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Economic, Environmental, and Climate Impacts of FGDs in Thermal Power Plants in India

National Institute of Advanced Studies
Bengaluru, India

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Economic, Environmental, and Climate Impacts of FGDs in Thermal Power Plants in India

Interim Study Report

Submitted

by

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To

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Cover photo: (Front cover) Raichur Power Corporation's 2 X 800 MW Yeramarus Thermal Power Station, Raichur district, Karnataka
(Back cover) Sri Damodaram Sanjeevaiah 2 X 800 MW Thermal Power Station, Krishnapatnam, Nellore district, Andhra Pradesh

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Table of Contents

Abbreviations

APC	Auxiliary Power Consumption
Bcm	Billion Cubic Meters
BESS	Battery Energy Storage System
Bt	Billion Tonnes
CEA	Central Electricity Authority
CERC	Central Electricity Regulatory Commission
CFBC	Circulating Fluidized Bed Combustion
CPCB	Central Pollution Control Board
DST	Department of Science & Technology
EDGAR	Emission Database for Global Atmospheric Research
FGD	Flue Gas Desulfurizers
FY	Fiscal Year
GCV	Gross Calorific Value
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GoI	Government of India
GW	Gigawatt
GWP	Global warming potential
HFC	Hydrofluorocarbon
Hg	Mercury
Kt	Kilo tonnes
Mcm	Million Cubic Meters
MOEFCC	Ministry of Environment, Forest, and Climate Change
Mt	Million Tonnes
NDC	Nationally Determined Contributions
NEP	National Electricity Plan
NO_2	Nitrogen dioxide

NPP	National Power Portal
PFC	Perfluorocarbon
PLF	Plant Load Factor
PM	Particulate Matter
RES	Renewable Energy Source
R&M	Repair and Maintenance
SO_2	Sulfur Dioxide
SDG	Sustainable Development Goal
T	Tonnes
TPP	Thermal Power Plant
TPS	Thermal Power Station
TWh	Terawatt hours
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
Y-o-Y	Year-On-Year

List of Tables

List of Figures

Table of Equations

Executive Summary

Electricity security can be achieved only by '*having a reliable and stable supply of electricity that can meet the demand at all times at an affordable price.*' The reliance on coal for affordable and reliable electricity is indicated by the fact that global coal-fired electricity generation recorded a new peak of 10,648 TWh in 2023, amounting to 35.66% of the World's total electricity generation[1].

Spurred by the sharp increase in peak demand in FY 2023-24, the Central Electricity Authority (CEA) has also raised its forecast for peak electricity demand in FY 2031-32 to 388 GW, which is a 5% increase over the peak demand estimated by the CEA in Volume 1 of the National Electricity Plan (CEA, 2023a; 2024b). Recently, the Ministry of Power (MOP) has increased its estimate of peak demand to 400 GW by FY 2031-32.[2] Therefore, MOP has asserted that the total coal-fired power generation capacity of the country must be progressively enhanced to 283 GW by 2032 from the current (October 2024) level of 217 GW to meet the growing demand for electricity to overcome India's development deficit[3].

On the other hand, the Working Group 1 (WG1) of the Intergovernmental Panel on Climate Change (IPCC) published its Sixth Assessment Report (AR6) quantifying the contribution of different gases to global warming. As per this report, the cumulative emissions of greenhouse gases like carbon dioxide (CO2) and methane have increased global warming by about 1.5^{0}C, while Sulfur dioxide (SO_2) emissions have masked global warming by approximately 0.5^{0}C in the 2010-2019 period relative to 1850-1900[4]. Studies conducted on the success of China in reducing SO_2 aerosol emissions by fitting FGDs indicate that the 'unmasked' warming caused by reducing the aerosol emissions would in turn compound the challenge and urgency of global climate mitigation efforts (Qian et al., 2020; Zheng et al., 2020).[5,6]

Therefore, energy production and consumption are intrinsically linked to climate change and air pollution. Unlike the developed countries which face zero or negligible growth in electricity demand, India has the twin challenge of enhancing electricity consumption to meet its human development needs while ramping up non-fossil fuel sources of energy to reach Net Zero by 2070. Ninety-two percent of the coal used by TPPs in India is supplied from domestic mines and this is the key driver for the affordability

1 IEA (International Energy Agency) (2024). World Energy Outlook 2024.

2 India's power demand forecast to surpass 400 GW by 2031-32: Power Secretary. The Economic Times on July 2, 2024. <https://energy.economictimes.indiatimes.com/news/power/indias-power-demand-forecast-to-surpass-400-gw-by-2031-32-power-secretary/111425728>

3 Press information Bureau, press release: "Total installed thermal power capacity is expected to be 283 GW and non-fossil-fuel-based capacity to be 500 GW by 2031-32: Union Power and New & Renewable Energy Minister." <https://pib.gov.in/PressReleaseIframePage.aspx?PRID=2003922>

4 IPCC (Intergovernmental Panel for Climate Change) (2021). Sixth Assessment Report: Working Group 1: The Physical Science Basis. Summary for Policymakers. <https://doi:10.1017/9781009157896.001>

5 Qian, Y., Scherer, L., Tukker, A., & Behrens, P. (2020). China's potential SO2 emissions from coal by 2050. *Energy Policy*, *147*, 111856. <https://doi.org/10.1016/j.enpol.2020.111856>

6 Zheng Yixuan, Qiang Zhang, Dan Tong, Steven Davies, and Ken Caldiera (2020). Climate effects of China's efforts to improve its air quality. *Environ. Res. Lett.* **15** 104052. <https://doi.org/10.1088/1748-9326/ab9e21>

of 24x7 electricity in India. Generally, Indian coals (barring Assam and Meghalaya coals) have very low Sulfur content (0.3% - 0.5%) and high-ash content unlike coals burnt by TPPs in countries like China.

The Central Pollution Control Board (CPCB) conducted studies on stack emissions in various climatic conditions in India before mandating the minimum stack heights of TPPs to be 220 m for TPPs having generation capacities between 200 MW and 499 MW and 275 m for TPPs capable of generating 500 MW or more.[7] This mandate has worked effectively over the past 40 years because the ambient air concentrations of SO_2 around the vast majority of TPPs in India is well below the National Ambient Air Quality Standards. However, TPPs located in eco-sensitive areas or those located less than 10 km from the boundaries of metropolitan cities and those using high-Sulfur coal (largely imported) have been granted Environment Clearance (EC) on the condition that they instal & operate Flue Gas Desulfurizers (FGDs) to reduce the SO_2 emissions from the stack and Electrostatic precipitators (ESPs) to reduce Particulate Matter (PM) emissions.

In December 2015, the MOEFCC amended the Environmental (Protection) Rules (EP Rules) to mandate ~600 TPPs in India to reduce SO2 concentrations in the TPP stacks by installing FGDs. However, only 44 of the 537 operating TPPs mandated to retrofit FGDs in India have installed FGDs till September 2024, although 233 FGDs were procured by TPPs till 2023.

In March 2023, the Office of the PSA sanctioned a research project to NIAS to estimate incremental CO_2 emissions from FGDs and quantify Sulphur dioxide emission factors for TPPs. This study aimed to address the unique requirements and implications of deploying FGDs in India and detail alternative technologies for air pollution control from TPPs. This interim report submitted by NIAS summarises the work done till date which was presented in the Stakeholder meeting organised by the office of PSA on November 13, 2024. The key findings of the NIAS study are summarised as follows:

Key Findings

- The average sulfur content of Indian coals used to generate 92% of the electricity produced by TPPs is less than 0.5%, which is very low by international standards.
- The stacks of TPPs in India are 220 m tall (< 500 MW TPPs) or 275 m tall (TPPs with capacity >= 500 MW) as per the Central Pollution Control Board (CPCB) (1984) standards. These stack heights were designed to ensure the effective dispersion of SO_2 over a large area under the climatic conditions in India so that the ground-level (ambient) concentrations of SO_2 comply with the National Ambient Air Quality (NAAQ) Standards. This design basis has proved to be effective all over India since all available data indicates that the ambient SO_2 levels around TPPs are compliant with the current NAAQ standard for SO_2 (80 $\mu g/m^3$ on a 24-hour basis and 50 $\mu g/m^3$ on an annual basis).
- NIAS conducted a study of the air quality around two large TPPs operated by Public Sector Undertakings (PSUs) which utilize the low-sulfur coal mined in the Ramagundam coalfield in

7 CPCB (Central Pollution Control Board) (1984). Comprehensive Industry Document Series. Emissions Regulations Part-1.

Telangana during the 2017-2020 period. In this study, the stack emission data provided by these TPPs was also analyzed (Chauhan et al., 2021).

- As shown in Figure E1 and Figure E2, the stack emissions of Particulate Matter (PM) in both TPPs were compliant with the applicable norms - 100 mg/Nm^3 for TPPs commissioned prior to 2003 and 50 mg/Nm^3 for TPPs commissioned between 2004 and 1st January 2017.
- The concentrations of SO_2 in the stack emissions of both TPPs were in 1500 – 1600 mg/Nm^3 range due to their exclusive use of low-Sulfur Indian coal. Since both TPPs are complying with the stack height norms (CPCB, 1984) and ensuring an adequate exit velocity for the flue gases, the annual average ambient SO_2 concentrations measured in all Ambient Air Quality Measurement Stations (AAQMS) maintained by the two TPPs and the coal mines in and around the Ramagundam town were found to be in the range of 10-15 µg/m^3 – which is less than one-third of the NAAQ standard (Chauhan et al., 2021).
- This was confirmed by analyzing the air quality data collected by the Telangana State Pollution Control Board (TSPCB) in the Godavarikhani AAQMS located in the Ramagundam town where the annual average SO_2 concentration has not exceeded 10 µg/m^3 between 2016 and 2023 even after a new TPP (2 x 600 MW) capacity was commissioned in FY 2016-17 in the vicinity (Figure E3). This proves that FGDs are not required in TPPs using low-sulfur (<0.5%) Indian coal to comply with the NAAQ Standard for SO_2.

Figure E1. Stack emissions from a pre-2003, 2600 MW sub-critical TPS using low-sulfur Indian coal without High-efficiency ESPs and FGDs

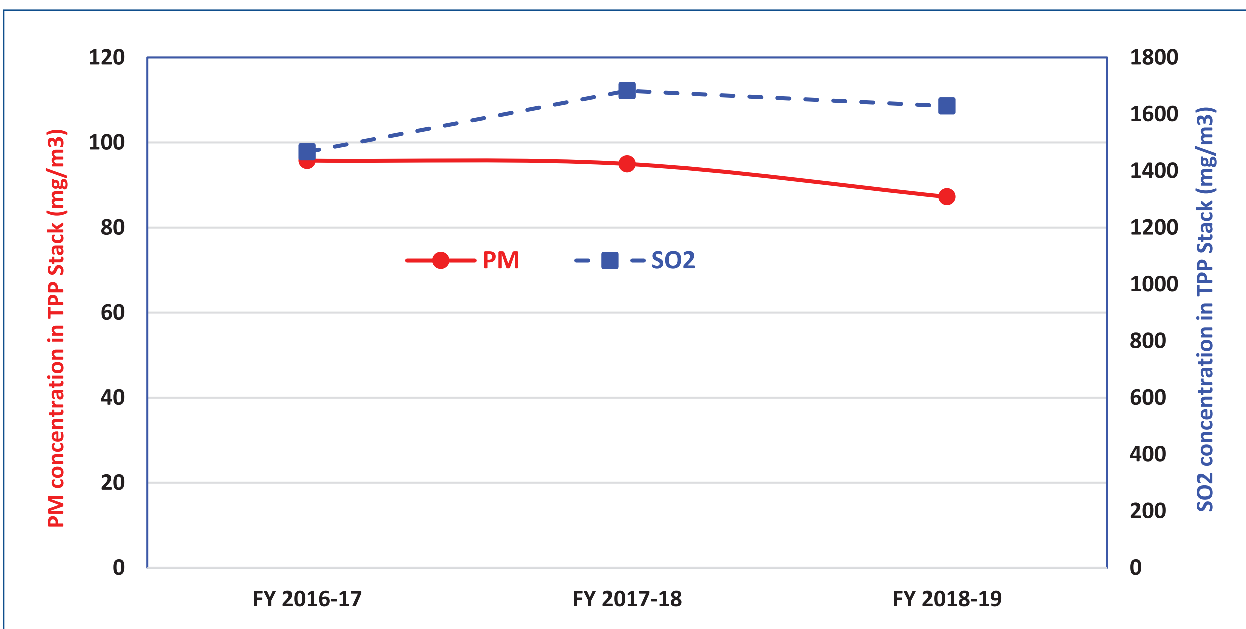


Figure E2. Particulate Matter (PM) concentration in the stack emission from a 1200 MW TPS equipped with sub-critical technology and a High-efficiency ESPs but no FGD

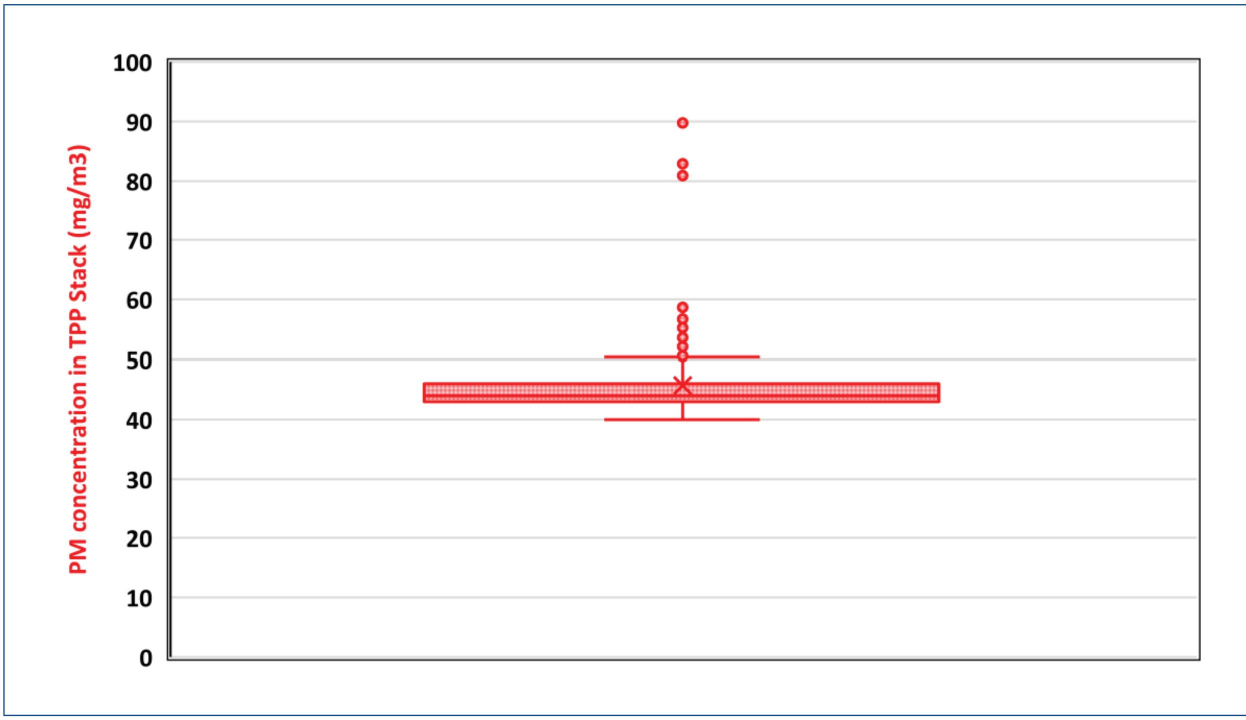


Figure E3. Sulfur dioxide (SO_2) concentrations recorded by the Telangana State Pollution Control Board AAQM station in Ramagundam comply with the NAAQ Standard.

