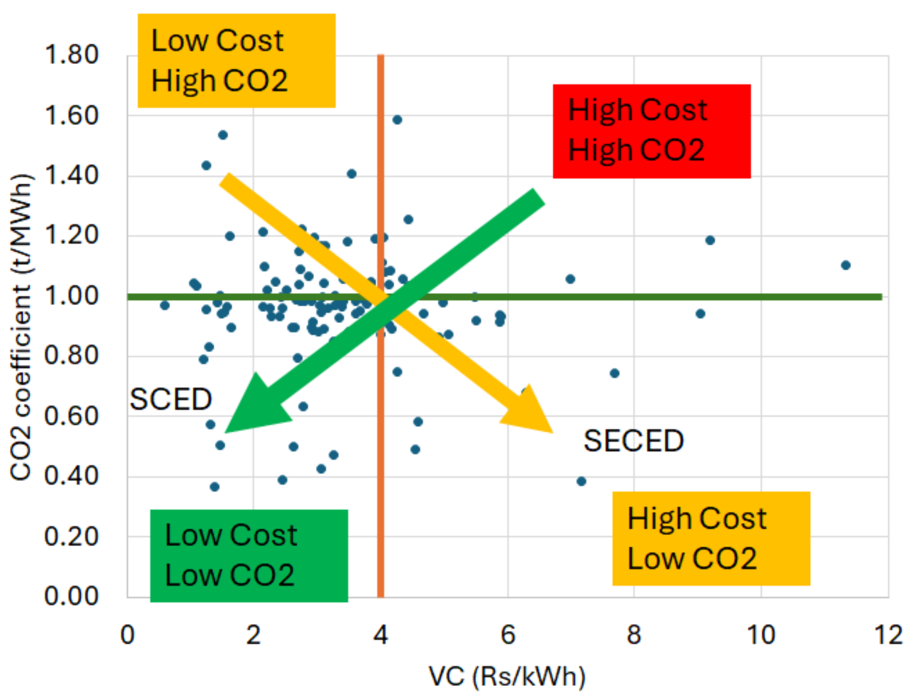
The discussion in section 1.6 alludes to a significant issue on how the carbon market and a centralized dispatch can co-exist and blended to provide an efficient outcome. Although the ICM is deemed to work by setting plant-wise targets and then allowing trading, SECED represents a complementary more centralized composite framework. In this model, implicit swapping among plants occurs while maintaining the same total system-wide MW output. The pool effectively consolidates CCC trades, generating earnings while ensuring that all plants benefit collectively. This bundled approach prioritizes carbon reduction, implicit trading, and creates shared gains, which are then distributed equitably. This method can be implemented around the incumbent SCED process and introduces indirect competition, fosters transparency, and enhances the accountability of the pool. SECED complements ICM because the latter casts the net more widely outside the power sector to secure carbon permits part of which may be cheaper than doing adjustments within the power sector. Generators that hold such permits (or free allocations if this forms part of the scheme) do not necessarily need to adjust their dispatch. On the other hand, where cheaper dispatch adjustment opportunities exist on certain days/months/seasons, requirement for permits can be avoided (or they can be banked for future usage depending on the design of the ICM).

2. SECED APPLICATION FOR EMISSIONS REDUCTION AND TRADING

2.1 SCED VS SECED

Figure 1 shows the trade-off between variable cost (VC on x-axis) vs the emission factors (tCO_2/MWh on the y-axis). The dots on this scatter plot indicates specific plants based on VC and CO_2 cost efficient of plants all over India. If these plants are divided into four quadrants based on an arbitrary cut-off of Rs 4/kWh and 1 t/MWh, it is useful to see how SCED and SECED may drive the dispatch in different directions. SCED will try to move the dispatch "horizontally" from high to low-cost units, while SECED will move them vertically. As the CO_2 emissions caps are imposed for the system, there will be "cross currents" shown by the two arrows, namely SECED will try to push the low cost but high CO_2 plants out of the dispatch, while SCED will try to move the high-cost plants out of the dispatch even if they have high CO_2. The LP/MIP based optimization neatly takes care of this process to find the optimal least cost dispatch to meet the CO_2 (and local pollutant) limits. Any dispatch adjustment across the dots has an implied cost of CO_2. For instance, if a MWh from a generating unit with (VC,CO_2) of (Rs 3 kWh, 1.2 t/MWh) gets replaced with that from one with (Rs 3.6/kWh, 0.9 t/MWh), the cost of CO2 reduction is (3.6-3.0)*1000/(1.2-0.9), or Rs 2000/t. The shadow price of the CO_2 cap in SECED (i.e., CO_2 Limit constraint μ) will report the *marginal* cost of meeting the last ton of CO_2 reduction. Annexure of this report has additional data showing the VC, emission factors and also the findings of the 2019 SCED studies.