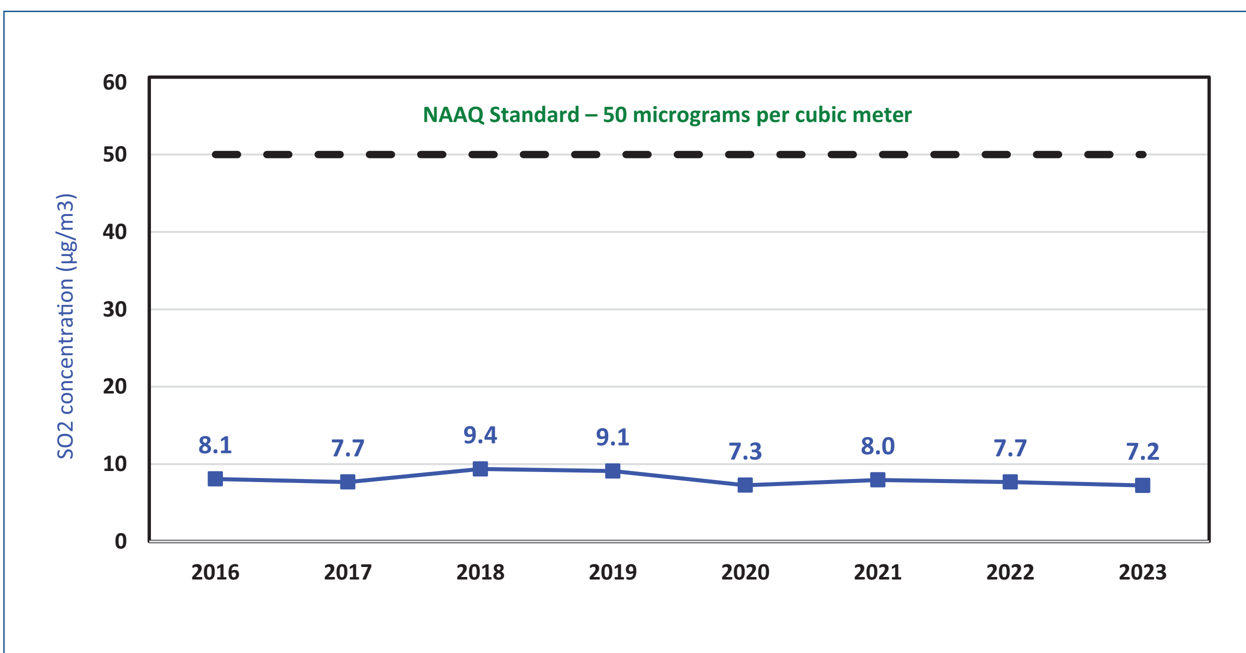
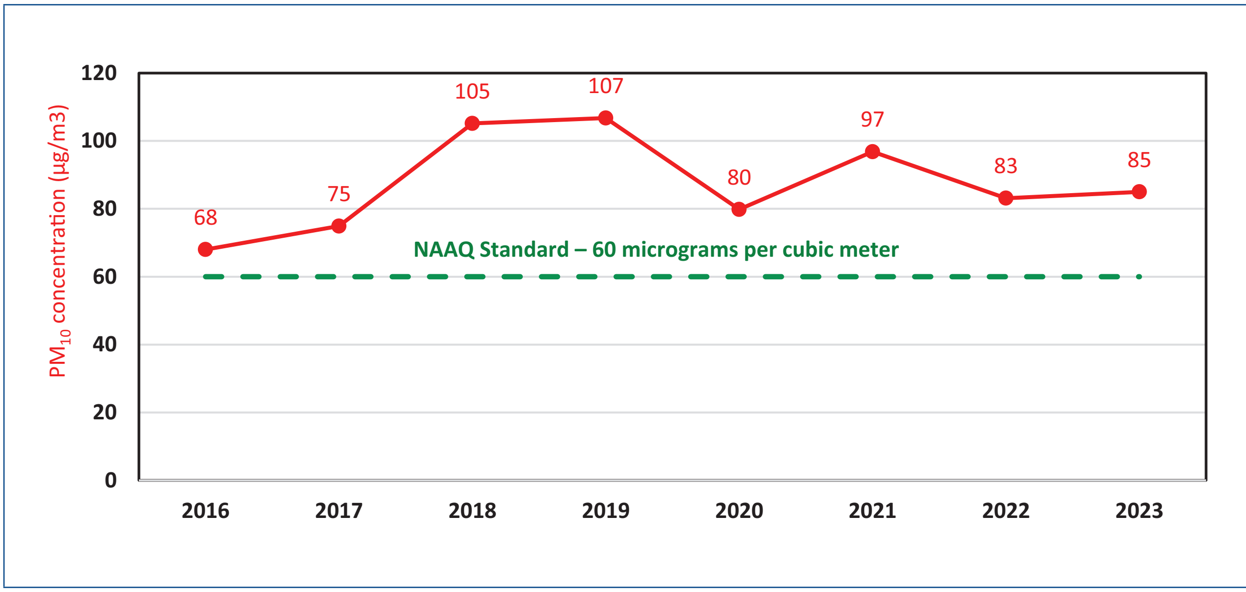


Figure E4. PM_{10} concentrations recorded by the Telangana State Pollution Control Board AAQM station in Ramagundam do not comply with the NAAQ Standard



- However, the PM_{10} concentrations recorded by TSPCB at the Ramagundam AAQM station continuously exceed the annual standard as shown in Figure E4. These measurements indicate that FGDs are redundant in controlling ambient air SO_2 concentrations in TPPs that use low-Sulfur Indian coal and comply with the stack heights specified in CPCB (1984) as well as the exit velocity of flue gases mandated in their original environment clearance.
- Studies by CSIR-NEERI (2024) and IIT-Delhi (2022; 2024) have also proved that FGDs have only a negligible impact on ambient air $PM_{2.5}$ concentrations in nearby towns. This is due to the predominance of other pollution sources (e.g., airborne dust, vehicular exhaust, various industries, use of coal/firewood for cooking) in urban areas and the very low (< 0.5%) Sulfur content of Indian coal coupled with the effective dispersion of SO_2 generated from TPPs due to the tall stacks and the climatic conditions in India.
- According to the CSIR-NEERI (2024) study, the ambient SO_2 concentrations around all TPPs in India (with and without FGDs) generally comply with the NAAQ standard.
- According to the IIT-Delhi (2024) report on FGDs, acid rain is not a significant issue in India due to the presence of alkaline substances in the dust. Even in coastal regions, the sea breeze, together with the alkaline nature of seawater droplets, effectively neutralizes any sulfuric acid formation in the atmosphere.
- On the other hand, installing FGDs in all TPPs by 2030 will increase the Auxiliary Power Consumption (APC) of the TPPs thereby adding approximately 69 million tons of CO_2 emissions to the atmosphere (2025-30) while reducing SO_2 emissions by ~17 million tons. While CO_2 accumulations in the atmosphere contribute to global warming, the IPCC AR 6 report states that anthropogenic SO_2 emissions have masked global warming by ~0.5^0C in the 2010-2019 period relative to the 1850-1900 period. Therefore, adding more long-lived CO_2 emissions while removing

short-lived SO_2 emissions by installing FGDs indiscriminately in all TPPs in India despite the low Sulfur content of Indian coal will enhance global warming.

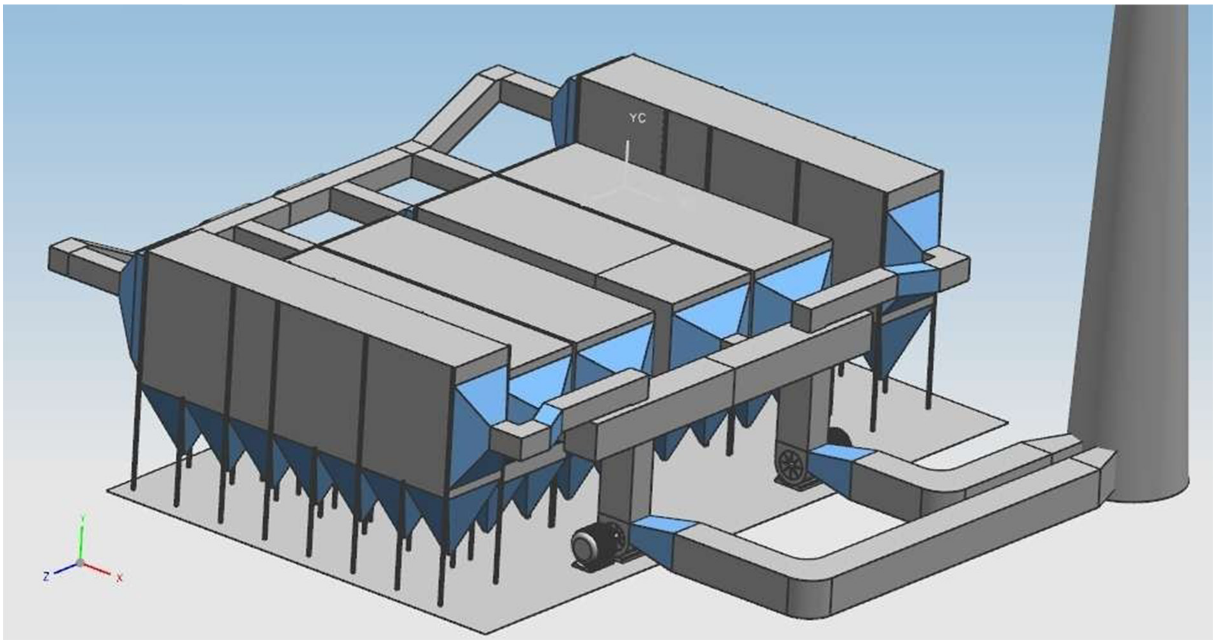
- Further, 80 GW of new thermal capacity (based on domestic, low-sulfur coal) will be added to the Power Grid to meet the baseload demand for electricity in India even after all obsolete and inefficient TPPs in operation today are progressively retired by the year 2032. Extending the study period to 2040 after accounting for the projected retirements and additions of TPPs, the cumulative CO_2 emissions from TPPs between 2024 and 2040 are estimated to be approximately 272 MT due to FGD installations.
- Installing wet FGDs in TPPs reduces their energy efficiency and increases freshwater consumption. Inland TPPs consume approximately 3.79 billion cubic meters of freshwater per year. NIAS estimates that freshwater consumption by TPPs will increase by about 9.6% in 2030 if FGDs are installed in all inland TPPs. Rather, MOP and the State Government can provide the policy support to enable TPPs to comply with the mandate to treat & use sewage water from municipalities within 50 km of the TPP. This is explained in Section 8.
- As per the Central Electricity Authority (CEA), 44 TPPs are equipped with FGDs while another 233 FGDs have been awarded out of 537 TPPs identified for installing FGDs in India. Retrofitting of FGDs in operating TPPs requires long shutdown times (+45 days), which is delaying the commissioning of FGDs even in TPPs that have awarded FGDs. Considering the low-Sulfur Indian coals, 220-275 m tall TPP stacks, and tropical climate around the TPPs in India, NIAS recommends no further need for FGD installations till further studies are undertaken to assess the impact of FGDs in controlling secondary PM pollution from 32 TPPs located within 10 km of cities with +1 million population which have either installed FGDs are at various stages of installing FGDs to comply with the MOEFCC (2015) SO_2 norms. In any case, there is no justifiable need to enforce the MOEFCC (2015) stack emission norms for SO_2 in TPPs in other areas of the country that use coal with less than 0.5% Sulfur content.
- The NIAS study also indicates that Particulate Matter (PM) pollution is the major problem attributed to TPPs using high-ash Indian coal. PM pollution from TPP stacks can be addressed quickly and cost-effectively by retrofitting indigenous High-efficiency ESPs in all TPPs irrespective of their size or location (Figure E5). Installation of High-efficiency ESPs will reduce the stack emissions of PM by 99.97% and enable TPPs to comply with the MOEFCC (2015) stack emission norms for PM (50 mg/m^3 for TPPs installed up to December 2016). Controlling PM emissions from TPP stacks at this level will make the maximum impact on air pollution from TPPs even without FGDs. Without such High-efficiency ESPs, the ambient air concentrations in the communities around TPPs will not comply with the NAAQ standard in the summer and post-monsoon seasons.
- Bharat Heavy Electricals Ltd. (BHEL) has retrofitted High-efficiency ESPs even in older TPPs with space constraints (Figure E6). Installation of such ESPs will cost only Rs. 25 Lakhs per MW compared to Rs. 120 Lakhs per MW for wet FGDs based on imported technology. Further, retrofitting High-efficiency ESPs in operating TPPs requires only 2 days of boiler shutdown for hookup, unlike FGDs which require ~45-day boiler shutdowns during FGD commissioning.

Key Recommendations

- Particulate Matter (PM) pollution is the key concern related to air pollution from TPPs. BHEL has demonstrated the retrofit of High-efficiency ESPs in TPPs with space constraints. Therefore, PM pollution control in TPPs to be prioritized by retrofitting High-efficiency ESPs in all existing TPPs to reduce PM pollution by 99.97% within the next two years.
- Since 32 of the 65 TPPs within 10 km of cities with +1 million population have either installed or awarded FGDs, the impacts of FGDs in terms of PM pollution reduction in these cities must be assessed before any future FGDs are awarded.

Figure E5. High-efficiency Electrostatic Precipitator (ESP) installed by BHEL in a TPP in India

Figure E6. Retrofit of a new, taller ESP field in parallel with the existing ESP by BHEL in a 210 MW TPP to reduce PM concentrations in the flue gases by 99.97%



- TPPs retiring by 2030 to be exempted from SO_2 stack emission norms since these will normally be the obsolete stations with a proportionately lesser contribution to the total electricity generation in the country. This will avoid saddling electricity consumers with large tariff hikes to recover the cost of the FGDs within a short period.
- There is no tangible benefit of fitting FGDs in TPPs not located within 10 km of cities with +1 million population if they are using low-Sulfur coal. Rather, they must be equipped with High-efficiency ESPs for the reasons explained earlier.
- The Environmental (Protection) Rules, 2015 to be amended to limit the SO_2 stack emission norms only to TPPs using Imported coal and/or High (> 0.5%) Sulfur coal.
- Since all new TPPs are (i) based on domestic low-Sulfur coal, (ii) designed with High-efficiency ESPs, and (iii) located more than 10 km away from any city with +1 million population, FGDs to be avoided in TPPs awarded from January 2024 onwards.
- Implementation of these decisions will reduce PM pollution without the adverse impacts of FGDs (higher levels of water consumption & CO_2 emissions), while limiting the financial burden on the power sector thereby minimizing electricity tariff hikes on account of FGD installations.
- India is the 2nd largest coal user after China. Hence, the impact on global warming by installing FGDs in all TPPs must be assessed as has been done in China (Section 1.2.3).
- The effect on India's NDCs if FGDs are installed in all TPPs must be quantified.