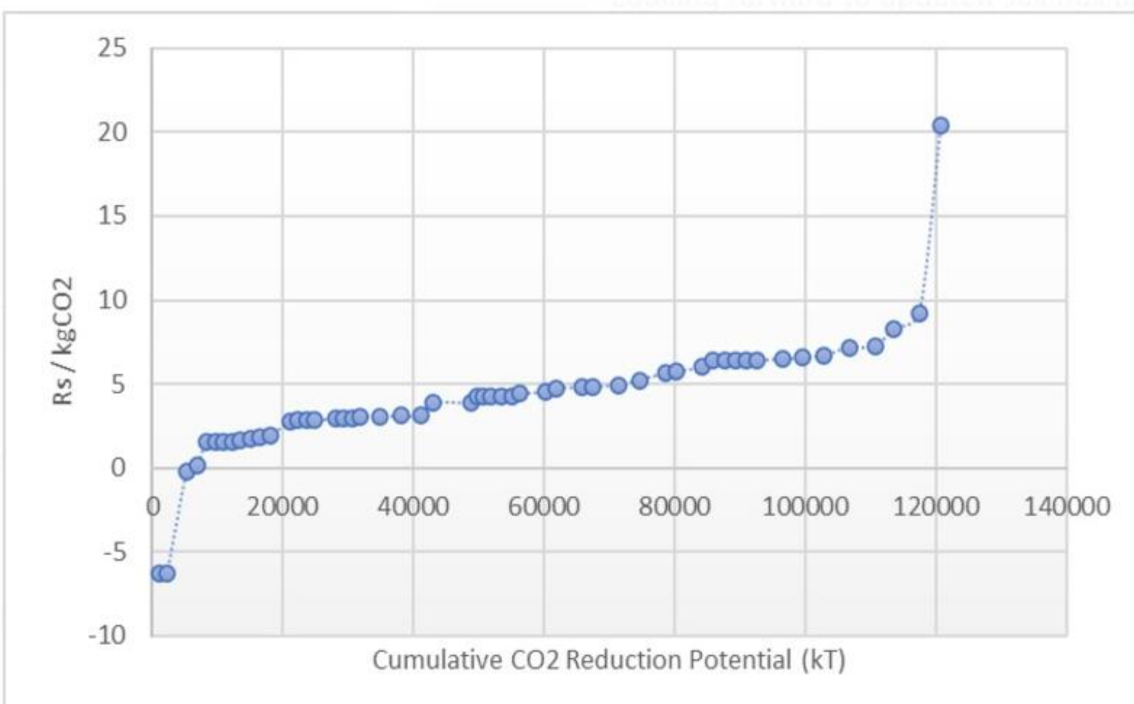
Figure 1 Variable cost vs emission trade-off: SCED vs SECED



2.2 COST OF CO2 REDUCTION

Figure 2 shows what a marginal abatement curve for CO_2 may look like if we keep on tightening the CO_2 limit (i.e., increase the CO_2 reduction). The plot below is NOT derived from a model that will look at all substitution possibilities including adjustments across the coal plants before resorting to measures like switching to existing gas plants, and more expensive long-term options like building new solar with battery storage etc. Instead, the plot below has a simple calculation to switch from individual coal plants in Maharashtra to a notional gas plant with a VC of Rs 5.8/kWh and an emission coefficient of 0.6 t/MWh. In reality, there is of course not enough gas capacity to switch from coal to gas but it nonetheless provides a simplistic benchmark on how costs will rise from close to zero (or even negative level as there are in fact gas plants in Maharashtra that has lower cost and lower emission coefficient than the arbitrary benchmark plant assumed here) Rs 1500-2000 for the first few million tons to Rs 3000-5000/ton for deeper cuts and so on. It does show that the initial few million tons can be achieved under Rs 2000/t by using the incumbent gas plants more and take dispatch away from the plants with emission coefficients well above 1 t/MWh.

Figure 2 Marginal CO_2 abatement curve for Maharashtra



Note: Simple calculations based on notional gas plant displacing all coal generation.

Table 3 shows a more accurate dispatch model-based calculation using a SCED database that was developed as part of a pilot study using data for Aug 9 – Oct 9 (32 days or roughly a month). The SECED model includes ramping and minimum generation limits and adjusts dispatch to meet the emissions target, or the objective function can be changed from cost to emissions. It shows cost will go up 18% to achieve the maximum possible emissions reduction of 11% (without shedding load) at a relatively high average cost of Rs 5173/t. It is also easy to impose a 8000 kT limit in the model that yields a lower average cost of reduction of Rs 1408/t for the first 392 kT (or 4.6%) reduction. The entire trade-off curve may be derived by changing the emissions limit from the unconstrained level down to the minimum emissions level.[3]

Table 3 Cost vs Emission trade-off for Maharashtra: Aug 9 – Sep 9, 2024 SECED analysis

	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

2.3 INDICATIVE ESTIMATES OF COST OF CO_2 EMISSIONS REDUCTION

Figure 3 shows an energy map of India indicating the location of major power plants in India.

Table 4 shows a summary of a few runs for an All-India version of SECED that progressively lowers the total CO_2 emissions from an unconstrained level of 1200 mt down to 1000 mt in steps of 50 mt. The emissions limits are applied at an annual level i.e., across all 8760 hours. This is closer to a SECED Planning model that may be used to project marginal and average CO_2 costs. As with the Maharashtra analysis, the average cost for 1150 mt scenario starts at Rs 1,673/t but quickly rises to Rs 3,805/t for 1100 mt target and rises to Rs 5,162/t for a 200 mt reduction. Marginal CO_2 costs are significantly higher, but it should be noted that at an annual (or monthly/daily) limit, the cost represents the very last ton of CO_2 reduction that may indeed come at a much higher cost by reducing generation from a low cost but slightly higher emission plant. As the emissions reduction target gets steeper, it is cheaper to shed load (which is assigned a cost of Rs 10/kWh reflective of cost of self-generation by customers) and as such generation from the thermal fleet goes down beyond the first 50 mt emissions reduction. The average cost of generation also increases as generation shifts from low to higher cost generators (but with less CO_2 emission intensity).