- Since coal supplied from domestic coal mines accounts for 92% of the power generated in India, and this reliance is going to increase in future, there should be a greater thrust on the enablers required to use high-ash, low-Sulfur Indian coal more efficiently.
- Using coal washed at the pithead will not only reduce air pollution from TPPs & coal transportation but will also enhance ESP performance as well as boiler efficiency thereby reducing CO_2 emissions. Using washed coal will also reduce water consumption in TPPs. The washeries must be designed & operated to ensure that the ash content of rejects is +62% so that they are unfit for any end-use other than backfilling the coal mine void.
- An integrated cost-benefit analysis of using washed coal in TPPs must be conducted since the dependence on high-ash domestic coal for power generation will continue in India.
- CO_2 emissions from TPPs can be minimized by burning coal more efficiently compared to the current levels of efficiency achieved in the super-critical power plants of India. Integrated Gasification Combined Cycle (IGCC) power plants use coal and water more efficiently and enable CO_2 capture in an efficient manner. While MOC is pursuing Coal gasification projects, MOP must incentivize deployment of IGCC-based power plants.

1. Introduction

1.1 BackgroundTop of Form

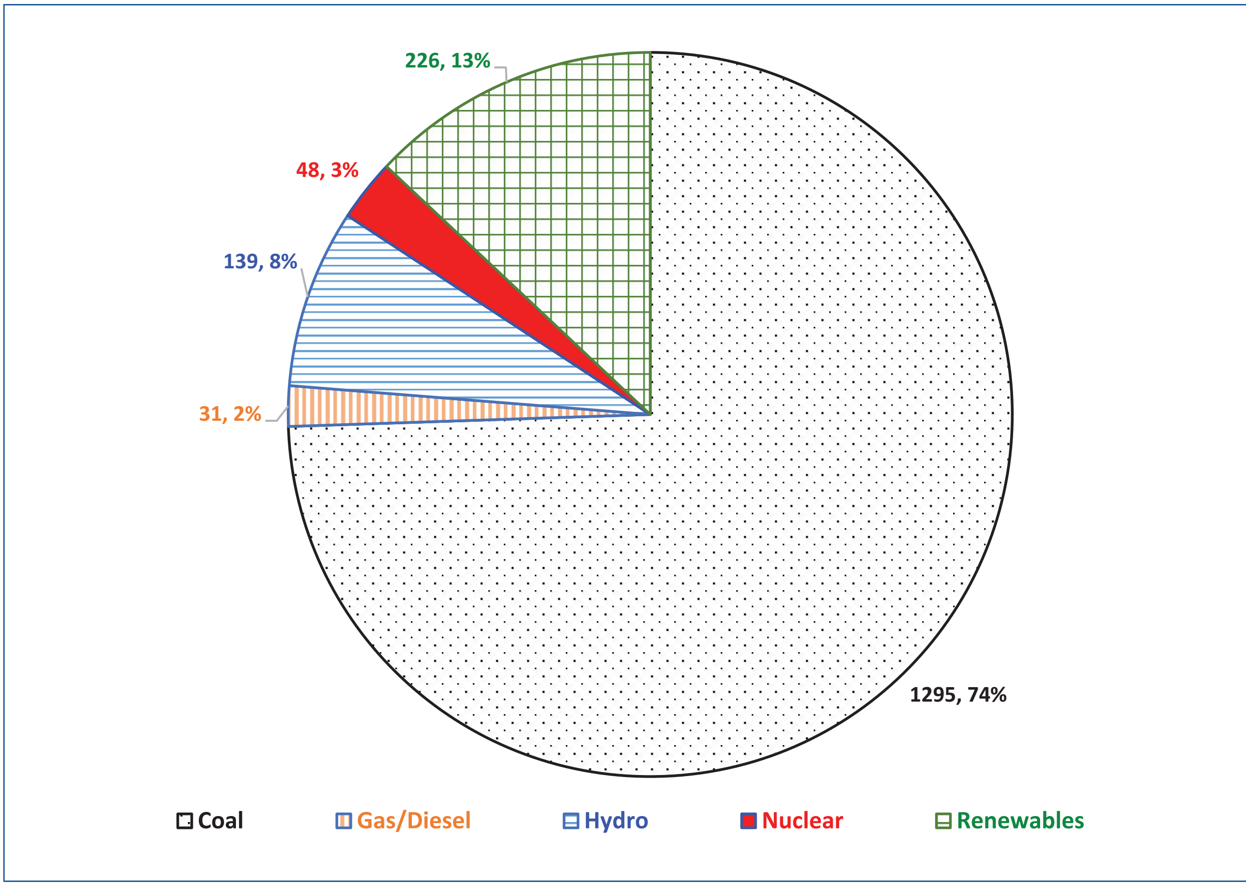
1.1.1 Power Scenario of India

India was ranked as the third-largest electricity producer in the world in 2023, generating 1814 TWh annually, following the China (9566 TWh) and USA (4412 TWh), respectively (IEA, 2024). The fuel-wise break-up of the 1735 TWh of electricity generated by utilities (power generators that supply electricity to the grid) during 2023-24 is shown in Figure 1. The total installed electricity generation capacity of utilities (power generators that supply electricity to the power grid) as of 31 March 2024 was 442 GW. Of this, non-fossil fuel based capacity (solar, wind, hydro, and nuclear) constitutes 45% (199 GW) and the balance consists of fossil-fuel based generation capacity including 218 GW of coal (CEA, 2024a). India's utility-based annual electricity generation reached 1735 TWh in FY 2023-24, marking a Y-o-Y growth rate of 7%. Out of this, coal-based thermal power plants (excluding the captive power plants) generated approximately 1295 TWh, accounting for 74.7% of the total electricity generation. Concurrently, the electricity generation from Variable Renewable Energy (VRE) sources (mainly, Solar and Wind) reached a record-high of 226 TWh, equivalent to 13% of the total electricity generated by utilities. Since VRE sources are intermittent in nature, balancing these sources will be crucial to ensure the stability of the electricity grid till the time storage facilities are developed to a sufficient degree.

The National Electricity Plan (NEP) projections indicate that the installed capacity of coal-based TPPs will reach 259.6 GW by 2031-32 even after assuming a higher contribution from RES and battery energy storage systems (CEA, 2023a). However, the power demand in India is increasing more rapidly than the projections in the NEP due to sharp economic growth prompting the CEA to increase its peak demand projection to 388 GW by FY 2031-32 from the 366 GW projected in the 20th Electric Power Survey and increase the targeted coal-based TPP capacity to 283 GW (CEA, 2022a; CEA, 2024b).

According to the International Energy Agency (IEA, 2024), in 2023, India's coal demand (721 Mt of coal-equivalent or Mtce) was the second highest in the World, only behind China (3469 Mtce) and just ahead of USA (294 Mtce). This indicates the continued reliance of the power sector on coal-based generation. Coal, being an abundant and consistent source of energy is capable of meeting the rapidly growing demand for electricity in India, thus playing a crucial role in ensuring energy security and affordability. Moreover, coal-based power generation significantly contributes to industrial growth directly impacting the economic growth of developing countries like India. The Plant-Load-Factor (PLF) of coal-based TPPs has been increasing continuously for the last 4 years after declining a steady decline between FY 2009-10 and FY 2020-21 (CEA, 2024a).

Figure 1 : Fuel-wise electricity generation by Utilities in India during FY 2023-24



In 2023-24, the total coal received by TPPs in India was amounted to 864.3 Mt, comprising 798.6 Mt (92%) of domestic coal, and 66 Mt (8%) of imported coal. Further, since coal production is showing an increasing trend due to the operationalisation of commercial coal mines as well as the improved performance of the PSUs engaged in coal mining, new TPPs envisaged in the next 8 years to meet the increasing baseload demand are based on domestic coal only. Therefore, the projected increase in coal-fired power generation capacity based on low-sulfur, high-ash domestic coal to meet the anticipated surge in energy demand underscores the need for TPPs to:

- reduce PM pollution by retrofitting indigenous High-efficiency ESPs in all TPPs on mission-mode;
- avoid increasing the CO_2 emissions factor and specific water consumption by indiscriminate use of FGDs in TPPs located outside 10-km from million+ cities and using domestic low-sulfur coal, and
- increase efficiency by increasing the use of washed coal and commencing the deployment of Integrated Gasification and Combined Cycle (IGCC) technologies.

These steps will facilitate our country's energy security while ensuring the sustainable development for power generation ensure energy security and environmental sustainability while meeting India's Nationally Determined Contributions or NDCs (Srikanth and Bhatt, 2023).

India is implementing a robust climate action plan through its updated NDCs, which include an ambitious clean energy transition. India has also submitted its Long-Term Low Carbon Development Strategy (LT-LEDS) to the UNFCCC in November 2022. India committed to achieving 500 GW of non-fossil energy capacity by 2030, thereby reducing the net carbon emissions by 1 billion tons by 2030. This is in line with the country's pledge to reduce carbon intensity by less than 45% by 2030 and achieve net zero carbon emissions by 2070 (MOEFCC, 2022).

1.1.2 The Role of Coal in India's Energy Transition

The reliance on coal-based power generation cannot be eliminated in India's energy mix in the foreseeable future. Intermittent RES cannot be considered to provide energy security, since they are not firm power sources and can cause large fluctuations in the power distribution network because of the diurnal and seasonal variabilities. The energy sector requires reliable baseload power sources to integrate variable RES and balance the grid, necessitating continued dependence on coal-based generation.

Given the rapid growth in electricity demand and slow-paced RES capacity addition during 2022-24, generation planning studies by CEA indicate that the coal-based installed capacity must reach 283 GW by FY 2031-32 from the present (October 2024) level of 217 GW (PIB, 2024). Aligning with these new projections, another 80 GW of coal-lignite-based additions are planned in the next 10 years as per a recent press release from the Ministry of Power (PIB, 2024). Against this, 29 GW of coal-based capacity is already construction while an additional 51 GW of thermal capacity is at various stages of planning & development to meet the power demand during & after FY 2031-32.

1.2 Thermal power plant emissions

Clean air is a crucial and non-negotiable element for environmental well-being as well as toward ensuring better health and quality of life. However, there have been serious concerns over the continuously deteriorating air quality in the dense urban centres across India, posing significant risks to the health of living beings and the environment. Air pollution can have short-term effects due to exposure within a few hours or days, as well as long-term effects such as reduced life expectancy and premature death due to prolonged exposure over several years.

Another critical area that needs holistic intervention is the socio-environmental impacts induced by climate change. Although greenhouse gases (GHGs) do not exhibit immediate health effects akin to toxic air pollutants, they are capable of trapping heat (long-wave radiation) reflected from the earth's surface, thereby increasing the temperature of the lower atmosphere.

While transitioning completely to renewable sources can tackle air pollution and climate change issues, the unreliability of variable RESs would affect the access to reliable power at the consumer end. Therefore, until clean, firm, and affordable power generation alternatives are identified, coal will continue to remain the backbone of the Indian power sector. This necessitates continuous exploration of avenues to ensure sustainable and responsible use of coal in power production. This was envisaged way back in 2012 when the 12th Five Year Plan was finalised and it was declared that all TPPs to be installed from the 13th Five Year Plan onwards will be based on supercritical technology. As a result of this far-sighted decision the average thermal efficiency of coal-based TPPs in India improved drastically over the years. As of 30 September 2024, supercritical and/or ultra-supercritical technologies are used in 100 TPPs with a total generation capacity of 69.53 GW which is nearly one-third of the total TPP capacity of 217.6 GW on the same date. Further, all 39 of the under-construction TPPs with a total capacity of 28.4 GW as of September 2024 are based on supercritical or ultra-supercritical technology (CEA, 2024c).

The Advanced Ultra-supercritical (AUSC) technology proven at a pilot plant scale in India has demonstrated an efficiency of 46 percent which will reduce CO_2 emission by 20% compared to a sub-critical TPPs and by 11% as compared to supercritical TPPs (MHI, 2023). This is yet another step in the journey of technology upgradation of India's thermal power sector to increase its efficiency and reduce its emissions intensity (PSA, 2019).

1.2.1 Characteristics of Indian Coal

The type of coal used in TPPs of India differs significantly from the coal used in other countries. These unique characteristics need to be understood in detail before introducing emission reduction technologies in TPPs. Generally, Indian coals (barring the tertiary coals found in Assam and Meghalaya) used in thermal power plants can be characterized by high ash content (35 – 45% by weight), high moisture content (4-20% by weight), low Sulfur content (0.2 – 0.7% by weight), and low calorific values (3500 – 4000 kcal/kg on an average). The Sulfur content in Indian coal is significantly lower than that found in the US (1-1.8%) and Chinese coals (+1%) and is therefore classified as "very-low sulfur coal" (Chen-Lin Chou, 2012; Shiyan Chang et al., 2016; Wang Qingyi, 2001).

1.2.2 CO_2 emissions from thermal power plants (TPPs)

Carbon dioxide is the most significant greenhouse gas (GHG) with the highest impact on global warming (IPCC, 2021). This is primarily due to its substantial abundance in the atmosphere although its global warming potential (GWP) is low compared to some other GHGs such as hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). An immense volume of CO_2 is emitted into the atmosphere continuously through fossil fuel combustion (coal, gasoline, and natural gas) and industrial processes. CO_2 requires a few centuries to equilibrate among the various carbon reservoirs of the atmosphere, the ocean, and the terrestrial biosphere. After equilibration with the ocean, a significant fraction (~ 20-40%) of CO_2 will be removed from the atmosphere via the slow weathering processes and deposition of $CaCO_3$ (which takes about 3000 to 7000 years). The residual quantum of CO_2 is abundant enough to have a substantial climate impact for thousands of years owing to its large half-life and long-wave radiation capture potential (IPCC, 2021). The climate change caused by the increase in CO_2 concentration will persist for a millennium due to the long atmospheric lifetime of CO_2, even after emissions cease. Some of the irreversible effects of global warming include a reduction in the off-peak rainfall in several regions and a substantial rise in sea levels due to the accelerated melting of glaciers & ice sheets, as well as the thermal expansion of the warming ocean. Therefore, the reduction of CO_2

emissions is of paramount importance to prevent long-term changes and irreversible damage to the overall climate (IPCC, 2021).

Since India's CO2 emissions have surged in recent years as the country tries to enhance energy access and overcome its development deficit, several commitments have been made under India's Nationally Determined Contributions (NDCs) to the United Nations Framework Convention on Climate Change (UNFCCC). These include a pledge to reduce the emissions intensity of its Gross Domestic Product (GDP) by 45% by 2030 (MOEFCC, 2022). These commitments reflect India's recognition of the urgent need to reduce CO_2 emissions and contribute to global efforts to combat climate change. Given India's current reliance on coal for more than 60% of its energy production, achieving these targets will require significant efforts (Srikanth and Bhatt, 2023).

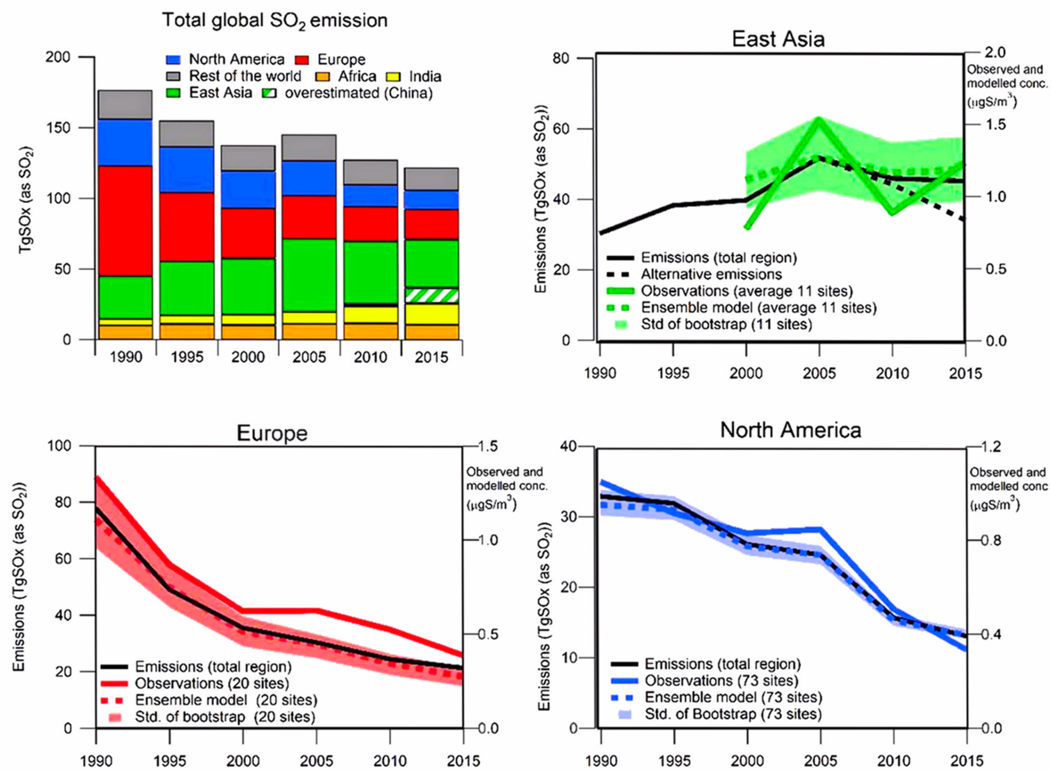
1.2.3 SO_2 emissions from TPPs

TPPs are major emitters of SO_2. The SO_2 emissions from TPPs depend on the sulfur content of coal that undergoes combustion inside the TPP boilers. Sulfur dioxide (SO_2) is a heavy, colourless, and poisonous short-lived gas with a pungent odour. High concentrations of SO_2 in the atmosphere form sulfurous smog and smog formation is further reinforced by the presence of particulate matter. Moreover, SO_2 can combine with nitrogen oxides and ammonia to form particulate matter. Burning of fossil fuels and natural volcanic eruptions emit SO_2 in larger quantities into the atmosphere.

Sulphate aerosols are formed by the oxidation of the SO_2 gas emitted from the stack. These aerosols impact the climate by modifying the radiative forcing, thereby affecting cloud reflectivity and precipitation. The sulphate aerosols scatter the solar radiation and cool the earth's surface resulting in a positive radiative forcing (IPCC, 2021). In 2021, the Working Group 1 (WG1) of the Intergovernmental Panel on Climate Change (IPCC) published its Sixth Assessment Report (AR6) quantifying the contribution of different gases to global warming. As per IPCC (2021), the cumulative emissions of CO_2 & methane have increased global warming by about 1.5^0C, while SO_2 emissions have masked global warming by ~0.5^0C in the 2010-2019 period relative to the 1850-1900 period.

Global SO_2 emissions declined by approximately 55 TgSO2 (31%) from 1990 to 2015 though the changes varied between regions (Aas, 2019). The largest reduction in worldwide SO_2 emissions from 1990 to 2000 was mainly due to a large reduction in Europe (~42 $TgSO_2$/~54%) coupled with a smaller decrease in North America (~7 $TgSO_2$/~21%) and an increase in East Asia (+10 $TgSO_2$/32%). In the 2000–2015, period, SO_2 emissions in Europe and the US decreased by ~14 and ~13 $TgSO_2$, respectively. While SO_2 emissions in Eastern Asia increased by more than 20 TgSO2 (70%) up to 2005, there was a reduction of ~6 TgSO2 (~13%) between 2005 and 2015. India's SO_2 emissions increased from 4.5 to 15 TgSO2 during the entire 25-year period from 1990 to 2015, which must be due to the steady growth in coal-fired power generation. These trends are shown in Figure 2 (Aas, 2019; 2020).

Figure 2 : Global trends in SO2 emissions (Aas, 2019)



Ensemble modeled and observed trends of sulfate in aerosols over the period 1990–2015 compared to the trend in emissions over the same period. The upper left panel includes a striped green part indicating possible overestimated emissions in China, and the dotted black line in the East Asia panel shows an alternative emission trend adjusted from more recent inventories[18,20]. The time series show the annual values for years given. The uncertainty is illustrated using the standard deviation of the bootstrap trend for each region.

Zheng et al. (2018) explain the various policy measures and technological improvements implemented in China to reduce the emissions of all air pollutants. Specifically, while the consumption of coal in China increased from 3,445 Mt in 2010 to 3,708 Mt in 2017, the emissions of SO_2, PM_{10}, and $PM_{2.5}$ from TPPs decreased by 62%, 38%, and 35%, respectively, mainly due to FGD installations. However, CO_2 emissions from the power sector increased by 16% during the same period (Zheng et al., 2018).

However, Qian et al. (2020) explain that the reduction in SO_2 emissions in China due to the operation of FGDs "*will result in an increase in global average temperature between 2016 and 2050, estimated at ~0.6^{0}C.*" Climate simulations conducted by Zheng et al. (2020) based on a fully coupled ocean and atmosphere climate model indicate that China's reductions in SO_2 emission rates by approximately 70 percent (23.5 million tons) by fitting FGDs in all TPPs between 2006 and 2017 "*may exert a net increase in global radiative forcing of 0.09 ± 0.03 W m^{-2} and a mean warming of 0.12 ± 0.01 °C in the Northern Hemisphere; and may also affect the precipitation rates in East Asia and in more distant regions.*" The success of Chinese policies to reduce aerosol emissions (mainly by fitting FGDs to reduce SO_2 emissions) may bring additional net warming, and this 'unmasked' warming would in turn compound the challenge and urgency of global climate mitigation efforts (Zheng et al., 2020).

When the SOx gases mix with moisture clouds, the suspended water molecules become more acidic, forming sulfuric acid that can cause acid rain in extreme cases. However, acid rain is not a significant issue in India due to the presence of alkaline substances in the dust. Even in coastal regions, the sea breeze, together with the alkaline nature of seawater droplets, effectively neutralizes any sulfuric acid formation in the atmosphere (IIT Delhi, 2024).

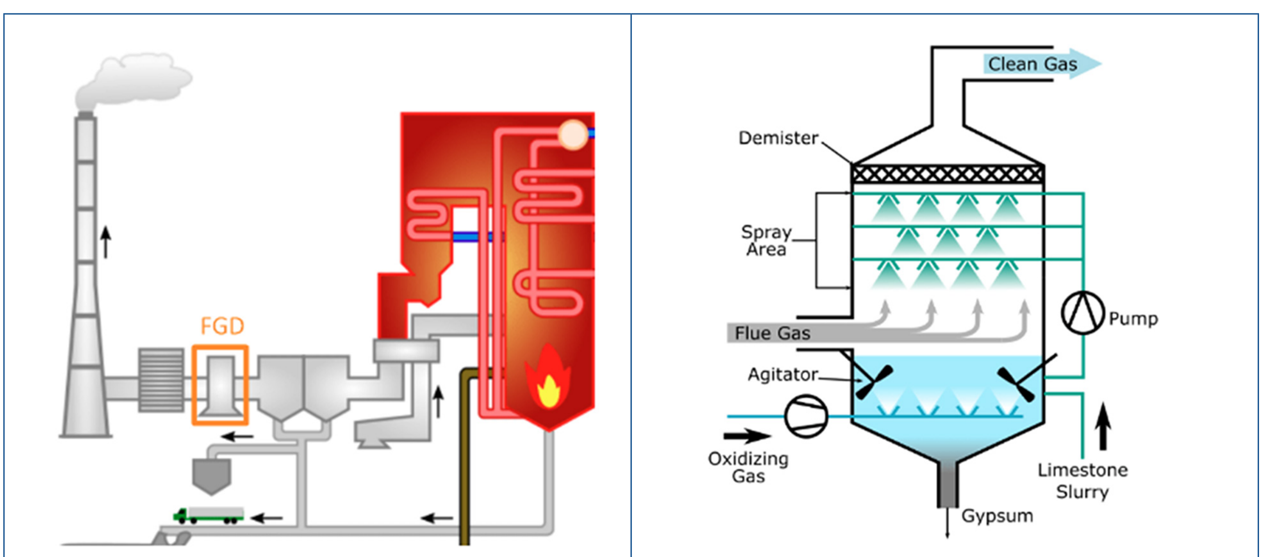
1.2.4 Flue Gas Desulfurizer (FGD)

During the combustion process, 95% of the sulfur present in the coal gets converted and released as SO_2 gas through the TPP stack. The production of SO_2 is directly proportional to the amount of coal consumed and the sulfur content in the coal. To achieve the new emission norms declared by the government, power plants are required to install scrubbers which are also called FGDs.

FGDs work on the principle that SO_2 gas can be neutralized using sodium or calcium-based alkaline reagents such as limestone or seawater. TPPs located along the sea coast (which are largely designed to use imported high-sulfur coal with or without blending domestic low-sulfur coal) use sea water to absorb the SO_2 from flue gas in power plants. Seawater FGDs are a low cost, environment-friendly option for coastal TPPs since they do not create any by-products or waste that need to be treated or disposed of, though they tend to raise the temperature of the outlet water by 1-2^{0}C which has to be mitigated by the TPP if the final temperature of the outlet water exceeds the norms (CEA, 2019a).

Wet FGDs used in inland TPPs use freshwater which is not useful to neutralise the SO_2 emissions on its own. In India, wet FGDs generally use limestone, which must be mined and transported to the TPP. The limestone is crushed to such a fine size that 90% of the crushed limestone passes through a 325-mesh screen and is therefore finer than 44 microns (CEA, 2017).

Figure 3 : Thermal power plant exhaust system and wet FGD schematic diagram



Wet FGDs are the dominant technology in fossil-fuelled large power plants. Most of the FGDs installed in India are wet FGDs. Figure 3 shows the exhaust system of a TPP along with the position of the FGD unit. Initially, the hot flue gas (150^0C) discharged from the boiler is passed through an electrostatic precipitator (ESP) and the fly ash is removed. Then the flue gas is fed to the SO_2 absorber. The absorber is steam-saturated with an absorbent (reagent) and water. The limestone absorbs the SO_2 present in the flue gas and converts it into gypsum The reactions happening in the FGD are described below.

1. Limestone Dissolution: Limestone is pulverized and made into a slurry.
   a. $CaCO_3 + H_2O \rightarrow Ca^{2+} + HCO_3^- + OH^-$
2. SO_2 Absorption: SO_2 is absorbed by water in the slurry converting it into sulfur-based acid.
   a. $SO_2 + H_2O \rightarrow H_2SO_3$
   b. $H_2SO_3 \rightarrow H^+ + HSO_3^-$
3. Oxidation: Sulphite (SO_3) is converted into sulphate (SO_4)
   a. $HSO_3 + O_2 \rightarrow H^+ + SO_4^{2-}$
4. Precipitation: The absorbed sulphate ion reacts with calcium and forms gypsum
   a. $Ca^{2+} + SO_4^{2-} + 2H_2O \rightarrow CaSO_4.2H_2O$ (gypsum)

1.2.5 Phased implementation Plan for FGD installation

To control the emissions by coal-based TPPs, MOEFCC amended the Environment Protection Rules, 1986 and notified the new emission standards for $PM/SO_2/NO_x$ on the 7 December 2015. The emission norms are based on the date of commissioning and the capacity of the plants. Initially, the TPPs were advised to strictly adhere to the norms by 2017, which was subsequently revised three times to prioritise the TPPs where FGDs have to be progressively fitted since the spare power generation capacity in the country is inadequate to permit the shutdowns (+45 days) required to hook up a large number of FGDs to the operating TPP while ensuring the required availability of power in the National electricity grid.

Since the process of FGD retrofits in existing TPPs takes at least three years from technical feasibility study to commissioning, a Task Force comprising representatives from MOEFCC, MOP, CEA, and CPCB categorized the TPPs into three categories A, B, and C with different timelines for emission norm compliance (CPCB, 2022). This Task Force also came up with estimates for the environmental compensation for the different TPP categories (A, B, and C) in case of non-compliance. Categories A and B were considered as critical categories since these TPPs are within 10 km of a city with a population of at least one million and a severely polluted area, respectively. Category C encompasses all other TPPs.

Table 1 shows the categorization with the latest timelines for compliance by non-retiring TPPs. Since Particulate Matter (specifically PM_{10}) pollution is the criteria pollutant to declare a city as a Non-Attainment city in India, there should have been a similar focus on compliance with PM emission norms forming part of the same MOEFCC (2015) notification. However, the focus on PM pollution from TPPs is missing.

Table 1 : New environmental norms for thermal power plants (MOEFCC, 2015)

Year of Installation	Standards in mg/Nm3			
	PM	SO2	NOx	Hg
Before 31st Dec 2003	100	< 500 MW – 600 ≥ 500 MW - 200	600	≥ 500 MW - 0.03
Between 1st Jan 2004 and 31st Dec 2016	50	< 500 MW – 600 ≥ 500 MW - 200	300	0.03
On or After 1st Jan 2017	30	100	100	0.03

The timelines for implementation of FGD for Categories A, B, and C were initially December 2022, December 2023, and December 2024, respectively. However, extensions were granted to these timelines twice considering the operational challenges faced by the TPPs. The TPPs would require undergoing a shutdown period of 5-6 months to retrofit FGDs into existing plants. In contrast, newly constructed TPPs require only 3-4 months to install these units. Since the prolonged shutdown of operational TPPs significantly impacts the revenues for Generating Companies (GENCOs), the retrofitting process has been delayed or temporarily halted even for those TPPs that have already placed orders for the FGDs. Besides the operational challenges, several financial and technical difficulties contribute to the delays in installing FGDs. The high cost of FGDs and the availability of limited funding pose significant financial constraints. The complexity of integrating FGDs into the existing infrastructure of older TPPs and the need for specialized equipment and skilled labour further complicate and prolong the installation process. As per the latest information obtained from CEA (Private Communication), the number of TPPs in which FGDs are installed till October 2024 is, 44 (22.6 GW), of which 12 TPPs are in Category A, three TPPs (1340 MW) are in Category B (1.8 GW), and the balance 29 TPPs (15.9 GW) are in Category C. Besides these 44 TPPs, 233 TPPs (102 GW) have awarded FGDs for which approximately Rs. 122,000 Crores are committed. Thirty-three (33) TPPs in Category A (7.3 GW capacity), 39 TPPs in Category B (11.9 GW), 188 TPPs in Category C (60.3 GW) have not ordered FGDs till now. These 260 TPPs (79.6 GW) must mobilise a capex of approx. Rs. 96,000 Crores for FGD retrofits alone.