[3] This of course assumes the demand side remains completely inflexible which is not the case. Energy efficiency, demand response and other measures can be modeled in the dispatch model. Some of the measures like demand response would be applicable for real-time/day-ahead scheduling, planned energy efficiency and demand reduction measures may be more appropriate for SECED planning studies to see their impact on resource adequacy, cost and emissions.

Figure 3 Energy map of India

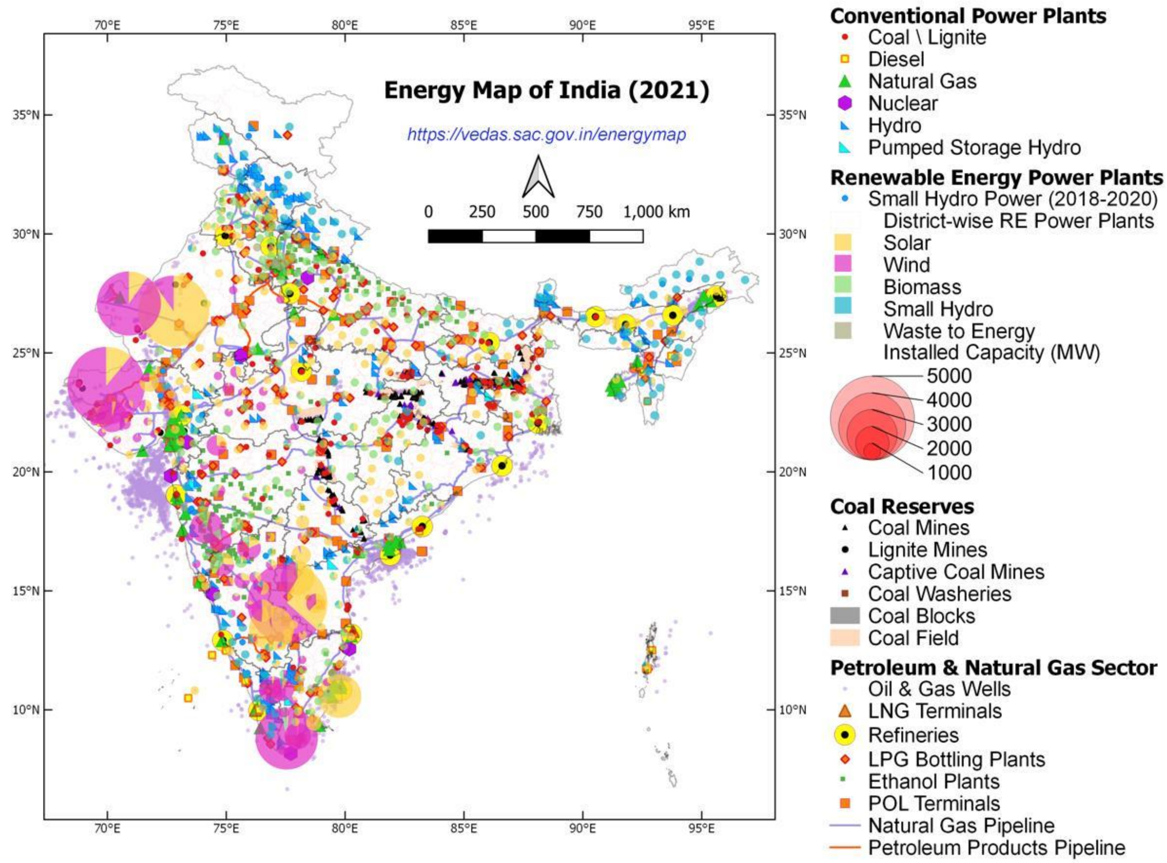
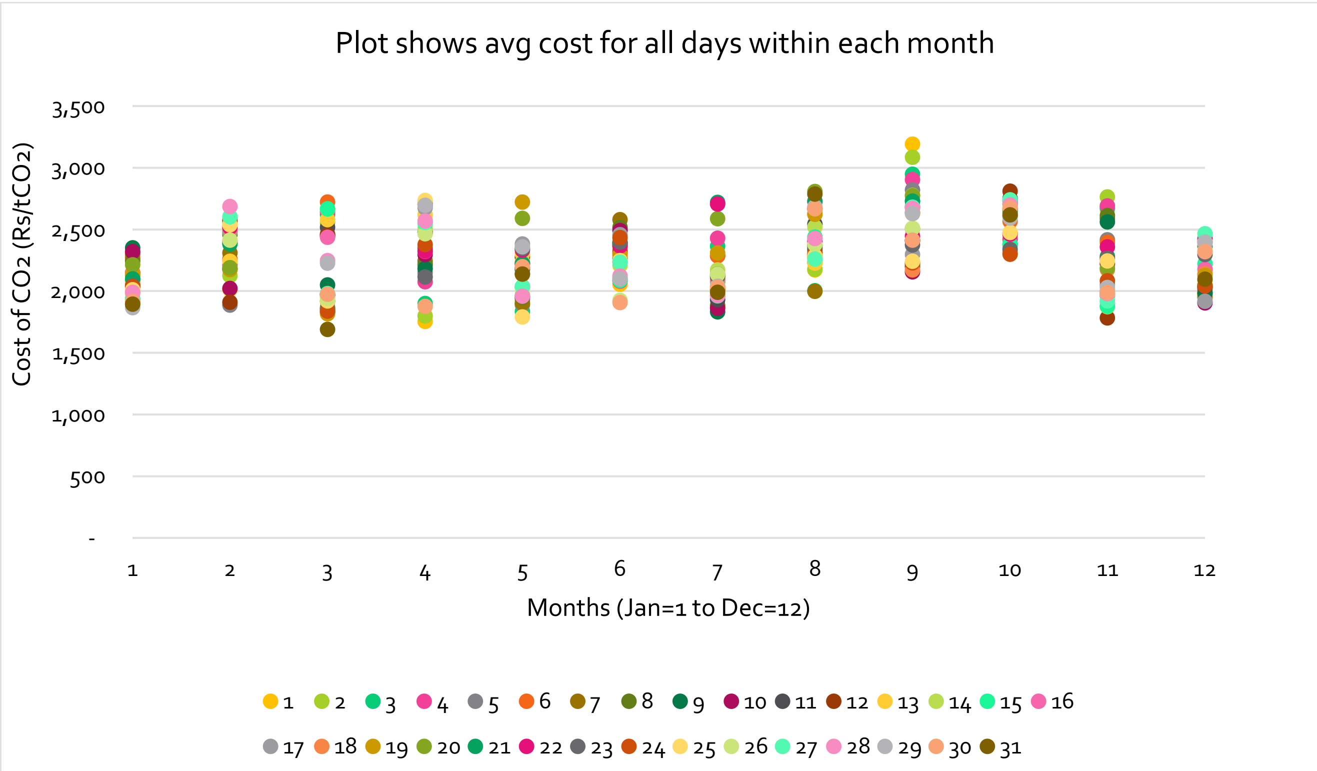