Table 2 : Categorization of TPPs for phase-wise installation of FGDs as per CPCB (2022)

Category	Location/Area	No. of Units (Capacity)	Timelines for compliance
A	Within a 10 km radius of the National Capital Region (NCR) or cities having a million plus population (as per the 2011 census of India)	65 (20.4 GW)	31st Dec 2024
B	Within a 10 km radius of Critically Polluted Areas or Non-attainment cities (as defined by CPCB)	66 (23.3 GW)	31st Dec 2025
C	Other than those included in categories A & B	406 (160.5 GW)	31st Dec 2026
Total	All non-retiring TPPs excluding CFBC-based TPPs	537 (204.2)	

2. Objectives

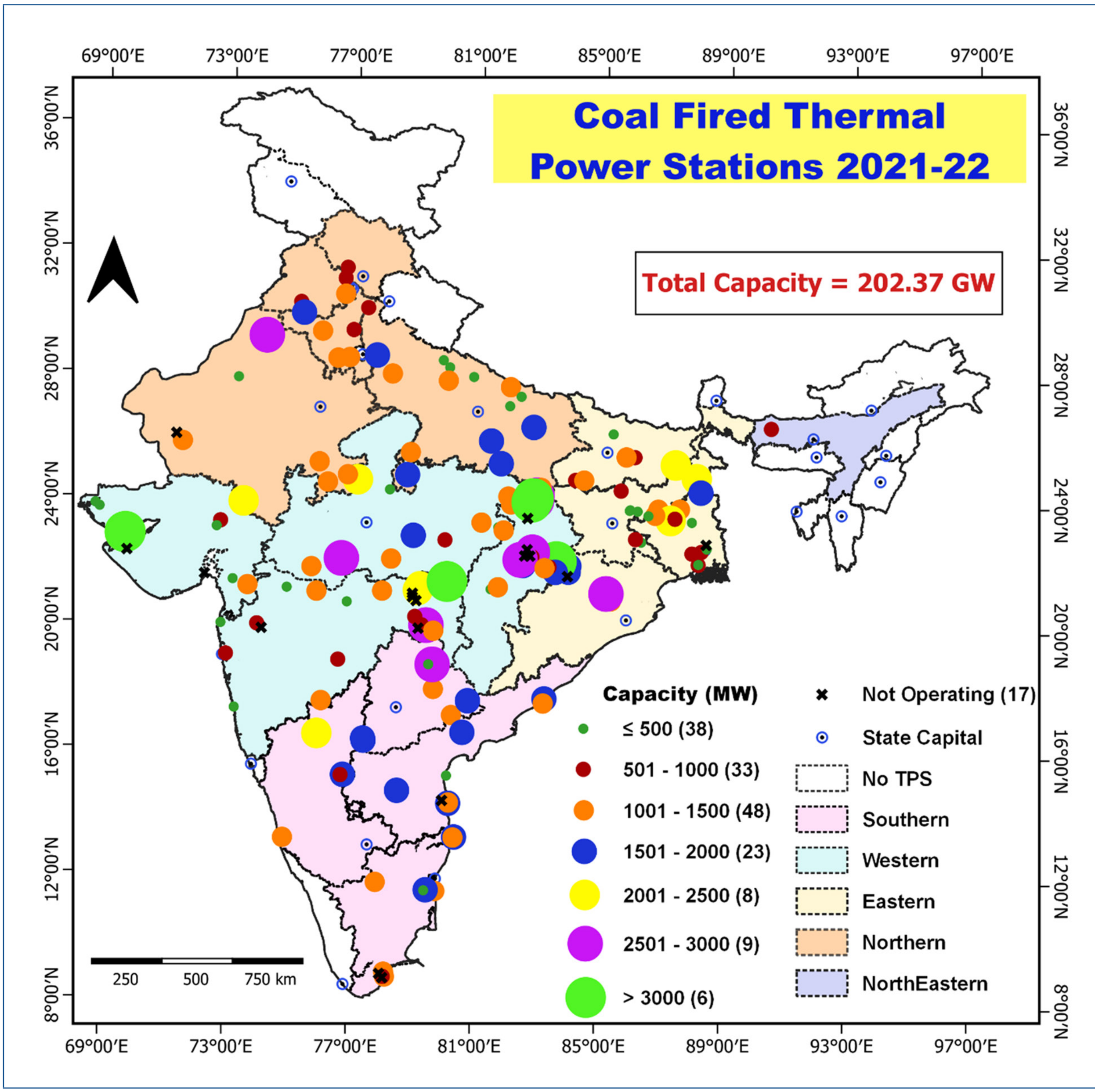
The overarching goal of this research project is to study the interactions between energy security, the environment, and climate change and advance our scientific understanding, which are directly related to the Sustainable Development Goals (SDGs). The objectives are:

- To quantify the CO_2 emissions from the existing and future coal-fired TPPs In India for the years 2030 and 2040, accounting for the projected electricity demand and newer technologies and their likely year of commissioning.
- To quantify the emissions attributed to coal-based TPPs considering the sulfur content of coal and the boiler technologies deployed in the TPPs.
- To estimate the increase in global average temperature between 2020 and 2040 based on the reductions in emissions from TPPs post installation of FGDs.
- To propose alternative strategies for air pollution control in TPPs based on their location, technology, efficiency, local meteorological conditions & affordability.

3. Study Area

Thermal Power Stations (TPSs) contribute the largest share of electricity in India. Initially, all the coal/lignite-based utility TPPs, operational in FY 2021-22 (base year) were considered for quantifying their CO_2 & SO_2 emissions. The locations of the operational TPS in India in FY 2021-22 are shown in Figure 4, with circular markers of different colours indicating their installed capacities.

Figure 4 : Geographical locations of operational Thermal Power Stations in 2021-22



Thermal Power Stations in India are typically divided into five regions: Eastern, North-Eastern, Northern, Southern and Western. These regions are also shown in different shades in the figure. The Western region has the highest installed capacity of coal-fired TPS (76.06 GW) followed by the Northern Region (58.53 GW) and the Southern Region (53.5 GW) with the Eastern Region coming last with 28.5 GW. with similar capacities, 45.6 GW (140 units) and 40.9 GW (105 units), respectively. The total installed generation capacity of utility-owned TPS as of March 2024 is 217.59 GW which is distributed among 17 states, with the highest installed capacity in Uttar Pradesh, followed by Chhattisgarh. Assam is the only state in the North-Eastern region with 949 GW of coal-fired TPP capacity as of March 2024. The total lignite-fired TPP capacity is only 3% (6.62 GW) of the total TPP capacity of 217.59 GW of coal-fired TPP capacity operated by utilities in India. There is hardly any growth in lignite-fired TPPs since lignite is mined in limited quantities only in three States (Tamil Nadu, Rajasthan, and Gujarat) though lignite-fired TPPs play a key role in providing electricity in these three States. The total lignite-fired electricity generation 34 (TWh) in India is only 2.6% of the total coal-based electricity generated by utilities (1295 TWh) in India (CEA, 2024a).

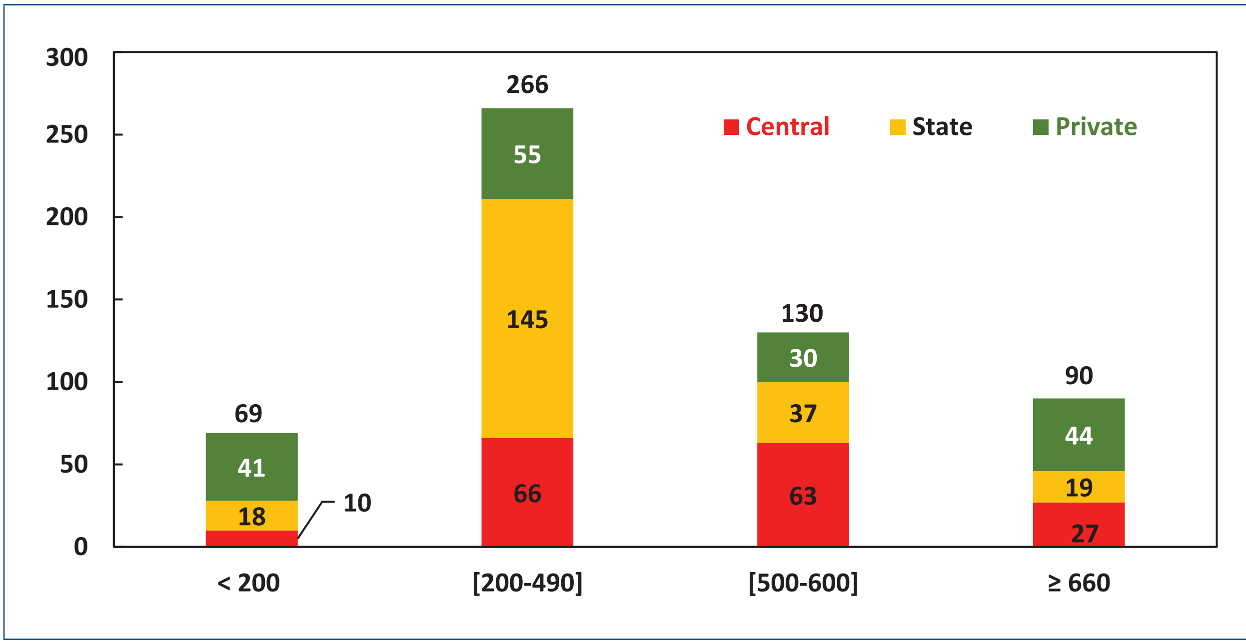
4. Data

The first step in this project was to create a database of operational TPPs along with their geographical coordinates and other parameters. FY 2021-22 is considered as the base year for building the database from the data collected from various government reports since this study commenced in April 2023. The list of operational TPPs along with their operational status and installed capacity is obtained from the CEA report for 2021-22 (CEA, 2023b). This report provides granular data on electricity generation, transmission, distribution, and consumption across various sectors/categories for the FY 2021-22. Among the TPPs, only utility TPPs are considered in the database. The list of operational TPPs is compared with the master list prepared by NIAS considering 2018-19 as the base year for first-level validation to prepare a consolidated database of TPPs in India. This consolidated database comprises key information such as location details (including geographical coordinates), year of commissioning and retirement, FGD unit installation status, installed capacity, generation profile, coal consumption (both domestic and imported), CO_2 emissions, and unit-wise specific water consumption levels.

The base year (FY 2021-22) included 591 TPPs in 182 thermal power stations in India. Among them, 509 units were found to be operating and actual data regarding their generation, fuel consumption, and CO_2 emissions were extracted from the relevant CEA reports. In addition, 46 TPPs with a total capacity of 23.44 GW which are commissioned but not operating since they are considered as '*stressed*' assets are also considered in the database. In addition to the inclusion of their locations, the precise coordinates of TPPs are collected from various reports and websites such as the Global Coal Plant Tracker to capture the geospatial distribution of the emissions from these thermal power plants. The units are clustered based on their geographical locations, and coordinates for the stations are marked in the database. The locations where planned TPSs are likely to be installed in the future, the TPSs that are not operational, and the TPSs with no information available in the open-source domain are marked using different symbols for distinct identification.

The total operating capacity of the 555 coal-based utility TPPs considered in the database is 202 GW which recorded a gross generation of about 1079 TWh. The TPPs use a considerable portion of their generated power to meet the in-house auxiliary power requirements. The average auxiliary power consumption in TPPs of India is around 8-9%. The open-source information suggests that the average auxiliary power consumed by the subcritical and supercritical TPPs is approximately 9.2% and 7.3 % of the gross generation, respectively. The net electricity generation from TPPs after considering the auxiliary power consumption is approximately 993 TWh in FY 2021-22. TPPs are categorized into three sectors, central, state, and private based on their ownership and operation. Sector-wise distribution of TPPs in 2021-22 is shown in Figure 5, along with the number of units in each nameplate capacity range. However, CEA (2024c) indicates that 39 TPPs with a total capacity of 28.4 GW are under construction as of September 2024 since there are expectations of a shortfall in the electricity generation by variable renewable energy (VRE) sources compared to the projections in the National Electricity Plan which is now under revision.

Figure 5 : Sector-wise TPP installed capacity in 2021-22



TPPs installed with Circulating Fluidised Bed Combustion (CFBC) technology and are not required to install FGDs since they capture the SO_2 gas from the flue gas and convert it to gypsum. Besides, there are a few smaller (pre-2003) TPPs with SO_2 emissions lesser than the applicable norms due to various reasons including the use of low-sulfur coal. The TPPs with FGDs/CFBC technology/other technologies are ignored for the purpose of this study. Similarly, lignite-based generation is assumed to be constant @34 TWh between now and 2040 since there is no plan for any major change in the installed capacity of lignite-fired TPPs in India.

The Baseline Carbon Dioxide Emission Database (Version 18.0) documented in CEA (2022b) was used as the source for the data regarding gross electricity generation (GWh), actual auxiliary consumption (%), net electricity generation (GWh), absolute CO_2 emission (tonnes), and specific CO_2 emission rate (t_{CO2}/MWh). Gross electricity generation is the annual total generated electricity in the plant considering their PLF. Net generation is the electricity available for distribution after auxiliary power consumption. The specific CO_2 emission rate is the average CO_2 emitted per unit of electricity generated in the grid. For the base year, the rate is calculated by dividing the absolute CO_2 emissions of all power stations by the total net generation. The station-wise specific CO_2 emissions for the base year are included in the database. As shown in Table 3, the specific CO_2 emissions are averaged over certain ranges of installed capacity for estimating the future CO_2 emissions of TPPs in this study.

The same formula is utilized to estimate the CO_2 emissions in the futuristic scenarios of 2030 and 2040. The annual coal consumption data of the stations are estimated from the station-wise coal receipt and consumption data for 2021-22 based on CEA reports. These reports provide the total amount of domestic and imported coal received by each TPS and the total quantum of coal consumed (Table 4). Data on unit-wise actual consumption of imported coal is not available in the public domain.

The TPS-wise coal consumption is distributed among the units (TPPs) within the TPS based on their installed capacities.

The total water consumption of the TPS can be estimated in a particular year based on the specific water consumption (amount of water consumed per unit of electricity generation) and the amount of electricity generated in that year. The actual specific water consumption of each TPS during FY 2021-22 is obtained from the CEA report of annual environmental emissions by TPPs. The specific water consumption levels available from various sources are compared with the relevant CEA norms and shown in Table 5.

Table 3 : CO_2 emission factors for different TPP capacities based on FY 2021-22 CO_2 data

Unit Capacity Range (MW)	Specific CO2 emission (t/MWh)
≤ 75	1.19
100-150	1.05
180-270	1.05
300-400	0.99
500 – 550 (Type 1- units before 1996)	1.00
500 – 550 (Type 2 – units after 1996)	0.97
600	0.97
660	0.87
800	0.85

Table 4 : Comparison between actual coal consumption and our estimates for 2021-2022

	Actual Data (MT)	Estimates from Database (MT)
Total Coal receipt	694.6	-
Domestic coal receipt	667.6	-
Imported Coal receipt	27	-
Total Coal consumption	697.3	695.14

Table 5 : Specific water consumption data versus CEA norms (Source: Various CEA Reports)

Category	Data available units	Norms (m3/MWh)	Average Specific water consumption (m3/MWh)
TPPs installed before 2017	2	3.5	3.77
TPPs installed after 1st January 2017	37	3	2.90

5. Methodology

5.1 Emission Modelling for FY 2021-22

For generating the database, a master sheet with TPPs actual data for 2021-22 is generated initially. For the distribution of station-wise data among units, validation of the methods, and estimation of emissions, python programming is mainly used. Using NumPy and Pandas libraries, the database is converted into a data frame and calculations are done. The master list consists of the details of the TPPs, metadata that describes the headers, descriptions of the parameters, their units, and other relevant details. The specific CO_2 emissions, specific coal consumption, and specific water consumption are also fed to the master list in the form of a table to be used during the generation of the database.

5.1.1 Preparation of 2021-22 database

For 2021-22, the actual data collected from various CEA reports are included in the database. The coal consumption and CO_2 emissions are available at the station level, which are distributed among their units based on this installed capacity. There are 21 TPPs (units) with no generation and CO_2 emission data available. Since their coal consumption data is available, we consider them as operational in the base year and the gross generation is estimated from the installed capacity and annual PLF of 2021-22.

PLF is commonly considered as a metric to quantify the efficiency of the power plant. The coal-based thermal plants in India are incentivized to operate with an average PLF of 85% which is also known as normative PLF. Analysis shows that a 10% reduction in PLF would result in decreasing the efficiency by 1.3% implying strong dependence of efficiency on PLF. Hence, considering the maximum efficiency, the normative PLF is usually considered for the estimation of specific coal consumption rate and CO_2 emission rate. When the PLF goes below than this normative value, efficiency reduces and in turn coal consumption and CO_2 emissions increase proportionally. In 2021-22, the average PLF achieved by TPPs (including captive power plants) was 58.87%, and 99 TPPs achieved a PLF higher than the All-India average in that year. However, the PLFs of TPPs have increased steadily with the growth in electricity demand. Specifically, the All-India average PLF of TPPs was 64.15% in FY 2022-23 which has increased to 69.09% in FY 2023-24 (CEA, 2024a).

The gross generation is estimated based on the PLF & installed capacity using Equation 1

$$Gross\ generation(GWh) = \frac{capacity\ (GW) \times PLF\ (\%) \times 24 \times 365}{100}$$

(1)

The CO_2 emissions of each TPS are estimated using Equation **(2),** based on an average auxiliary power consumption of 8%, the gross electricity generation from the TPS and the CO_2 emission factor based on the average values given in Table 3.

$$Abs.CO_2\ Emission(Mt) = Gross\ generation(GWh) \times Specific\ CO_2\ rate\left(\frac{t}{MWh}\right) \times 10^{-3}$$

(2)

5.1.2 Validation of the absolute CO_2 emissions estimation method

Since an average CO_2 emission factor is used for each TPP capacity range (Table 3), an error may be introduced in the estimation of CO_2 emissions in futuristic scenarios. Hence, to validate the method utilized for the estimation of absolute CO_2 emissions, the CO_2 emissions for the base year are estimated using the actual gross generation and CO_2 emission factor (Table 3) and are compared with the actual data provided by the CEA-CDM database (CEA, 2022b). The average error introduced due to the use of an average CO_2 emission factor was found be only ~2%. Therefore, this methodology is adopted to estimate future CO_2 emissions in this study.

5.1.3 Estimation of SO_2 emissions by TPPs in 2021-22

The SO_2 emissions from the stacks of TPPs can be estimated using suitable emission factors in conjunction with coal consumption data (Varshney and Garg, 1978). Emission factors are developed based on previous stack gas sampling data and material balances for specific gaseous emissions from point sources. Considering the average sulfur content of domestic coal as 0.4%, the SO_2 emissions from the TPPs using domestic coal can be estimated using Equation **(3)**.

$$SO_2\ emission\ (Mt) = 19 * 0.4 * \text{domestic coal amount (kt)} \times 10^{-6}$$

(3)

To estimate the SO_2 emissions from TPPs using imported coal, the average sulfur content of imported coal used by TPPs is considered to be 0.9%. For a plant installed with a FGD, it is assumed that about 90% of the SO_2 gas in the flue gas produced is captured and removed as gypsum. Hence only 10% of the estimated SO_2 emissions from the stack are considered as the actual emissions from a TPP fitted with a FGD.

5.1.4 Estimation of total freshwater consumption by TPPs in 2021-22

Water is one of the key requirements for power generation. It is required for the cooling process in the condenser, for ash disposal, to remove heat generated in plant auxiliaries, and other purposes. For inland TPPs water is drawn from the freshwater sources such as rivers, reservoirs, and barrages. For coastal areas, plants make use of seawater for cooling processes and auxiliaries and install desalination plants for other water requirements The water consumption of each TPP can be estimated using Equation **(4)** utilizing the specific water consumption value available in our database.

$$Water\ consumption(Bcm) = Gross\ gen.(GWh) \times Sp.consumption\ rate\left(\frac{m^3}{MWh}\right) \times 10^{-6}$$

(4)

The average specific water consumption levels for the sub-critical and super-critical TPPs are estimated separately (Table 5) to arrive at the overall water consumption of TPPs. This provides an estimate of freshwater consumption by all the operational TPPs.

5.2 Emission Modelling for FY 2023-24

To conduct a comparative analysis between the base year and current year FY 2023-24, the actual data on total installed capacity is collected from the capacity reports provided by National Power Portal. The details of new additions and retirements are considered from the power plant database provided by the 'Indian Climate and Energy Dashboard' portal. The database is modified for TPPs that have been retired or commissioned to ensure that the capacity information accurately reflects the current status. Using this updated capacity data, gross generation at an 85% PLF is estimated using Equation **(1)**.

Given that the TPP-wise CO_2 emissions for FY 2023-24 have not yet been published by the CEA, our estimates are based on the estimated gross generation of each TPS (NPP, 2024). Utilizing the actual count of TPPs within each capacity range considered by the CEA for specific CO_2 emission levels, a weighted average of the specific emission levels across the operational TPPs is estimated and applied to Equation **(2)** to estimate the total CO_2 emissions from the operational TPPs in FY 2023-24.

To estimate the SO_2 emissions for FY 2023-24, the station-wise gross consumption estimates of both imported and domestic coal are obtained from CEA reports. Assuming a 90% capture efficiency for FGDs, the SO_2 emissions are computed separately for these two categories using Equation **(3)**. The summation of the SO_2 generated from each TPP in the database is estimated to be the total SO_2 emitted from the thermal power utilities in India in FY 2023-24.

To estimate the freshwater consumption from TPPs in FY 2023-24, the average specific water consumption rates for the sub-critical and super-critical TPPs derived for FY 2021-22 (Table 5) are multiplied with the corresponding generation from individual TPPs in the FY 2023-24.

5.3 Emission Modelling for FY 2030-31

Our primary objective is to quantify the incremental CO_2 and decrease in SO_2 emissions resulting from the installations of FGDs in TPPs. Despite the mandate by MOEFCC for the installation of FGDs in all the operational and new TPPs, delays caused by various factors have hindered progress. Therefore, three realistic scenarios for the year 2030-31 based on the FGD implementation in TPPs have been proposed to assess the incremental or decremental emissions caused by the installation. Each scenario involves estimating plant-specific emissions followed by cumulating them to quantify the total volume of emissions attributable to FGD installations.

5.3.1 Preparation of the 2030-31 database

As previously stated, all the operational TPPs in 2021-22 are included in the 2030-31 database. The data on the progressive retirements of TPPs have been sourced from the DST final report on the Transition plans of TPPS provided by NIAS. The retirement is determined based on criteria such as obsolete technologies, higher auxiliary power consumption, significant declines in operational performance, increased specific fuel consumption & costs, and an increase in the emission intensity rates of the TPPs. For the TPPs that were retired between 2022 and 2024, the actual retirement year of the TPPs is updated in the database. For potential retirements in the period of 2024-2030, the projected retirement years as per the NIAS-DST report are recorded. This expansion of generation is planned based on the premise of meeting the peak demand and energy requirements for the period 2022-2032 at the lowest possible cost. Specifically, 170 TPPs (out of the 591 operational units in 2021-22) with a combined capacity of 32,143 MW are projected to retire, while 37 units (26,240 MW) are added. Consequently, there are 458 operational units included in our FY 2030-31 database. Among the 170 TPPs projected for retirement between March 2022 and March 2031, four TPPs are equipped with FGDs while four TPPs are equipped with CFBC technology.

The gross electricity generation of TPPs is estimated using equation **(1)** considering the installed generation capacity. As previously noted, the normative PLF at which the TPPs operate with optimum efficiency is 85%. In FY 2023-24, the All India PLF of coal-fired thermal power stations has escalated to 69.09% while the PLF of central sector TPS has surpassed 75% in FY 2023-24 (CEA, 2024a). Given the rapid growth in energy demand, the predominance of central sector TPPs with supercritical/ultra-supercritical technology in the TPPs under construction, and the preference for pithead locations for new TPPs, we foresee that the average PLF of TPPs will reach 85% by FY 2030-31 to fulfil the energy requirements in an efficient manner. To facilitate an accurate comparison of the various scenarios considered in each time horizon, gross generation is kept constant and the additional generation to offset the auxiliary power consumption of FGDs is not included in the estimation.

The CO_2 emissions from the TPPs are estimated using Equation **(2),** considering the specific CO_2 emission levels derived from the 2021-22 data. To compensate for the auxiliary power consumption of FGDs, we assume that an additional 2% of the absolute CO_2 emissions will be produced by the TPPs when FGDs are in operation. If a TPP is equipped with an FGD unit, 2% of the gross generation is utilized for its power requirements. Consequently, this necessitates a 2% additional coal consumption leading to a corresponding 2% increase in CO_2 emissions. For better comparison among the scenarios, the generation is maintained constant, and the changes in auxiliary power consumption due to FGDs are reflected in the incremental amount of coal consumed and the consequent increase in CO_2 emissions.

To estimate coal consumption by the individual TPPs, the normative coal consumption stipulated by the CERC on 27th March 2019 for various capacity ranges of power plants are utilized. The norms provide a specific coal consumption rate, which represents the annual coal consumption by a TPP of a particular capacity range per unit capacity (CEA, 2019b). The normative coal requirement for TPPs is also given at a normative PLF of 85%, aligning with our assumptions. The specific coal consumption rates used in the calculations for different capacity ranges of TPPs are detailed in Table 6.

Table 6 : Normative coal requirement of the TPPs in the period 2019-24 (CEA, 2019)

Unit Capacity (MW)	Annual Specific Coal Consumption Rate (t/MW)
< 100	5840
100 - 200	5840
200 - 250	5615
250 & above (subcritical)	5335
660 MW (supercritical)	5054

The annual coal consumption is estimated using Equation (**5)**, with an additional 2% factored into the calculations for the coal consumed to meet the power requirements of FGDs.

$$Absolute\ coal\ consumption\ (Mt)\ = \frac{specific\ coal\ rate\ \left(\frac{t}{MW}\right) * Capacity(MW)}{10^6}$$

(5)

In FY 2023-24, only 8 percent of the coal used in TPPs was sourced through imports with the balance 92 percent supplied by domestic coal mines. In FY 2031-32, CEA (2023a) has projected that only 28.9 Mt (<3%) of imported coal will be used out of a total coal consumption of 1025.8 MT by TPPs to generate 1566 TWh of electricity. Given the decline in use of imported coal due to the higher landed costs and the increase in supply of coal from domestic mines after the commencement of commercial coal mining by the private sector, we assume that coal-fired baseload power generation in India will rely almost entirely on domestic coal beyond 2030. Knowing the changes in the technology mix of TPPs we can therefore estimate the annual coal consumption (and the associated emissions) by TPPs for future years based on the use of domestic coal and the future thermal power scenarios, while individual TPP-wise CO_2 & SO_2 emissions can also be assessed separately in the final report of this study.

Considering the sulfur content in domestic coal as 0.4%, the SO_2 emissions from the TPPs are computed using Equation (**3)**. After the removal of SO_2 gas by FGDs, it is assumed that only 10% of the estimated emissions are released through the stack, thus, only 10% is accounted as the total SO_2 emissions. The total water consumption is estimated using the Equation (**4)** and the specific water consumption levels outlined in Table 7.

Table 7 : Specific water consumption values used to estimate overall water consumption by TPPs

Type	Specific Water Consumption (m^3/MWh)
Subcritical (< 660 MW)	4
Supercritical (≥ 660 MW)	2.5

These are derived based on the new water consumption norms set by the CEA. For TPPs installed with FGDs, an additional 0.4 m^3/MWh is incorporated into the basic specific water consumption rate to offset the additional water requirements of the FGDs. The total water consumption for TPPs with FGDs installed can be estimated using the Equation (**6**).

$$Water\ consumption\ (Bcm) = Gross\ gen.(GWh) \times (Sp.consumption\ rate + 0.4) \times 10^{-6}$$

(6)

6. Scenario Development for FY 2030-31 and FY 2040-41

To assess the projected impact of FGD unit installation on emissions and water consumption of the TPPs, three scenarios are delineated based on the number of FGD installations anticipated in the period 2021-2030. As per the latest timelines for the compliance of FGDs, all operating TPPs in India are mandated to install FGDs by the December 2026. However, the current data from the CEA indicates that the progress significantly lags behind these timelines. The current (September 2024) status of FGDs in TPPs categorised as per CPCB (2022) is summarised in Table 8.

As shown in Table 13, only 44 TPPs (22.6 GW) have installed FGDs out of the 537 TPPs identified for FGD retrofits by the Central Electricity Authority as of September 2024, after accounting for retirement of TPPs and TPPs using CFBC technology. Out of the 65 TPPs identified as Category A TPPs located within 10 km of the National Capital Region (NCR) or +1 million population cities, only 12 TPPs have installed TPPs while 20 more operating TPPs have awarded contracts for the procurement, installation, and commissioning of FGDs. As per the current guidelines, all these 65 TPPs are mandated to have FGDs retrofitted by 31 December 2024. Since less than 20 percent of the TPPs in Category A have installed FGDs till date, it is clear that an extension of the deadline will be required in any case.

As shown in Table 8, 233 TPPs (102 GW) have awarded contracts for FGDs besides the 44 FGDs already installed. The lag between the award of FGD contracts and the commissioning of FGDs in so many TPPs is mainly due to the lack of the requisite 45-60 days shut-down period necessary for hooking up the FGD to the TPP. It is worth noting that critical FGD components costing about 20-30% of the FGD contracts by value are still imported, largely from China (CEA, 2024d).

While all 39 TPPs under construction (all with supercritical/ultra-supercritical technology) with a total installed capacity of 28.4 GW will be progressively commissioned 2030 along with FGDs, 33 TPPs in Category A (7.3 GW capacity), 39 TPPs in Category B (11.9 GW), and 188 TPPs in Category C (60.3 GW) have not ordered FGDs till now. These 260 TPPs (79.6 GW) are forced to mobilise a capex of approximately Rs. 96,000 Crores for FGDs at the current average FGD cost of Rs.1.2 crores per MW of installed TPP capacity (CEA, 2024d). Many TPPs among these 260 TPPs are not in a position to justify the exorbitant investments in FGDs since they use obsolete & inefficient technology and are due for retirement within 10 years.