Table 4 Comparison of CO_2 emissions reduction scenarios: All India

	Unconstrained	1150 MT	1100 MT	1050 MT	1000 MT
System Cost Rs mill	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 (Rs/t)		4,689	6,224	6,508	6,647
Avg Cost of CO_2 (Rs/t)		1,673	3,805	4,682	5,162
Average generation cost (RS/MWh)	2,600	2,668	3,020	3,434	3,894

Figure 4 shows a separate run with daily limits corresponding to a 5% or 60 mt reduction. Prices over the 8760 hours average at Rs 2287/t or $27/t. The variability of prices across the days within each month is significant and over the years, prices range from Rs 1731/t to Rs 3191/t.

Figure 4 Average Cost of CO_2 Reduction (Rs/t) for 5% (or 60 mt) Reduction: All India



Although the CCC targets are typically set a year ahead and compliance is performed at the end of the year (including paying a penalty for being above the cap), the daily auctions may see significant variability in prices.[4] It is important to develop insights into how this variability of CO_2 prices may play out using a dispatch model in the first instance to understand the role dispatch adjustment play to meet the initial reductions. During the initial stage – if power generation is brought under the fold of ICM – there may well be free allocations of permits.[5] Nevertheless, SECED will be useful on two counts:

(a) Inculcate good dispatch practice to ensure the cheaper emission reduction opportunities are availed to meet the rest of the emission reduction requirements; and

[4] See for example, (Fazekas, 2008). This presents the Phase 1 of EU ETS in its early days in which four countries had participated. Narassimhan et al (2018) provides an overview of the ETS across eight jurisdictions: the EU, Switzerland, the Regional Greenhouse Gas Initiative (RGGI) and California in the US, Québec in Canada, New Zealand, the Republic of Korea and pilot schemes in China.

[5] The Chinese national emissions trading system allows for very significant free allocations that largely explains the low permit prices around $10/t. The EU ETS scheme also included free allocations but there has been over the years a shift towards market/auction based permits – see Lofgren et al for an excellent review of the EU ETS allowance allocation: https://www.journals.uchicago.edu/doi/full/10.1093/reep/rey012

(b) SECED planning will be useful to make sure the generators are in a good position to plan ahead and evaluate when to best use the free allocations, buy/sell the rest over the months, and clean generation options.

2.4 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;

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

3. The model can also be useful in making decisions on retirement of older coal generating units (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), 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.;

4. As with the electricity market vs SCED – it is possible for an emissions constrained dispatch to reduce the emissions reduction target for multiple generation companies collectively, to coexist with market-based trading system through auctions etc. The allocation of benefits will need to consider additional factors that are currently not part of the SCED system (in NLDC) such as permits already held by the generators (including any free allocation they may get) that they would like to exercise on the day, shadow price of emissions against the daily cap that need to be collectively met and the resultant optimal dispatch.

5. SECED presents a natural extension to SCED which augurs well with the objectives of the ICM. It is a mechanism that can be piloted even before the ICM starts. It will provide a good understanding of how reduction in CO_2 level may be achieved within the power sector including a useful benchmark CO_2 price that can be generated through the SECED model.