Table 8 : Status of FGD installations in Thermal Power Plants in India as of September 2024

Categorization of Thermal Power Plants as per CPCB and CEA	FGDs to be installed in (Excl. CFBC)	Timelines for Compliance		FGDs installed Nos./ (GW)	FGDs awarded Nos./ (GW)
		Other than SO2 emissions	SO2 emissions		
Category A TPPs (Within 10-km radius of cities with +1 million population)	65 TPPs (20.4 GW)	31 December 2022	31 December 2024	12 (4.9 GW)	20 (8.1 GW)
Category B TPPs (Within 10-km radius of a Critically Polluted Area or a Non-Attainment City)	66 TPPs (23.3 GW)	31 December 2023	31 December 2025	3 (1.8 GW)	24 (9.6 GW)
Category C TPPs (other than those in Category A & B)	406 TPPs (160.5 GW)	31 December 2024	31 December 2026	29 (15.9 GW)	189 (84.3 GW)
Total	537 TPPs (204.2 GW)			44 (22.6 GW)	233 (102 GW)

Notes (CPCB, 2022; CEA, 2024d):

1. Out of the 600 identified TPPs operated by utilities in India as of September 2024, 53 TPPs are equipped with Circulating Fluidised Bed Combustion (CFBC) technology and are not required to be equipped with FGDs since they can remove SO2 emissions directly.
2. Further, 10 more TPPs have retired between 2022 and 2024. This leaves a total of 537 operational TPPs (600 – 53-10) to be retrofitted with FGDs as of September 2024.

Lastly, the retrofit of FGDs will increase electricity tariffs of TPPs with power purchase agreements (PPAs) by 50-55 paise per kWh which the State-owned DISCOMs (power distribution companies) have to recover from the final consumer (CEA, 2024d; MOP, 2018).

To establish a baseline for CO_2 and SO_2 emissions from TPPs in 2030-31, **Scenario 1** presumes no further FGDs will be retrofitted in currently operational TPPs beyond the current installations of 44 FGDs and all 39 TPPs currently under construction. This will result in a total of 83 units fitted with FGDs among the 458 TPPs likely to be operational by 2030. The projected generation of 1514 TWh from coal-based Thermal Power Plants (TPPs) in 2030-31in our study is higher than the projection for coal-based power in the National Electricity Plan (NEP) which is only 1335 TWh compared to the 1295 TWh of coal-fired generation in FY 2023-24 . However, CEA (2023a) also projects the coal requirements for power generation in FY 2031-32 based on a projection of 1566 TWh of thermal power generation, which is 63% of the total electricity requirement from utilities. Since the peak demand projection for FY 2031-32 has been hiked to 388 GW (Vol II NEP) from 366 GW (Vol 1 NEP) and 80 GW of new TPP capacity is being progressively set up, a 63% share of coal in India's electricity generation in FY 2031-32 appears to be reasonable (CEA, 2023a; 2024b; PIB, 2024).

Scenario 2 is predicated on the assumption that all 233 TPPs (102 GW) where FGD contracts have already been awarded will be retrofitted with FGDs besides the 39 coal-fired TPPs (28.4 GW) under construction with FGDs (CEA, 2024c). Consequently, 272 more TPPs (130.40 GW) will be equipped with FGDs by 2030-31 compared to the current scenario where only 44 FGDs are retrofitted in TPPs with a total generation capacity of 22.6 GW. Overall, TPPs with a total generation capacity of 153 GW (22.6+102+28.4) will be fitted with FGDs by FY 2030-31 as per this scenario.

Scenario 3 is the final scenario where all the 458 operating TPPs in FY 2030-31 will be retrofitted with FGDs regardless of necessity, except for those being scheduled for decommissioning. **Scenario 1** will provide the baseline emissions projected for 2030-31, while **Scenarios 2** and **3** will elucidate the potential consequences of FGD installations on emissions from the TPPs and their water consumption.

Considering the three scenarios, gross generation, coal consumption, CO_2 and SO_2 emissions as well as water consumption are estimated using the pertinent equations. The emissions can be compared to quantify the additional emissions attributable to the installation of FGDs in TPPs.

To maintain a consistent interval between the study periods, FY 2040-41 has been chosen as the next time horizon following FY 2030-31. Recent generation planning studies by CEA indicate that the coal-based installed capacity must reach 283 GW by FY 2031-32 from the level of 259.6 GW projected in the NEP (CEA, 2023a; PIB, 2024). We anticipate the additional capacity to come fully on stream only in the mid-2030s since only 18.4 GW of thermal capacity has been awarded till October 2024 besides the 29.2 GW of capacity under construction, while another 47 GW of thermal capacity is still at various stages of planning & development today (MoP, 2024a). The new thermal power projects will take time to achieve financial closure and secure all clearances before commencing construction.

The impact of adhering to the FGD implementation mandate in FY 2040-41 can be analysed by estimating the incremental CO_2 emissions and reductions in SO_2 emissions for this particular year. The three scenarios formulated for FY 2030-31, based on the implementation strategy of FGDs, are also considered for the FY 2040-41 period. The potential retirements during the period 2030-40 are not documented in any government reports. Therefore, the first objective is to project the capacity and energy demand for 2040-41, followed by the identification of potential retirements and additions.

Given this context, it is necessary to adopt a plausible scenario where the energy requirement is satisfied despite possible retirement. The TPPs older than 25-30 years and those with lower capacities (< 490 MW) must be retired due to their lower efficiency compared to the supercritical and ultra-supercritical TPPs that will dominate the power sector in the 2030s. While all TPPs with obsolete sub-critical technology below 490 MW of unit capacity are projected to retire, 135 efficient TPPs with sub-critical technology with unit capacities ranging between 490 MW and 600 MW are projected to be operating up to 2040 by when some of them would be 40 years old (Table 14).

The 20th Electric Power Survey (20th EPS) projects a robust demand growth of 4.06% - 4.59% (CAGR) in the electrical energy required between 2031-32 and 2041-42, and a CAGR of 4.30% - 4.91% in the peak demand during the same period (CEA, 2022a). The All-India peak demand is projected to increase from 388 GW (updated projection in Vol II of the NEP) in 2031-32 to 466 GW (20th EPS) in FY 2036-37 and 575 GW (20th EPS) in FY 2041-42 (CEA, 2022a; 2024b). Further, the electrical energy required to be generated by utilities is projected to increase from 1734 TWh in FY 2023-24 to 2378 TWh in FY 2030-31 (20th EPS baseline scenario) and 3776 TWh (20th EPS baseline scenario) in FY 2040-41 (CEA, 2022a). We project that coal-based generation will rise to about 1548 TWh in 2030 and 2068 TWh in FY 2040, with 34 TWh of lignite-based generation in all scenarios studied. This implies that the share of coal in India's total electricity generation by utilities will come down from the current (FY 2023-24) level of 75% to about 65% in 2030 and 57% in 2040 even if the coal-fired generation increases in absolute terms till 2040. Therefore, India's coal generation will peak beyond 2040 by which renewable (backed with adequate storage), hydro and nuclear energy should be ramped up to taper down coal.

Table 9 : Technology-wise projections of TPPs and Coal-fired generation by utilities

Year	**No. of Coal-fired Units** (after retirement of obsolete & inefficient TPPs & addition of new TPPs with supercritical/ultra-supercritical technology)			Coal-based (excluding lignite) Electricity Generation (TWh)	Electrical Energy Requirement as per the 20th Electricity Power Survey (TWh)
	Sub-critical < 490 MW	Sub-critical 490 - 600 MW	Supercritical 660 - 800 MW		
2022 (actual)	333	132	90	1041	1380
2024 (actual)	359	135	108	1261	1626
2030 (projected)	196	135	127	1514	2378
2040 (projected)	NIL	138	288	2034	3776

Notes: The 2030 and 2040 projections may be seen in the light of the following facts:

1. The lignite generation in India is assumed to be constant @34 TWh (at the FY 2023-24 level) between now and 2040 over & above the above the projections of coal-based generation.
2. As per the National Electricity Plan (NEP), CEA (2023a) has projected a requirement of 1566 TWh of coal-based power generation in FY 2031-32 as a contingency plan against any deficit in meeting the ambitious targets for non-fossil fuel (VRE sources, hydro, and nuclear) sources in that year.
3. More recently, Vol II of the NEP (CEA, 2024b) projects the peak demand in FY 2031-32 to be 388 GW versus the NEP-Vol I estimate of 366 GW (CEA, 2023a).
4. Recent generation planning studies by CEA indicate that the coal-based installed capacity must reach 283 GW by FY 2031-32 from the level of 259.6 GW projected in the NEP (PIB, 2024).

7. Findings and Conclusions

This chapter presents a comparison of installed capacity, gross generation, CO_2 and SO_2, emissions as well as water consumption of base year FY 2021-22 and the projected scenarios of 2030 and 2040. The variations between FY 2023-24 and 2030 **Scenario 1** can be attributed to the increased generation, higher PLF adopted for all TPPs, and a rise in the share of electricity generation from modern & more efficient supercritical TPPs compared to older, subcritical TPPs. The differences among the three scenarios in the same year (either 2030 or 2040) is primarily due to the varying number of FGDs retrofitted in the 537 operational TPPs (Table 8) since we have assumed for the purpose of this study that all new TPPs under construction now or being awarded will be commissioned with FGDs. This assumption is more conservative compared to a scenario where the TPPs awarded in the last 12 months (18.4 GW) and the TPPs yet to be awarded (47 GW) are not fitted with FGDs during actual construction depending on the nature & scope of any amendment of the Stack emission mandate by MOEFC.

The major difference between the 2030 and 2040 scenarios is the progressive retirement of the inefficient and obsolete sub-490 MW TPPs operated by utilities once the additional 80 GW capacity in the form of new supercritical/ultra-supercritical TPPs is progressively commissioned in the 1st half of the 2030s (PIB, 2024). These changes help us to understand the changes in CO_2 emissions intensity and specific water consumption in TPPs due to the impact of FGDs in partly masking the higher efficiencies of supercritical and ultra-supercritical technology.

Table 10 provides the comparative analysis of key metrics for the base year and the three scenarios each in 2030 and 2040 based on the status of FGD installation and the projected increase in coal- and lignite-fired electricity generation from 1295 TWh in FY 2023-24 to 1548 TWh in the year 2030 and 2068 TWh in the year 2040. This table is explained based on two extreme scenarios:

7.1 Impact of FGDs on CO2 emissions:

7.1.1 Scenario 1

Other than the 44 TPPs already retrofitted with FGDs, none of the remaining 493 (537-44) operating TPPs are retrofitted with FGDs due to an amendment in MOEFCC's SO_2 stack emission mandate (MOEFCC, 2015). However, the 39 supercritical TPPs (28.4 GW) under construction are assumed to be progressively commissioned with FGDs between now and 2030 while all TPPs that have not yet commenced site construction are not equipped with FGDs. On the other hand, all operating TPPs (old & new) are equipped with High-Efficiency Electrostatic Precipitators (ESPs) to reduce the Particulate Matter (PM) concentration in the stack to 50 mg/Nm^3 (milligrams per Normal m^3) irrespective of age. This requires tightening the norms for PM emissions from the current level of 100 mg/Nm^3 for the pre-2003 TPPs and the relaxation of the norm to 50 mg/Nm^3 from the current standard of 30 mg/Nm^3 for post-2016 TPPs which requires usage of washed coal to reduce the ash which is critical to increase the efficiency of the ESPs beyond the level of 99.97%.

Table 10 : Impact of FGDs on key parameters for different scenarios

Scenario	Gross Generation from TPPs (TWh)	Coal + Lignite consumption (Mt)	CO_2 emissions (Mt)	SO_2 emissions (Mt)	Water Consumption (Billion Cubic Meters, Bm^3)
2021-22	1079	743	977	5.27	2.96
2023-24	1295	907	1174	6.45	3.79
2030-Sc1	1548	1110	1427	6.66	4.63
2030-Sc2		1120	1440	3.42	4.87
2030-Sc3		1128	1450	0.82	5.07
2040-Sc1	2068	1458	1835	5.62	
2040-Sc2		1467	1847	2.68	
2040-Sc3		1472	1853	1.09	

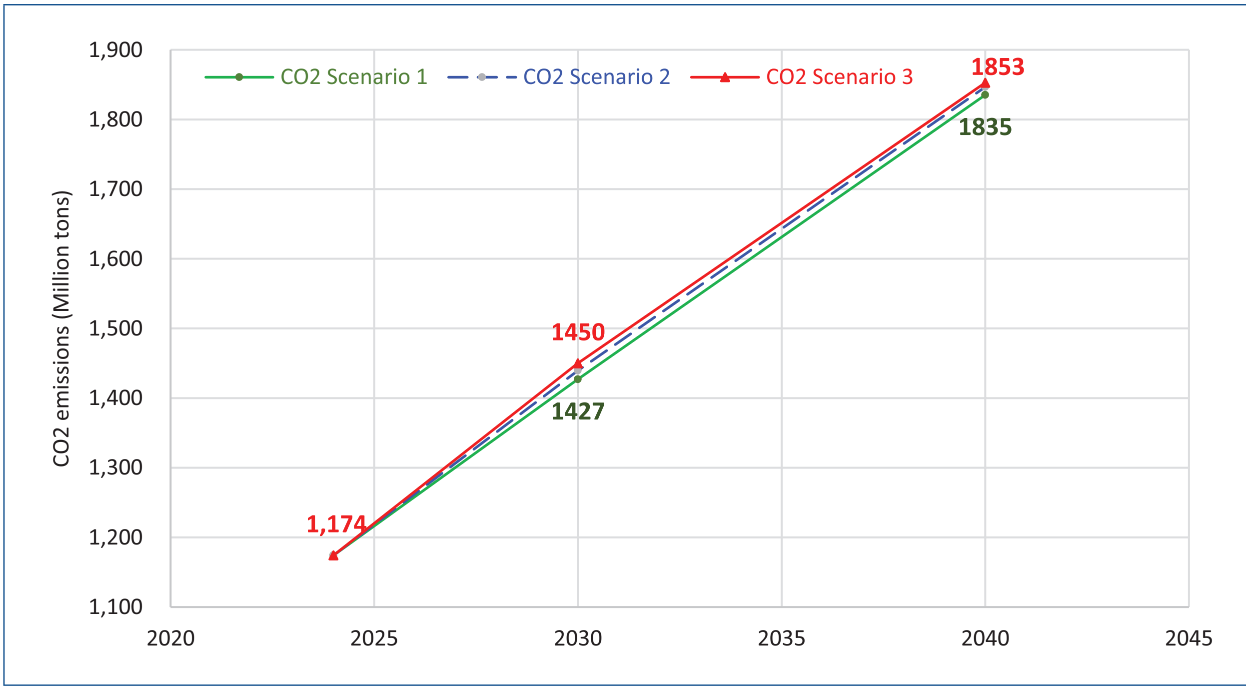
In this scenario, the coal & lignite required for power generation by utilities is projected to increase from the FY 2023-24 level of 907 Mt to 1110 Mt in 2030 and 1458 Mt in 2040 due to the increase in auxiliary power consumption by approximately 2% due to the operation of the FGDs. In this scenario, the CO_2 emissions are projected to increase from 1174 Mt in FY 2023-24 to 1427 and 1835 Mt in 2030 and 2040, respectively. However, the SO_2 emissions from TPPs are projected to increase marginally from 6.45 Mt in FY 2023-24 to 6.66 Mt in 2030 (due to the increase in coal generation) before reducing to 5.62 Mt in 2040 due to the progressive retirement of the obsolete & inefficient sub-490 MW TPPs with the addition of 65.4 (18.4 GW awarded and 47 GW to be awarded) of additional TPP capacity based on supercritical/ultra-supercritical technology. The freshwater consumption of TPPs is projected to increase from 3.79 million cubic meters (Mm^3) to 4.63 Mm^3 in 2030.