3. REFERENCES

Anke, C. et al. (2020). "Coal phase-outs and carbon prices: Interactions between EU emission trading and national carbon mitigation policies", *Energy Policy*, vol.144, September.

Bari, M. (2024), "Carbon Credits Trading Scheme (2023): A greener future", IMPRI, India. https://www.impriindia.com/insights/carbon-credits-trading-scheme-2023/#:~:text=Hence%2C%20the%20primary%20objective%20of,%2C%20steel%2C%20and%20cement%20sectors

Bureau of Energy Efficiency (BEE) (2024) *Carbon Market in India*, https://beeindia.gov.in/en/programmes/carbon-market.

Bureau of Energy Efficiency (BEE) (2024a), *Detailed Procedure for Compliance Mechanism under the CCTS*, New Delhi. https://beeindia.gov.in/sites/default/files/Detailed%20Procedure%20for%20Compliance%20Mechanism.pdf

Bureau of Energy Efficiency (BEE) (2023) *National Carbon Market: Discussion paper on voluntary carbon market in India*, https://beeindia.gov.in/sites/default/files/publications/files/NCM%20Final.pdf

Central Electricity Regulatory Commission (CERC). (2024). Regulation to create a framework for the exchange of Carbon Credit Certificates for the Obligated and the Non-Obligated entities on Power Exchanges. https://www.cercind.gov.in/2024/draft_reg/DN-PoCCC-2024.pdf

Chattopadhyay, D. (1995), "Cost versus emission minimization in thermal electricity generation: A case of so2 emissions reduction from the Indian power system" *International Journal of Energy Research*, November Issue. https://onlinelibrary.wiley.com/doi/abs/10.1002/er.4440190809

Chattopadhyay, D. (1995a), "An energy brokerage system with emission trading and allocation of cost savings" *IEEE Transactions on Power Systems*, November Issue. https://ieeexplore.ieee.org/document/476061

Fazekas, D. (2008), "Auction design, implementation and results of the EU ETS", Department of Environmental Management and Technology, Corvinus University of Budapest, Hungary.

https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=e2ffc2bc8319093877e0aadbdfe2b94601c1dd99

Grubb, M. (2007) *The European Emissions Trading Scheme: An Overview of Operations and Lessons*, *CESifo DICE Report*, Institut für Wirtschaftsforschung an der Universität München, München, Vol. 05, Iss. 4, pp. 17-25. https://www.econstor.eu/bitstream/10419/166922/1/ifo-dice-report-v05-y2007-i4-p17-25.pdf

Jennifer, L., (2024), India Revises Its Carbon Credit Trading Scheme for Voluntary Players, Carbon Credits, https://carboncredits.com/india-revises-its-carbon-credit-trading-scheme-for-voluntary-players/

Lorfgren, A. et al (2018), "Distribution of Emissions Allowances and the Use of Auction Revenues in the European Union Emissions Trading System" *Review of Environmental Economics and Policy*, volume 12, issue 2, Summer 2018, pp. 284–303 https://www.journals.uchicago.edu/doi/full/10.1093/reep/rey012

Narassimhan, E. et al (2018), Carbon pricing in practice: a review of existing emissions trading systems, *Climate Policy*, https://www.tandfonline.com/doi/full/10.1080/14693062.2018.1467827#abstract

Philiip, D.K. (2024), India's Carbon Market Revolution: Balancing Economic Growth with Climate Responsibility, https://www.investindia.gov.in/team-india-blogs/indias-carbon-market-revolution-balancing-economic-growth-climate-responsibility

Policy Circle Bureau (2024), India's carbon credit trading scheme stumbles on starting line, 1 November. https://www.policycircle.org/environment/indias-carbon-credit-trading-lags/

POSOCO (2020), *Security Constrained Economic Dispatch: Detailed feedback report on pilot of interstate generating stations pan India*, New Delhi. https://posoco.in/wp-content/uploads/2020/02/POSOCO_SCED_Pilot_Detailed_Feedback_Report_Jan_2020.pdf

Tekin, E. et al (2024). Impact of different CO_2 price paths on the development of the European electricity system, *Energy Strategy Review*, volume 55.

ANNEXURE: ADDITIONAL COST AND EMISSIONS DATA

A.1 TRENDS OF EMISSION FACTOR VIS-À-VIS VARIABLE COST

The variable cot and the emission factor of 521 units has been compiled and plotted IN Figure 5 to observe the pattern and study the emission constrained power despatch. The plot shows a worrying trend that both the variable costs and the emission factors exhibit an increasing trend with the time.

Figure 5 Variable cost vs emission factor: variation with vintage of plants

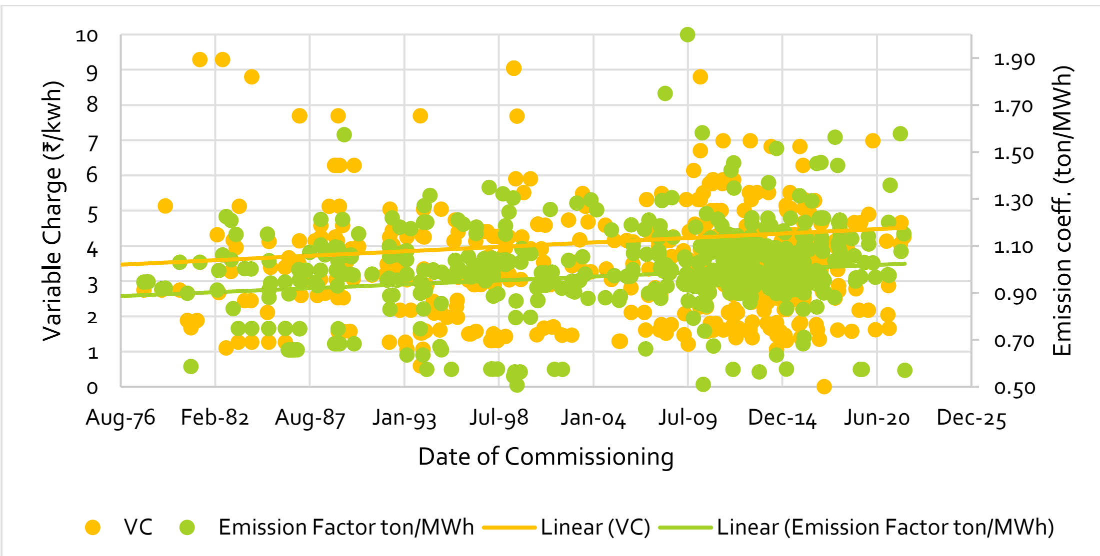


Figure 6 shows that the variable cost is varying between Rs (₹) 1.5 to Rs 5.5 for a total capacity of around 120 GW. The high variable cost i.e. between Rs5.5 to Rs9.5 is for gas based generation (in operation) which is having a total capacity of only 10 GW.

Figure 6 Variable cost vs cumulative capacity

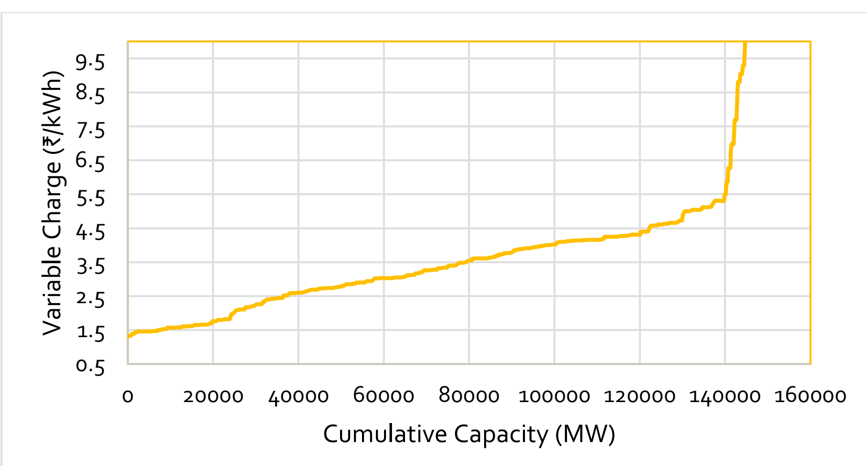


Figure 7 shows that the emission factor is varying between 0.85 to 1.3 ton/MWh for most the capacities which is around 125 GW. The lower emission factor i.e. < 0.6 is mainly of the gas-based generation.

Figure 7 Emission factor vs cumulative capacity

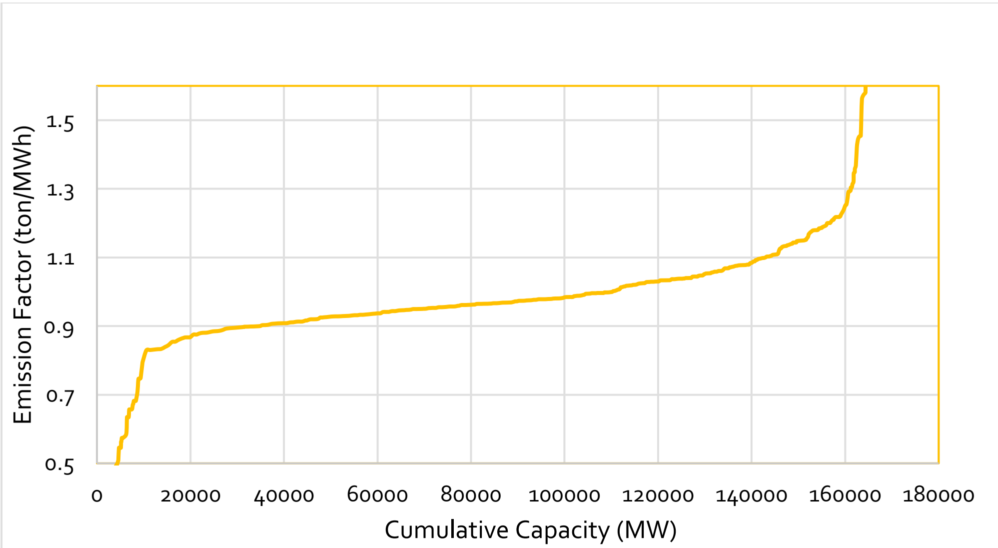


Figure 8 scatter plot clearly shows that production cost will be more with reduction in emission. Similar plot in Figure 9 when the axes are swapped also confirms that the Emission Factor is reducing with increase in variable cost and hence reduction of emission will lead to higher cost of production.

Figure 8 Emission factor vs variable cost

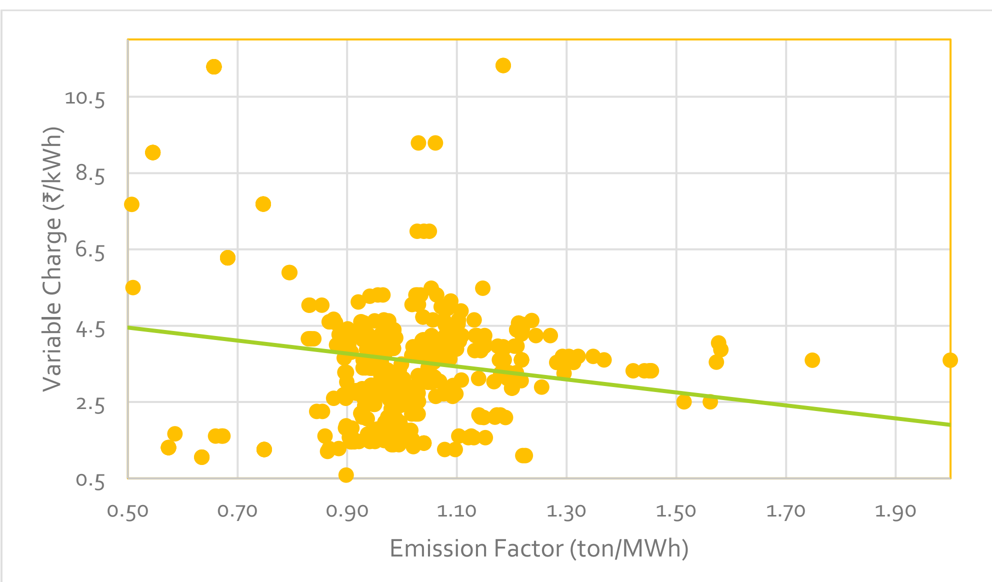
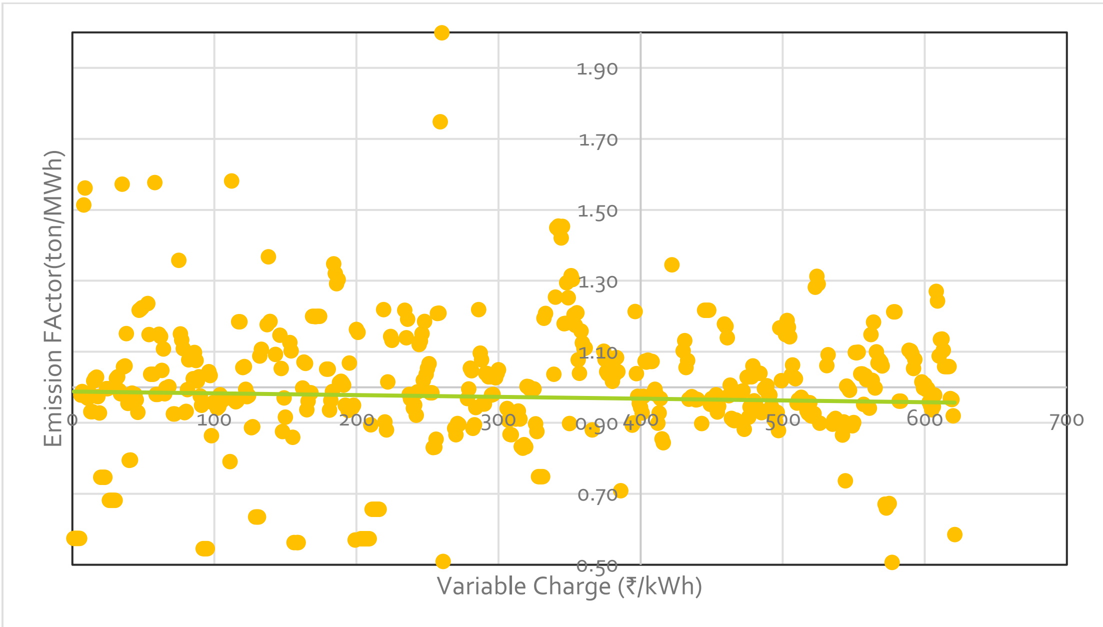


Figure 9 Variable cost vs emission factor



A.2 POSOCO SCED DATA FROM MAY 2019

Figure 10, Figure 11 and Figure 12 are reproduced from the POSOCO SCED 2019 report that provide further confirmation of the data from actual SCED runs. It also shows that when costs and emissions are in alignment, a SCED run itself may lead to a small reduction in emissions

Figure 10 SCED data on emission factor and variable cost

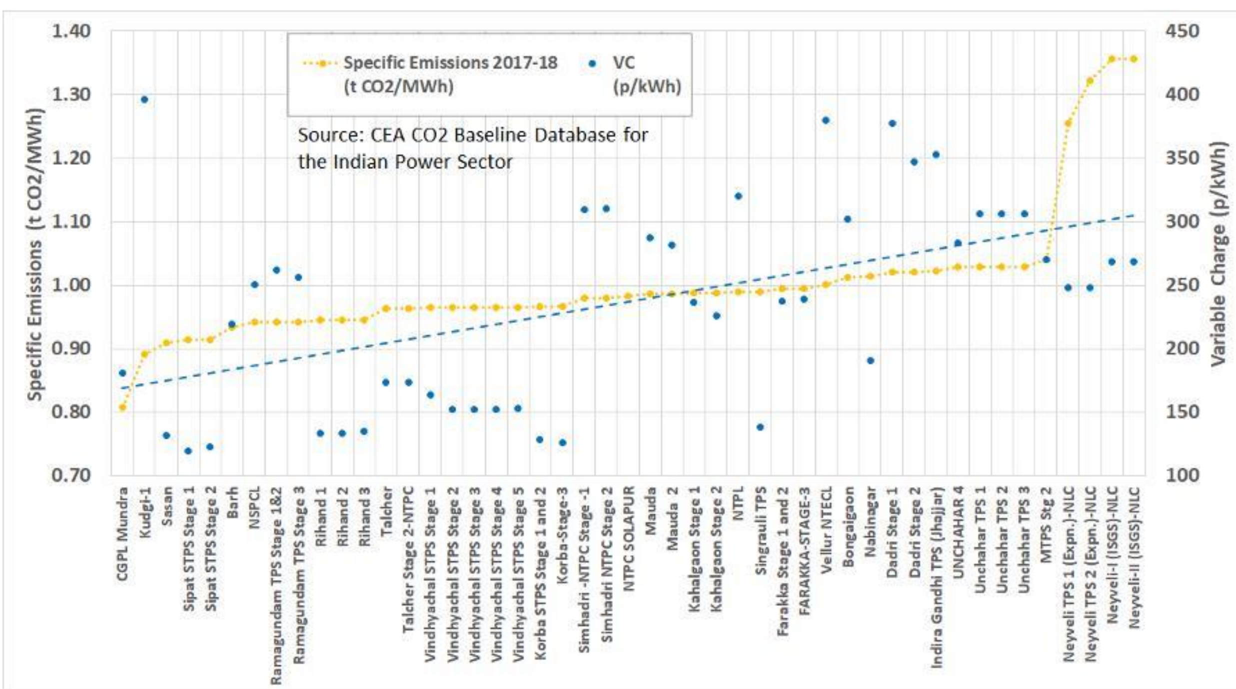


Figure 11 SCED data on changes in CO_2 emissions for May 2019

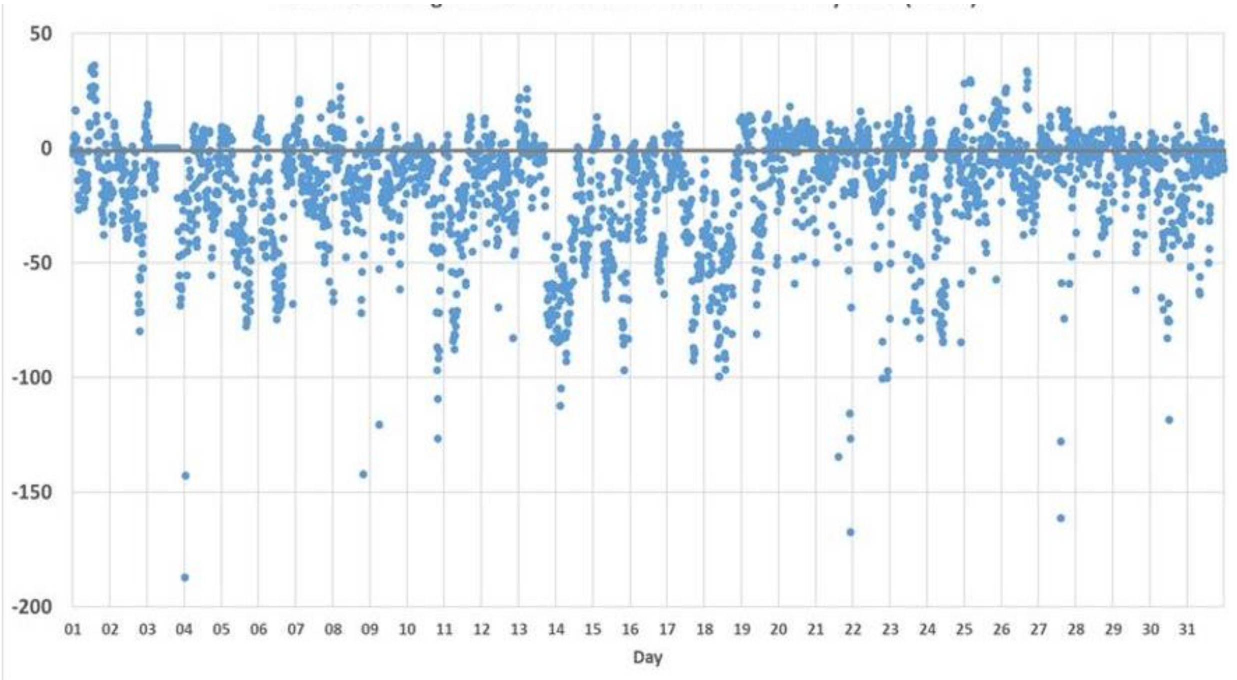


Figure 12 SCED data on changes in CO_2 emissions in May 2019 (block wise change in %)