7.1.2 Scenario 3

In this scenario, all the 537 operating TPPs are projected to retrofitted with FGDs irrespective of the sulfur content of coal or the size, age, and location of the TPP. In this case, the coal & lignite required for power generation by utilities is projected to increase from the FY 2023-24 level of 907 Mt to 1128 Mt in 2030 and 1472 Mt in 2040 with a concomitant increase in CO_2 emissions from 1174 Mt in FY 2023-24 to 1450 and 1853 Mt in 2030 and 2040, respectively. The impact of FGDs on CO2 emissions in each of the three scenarios during FY 2023-24, 2030, and 2040 is depicted in Figure 6.

This significant increase in emissions each year will accumulate over time due to the longevity of CO_2 in the atmosphere, typically considered as 100-1000 years. Hence, to quantify the total CO_2 emissions from the TPPs over three decades, a cumulative approach is employed. The average emissions of FY 2023-24 and FY 2030-31 are estimated and multiplied by six to estimate the cumulative emissions for the intervening six years. For the next decade (2030 – 2040) the average emissions are computed and multiplied by ten to obtain the cumulative emission for that period.

Figure 6 : CO_2 emissions from TPPs projected in the three scenarios



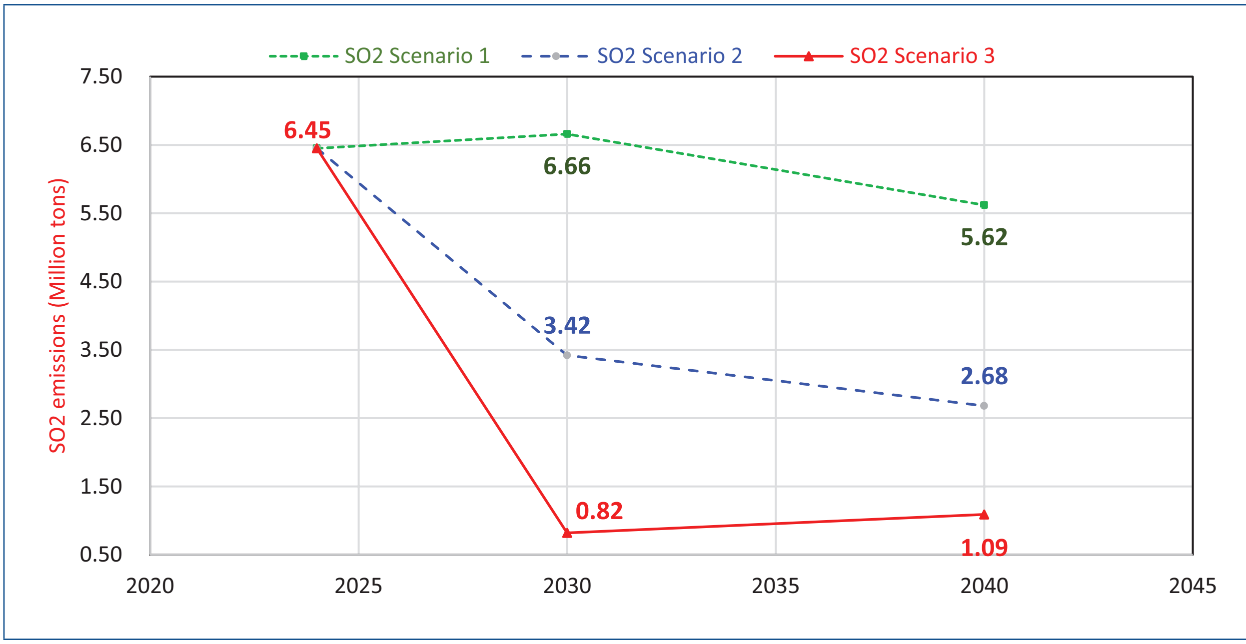
By completing the above computation, we estimate that, installing all the procured 233 FGDs (Scenario 2) will add 158 Mt of CO_2 between 2024 and 2040 compared to no more retrofit of FGDs (Scenario 1), while installing FGDs in all TPPs (old & new) will add 272 Mt of CO2 between 2024 & 2040 compared to Scenario 1. These accumulations of CO2 will increase the global warming by trapping more long wave radiation and thus increasing the global temperature. Increase in global mean temperature have devastating effects on climate, including climate extremes, sea level rise, and much more. This highlights the adverse impacts of FGD installation in terms of incremental CO_2 emissions with its knock-on effects on global warming, extreme weather events, sea level rise, etc.

7.2 Impact of FGDs on SO2 emissions

The trends in SO_2 emission from the TPPs in the three scenarios explained above are shown in Figure 7. Though there will be a reduction in SO_2 emissions by the retrofit of FGDs in all operating TPPs that have not yet done so, this will only be accomplished at the cost of a significant increase in CO_2 emissions (Figure 6) and freshwater consumption (Figure 8).

As shown in Figure 7, the SO_2 emissions from TPPs are projected to reduce sharply from 6.45 Mt in FY 2023-24 to 0.82 Mt in 2030 with a marginal increase to 1.09 Mt in 2040 despite the increase of 33.6% in coal-fired power generation between 2030 and 2040. This is due to the change in technology mix with the progressive retirement of all sub-490 MW obsolete & inefficient TPPs after completing their useful economic lives and the addition of High-Efficiency, Low-Emission TPPs (HELE) with supercritical/ultra-supercritical technology.

Figure 7 : SO_2 emissions from TPPs projected in the three scenarios



In 2040, considering the significant number of TPP additions to meet the growing demand for 24x7 baseload electricity, the SO_2 emission will increase from the FY 2030 estimates in all three scenarios. Overall, **Scenario 3** can be considered as an extreme reduction path compared to **Scenario 2**. However, this substantial reduction in SO_2 can be realized at the expense of escalated CO_2 emissions, augmented coal consumption, and increased water usage. This trade-off underscores the complexity of environmental management and the need for balanced strategies. Since SO_2 has a short atmospheric lifetime measured in days, it cannot accumulate when emitted from the tall (220 – 275 m) stacks in TPPs in India because of the excellent dispersion of stack emissions under the climatic conditions generally prevalent in India.

7.3 Impact of FGDs on freshwater consumption

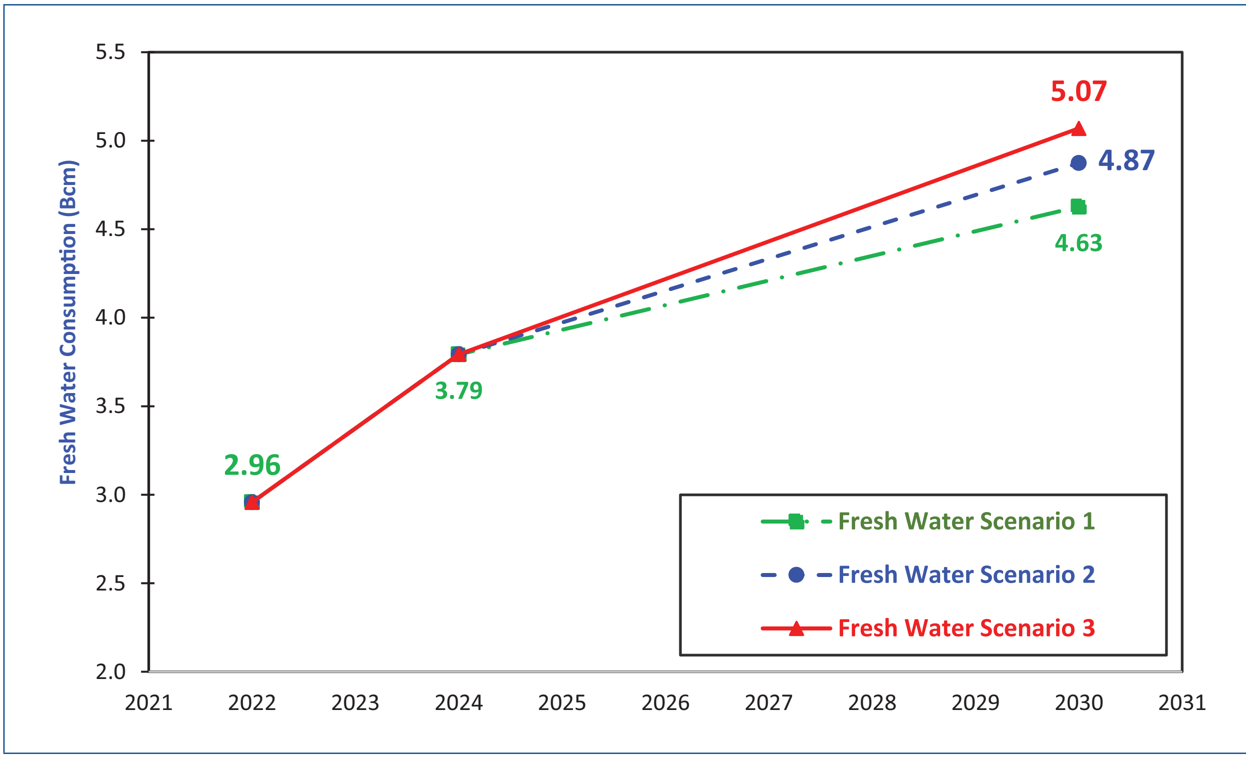
For the estimation of freshwater consumption, the TPPs are categorized into non-coastal (inland) and coastal TPPs, with the assumption that coastal TPPs utilize only seawater to meet their water requirements. The actual specific water consumption data for inland TPPs is procured from the CEA report, and the total water consumption is computed based on their gross generation for FY 2021-22. The database includes 516 inland TPPs, of which 435 are subcritical and 81 are supercritical units. Using the average specific water consumption of 3.4 m^3/MWh for subcritical TPPs and 2.69 m^3/MWh for supercritical TPPs, the water consumption for all operational TPPs is estimated.

For FY 2023-24, the gross generation data for individual stations, obtained from the NPP report, is distributed among the TPPs according to their capacity. By applying the formula and average specific water consumption rate from FY 2021-22, the total water consumption for FY 2023-24 is projected.

The specific water consumption norm of each class of TPPs is used to estimate the total freshwater consumption of TPPs based on their generation in 2030.

The trend in freshwater consumption by TPPs from the base year (FY 2021-22) to 2030, for each of the three scenarios is shown in Figure 8. In FY 2021-22, the total freshwater consumption by all operational TPPs is estimated to be 2.96 billion cubic meters (Bcm). This is likely to have increased to 3.79 Bcm in FY 2023-24 due to the increase in coal-fired power generation from 1079 to 1295 TWh between FY 2021-22 and FY 2023-24.

Figure 8 : Freshwater consumption by the TPPs in the base year and future scenarios.



Since coal-fired power generation is projected to increase further to 1548 TWh in FY 2030-31, all three scenarios (in relation to FGD retrofits) involve further increases in freshwater requirements to operate these FGDs. The total consumption in 2030 (**Scenario 1)** is estimated to be 4.63 billion cubic meters (Bcm), reflecting a 30% growth over eight years due to increased generation. This is expected to increase further to 4.87 Bcm **in Scenario 2,** which is an additional increase of 0.24 Bcm from **Scenario 1**. The freshwater consumption by TPPs is projected to increase further to 5.07 Bcm in **Scenario 3** due to the installation of FGDs across all TPPs irrespective of location, coal characteristics, and age.

The freshwater consumption in 2040 will go up further due to the projected increase in coal-fired power generation from 1548 TWh in 2030 to approximately 2068 TWh in 2040. In the 2030s, all the 196 sub-490 MW TPPs operated by utilities are projected to progressively retire after outliving their useful economic lives. They will be replaced with 161 supercritical/ultra-supercritical TPPs with higher capacities (660/800 MW each) and lower specific coal and water consumptions. As per MOP (2024a), an aggregate capacity of 65.64 GW of such TPPs is under bidding/consideration today. In case these TPPs are also fitted with FGDs, the total freshwater consumption in 2040 on this count alone will increase by 0.20 BCM. Therefore, it is recommended that these HELE TPPs not be saddled with FGDs.

8. Policy Recommendations

Coal-based power plants remain the cornerstone of India's power sector, significantly contributing to the country's energy generation due to the abundant availability of indigenous coal and the current limitations of renewable energy technologies and storage solutions. India's updated Nationally Determined Contributions (NDCs) submitted to UNFCCC in August 2022 include a commitment to *reduce Emissions Intensity of its GDP by 45 percent by 2030, from 2005 level* (MOEFCC, 2022). Since the installation of FGDs impacts the energy efficiency and emissions intensity of TPPs, a blanket implementation will adversely affect India's performance concerning its updated NDCs. Further, three independent studies conducted by NIAS, NEERI, and IIT Delhi demonstrate with different case studies and methods that, FGDs hardly have any impact on Particulate Matter (PM) pollution which is the major problem attributed to TPPs using high-ash Indian coal. PM (not SO2) is also the criteria pollutant in all non-attainment cities in India. Therefore, the authors submit the following recommendations based on this study:

- PM pollution from TPP stacks can be addressed quickly and cost-effectively by retrofitting indigenous High-efficiency Electrostatic Precipitators (ESPs) in all TPPs irrespective of their size or location. This will enable all TPPs to reduce PM pollution by 99.97% in a cost-effective manner without shutdowns while complying with the MOEFCC (2015) stack emission norms for PM (50 mg/m^3 for TPPs installed up to December 2016). Controlling PM emissions from TPP stacks at this level will make the maximum impact on air pollution from TPPs even without FGDs.
- Bharat Heavy Electricals Ltd. (BHEL) has retrofitted High-efficiency ESPs even in older TPPs with space constraints. Installation of such ESPs will cost only Rs. 25 Lakhs per MW compared to Rs. 120 Lakhs per MW for wet FGDs based on imported technology. Further, retrofitting High-efficiency ESPs in operating TPPs requires only 2 days of boiler shutdown for hookup, unlike FGDs which require ~45-day boiler shutdowns during FGD commissioning.
- Since 32 of the 65 TPPs within 10 km of cities with +1 million population have either installed or awarded FGDs, the impacts of FGDs in terms of PM pollution reduction in these cities must be assessed before any future FGDs are awarded.
- TPPs retiring by 2030 to be exempted from SO_2 stack emission norms since these will normally be the obsolete stations with a proportionately lesser contribution to the total electricity generation in the country. This will avoid saddling paying electricity consumers with large tariff hikes to recover the cost of the FGDs within a short period.
- There is no tangible benefit of fitting FGDs in TPPs not located within 10 km of cities with +1 million population if they are using low-Sulfur coal. Rather, they must be equipped with High-efficiency ESPs for the reasons explained earlier.
- The Environmental (Protection) Rules notified on December 7, 2015, to be amended to limit the SO2 stack emission norms only to TPPs using Imported coal and/or High (> 0.5%) Sulfur coal.

- Since all new TPPs are (i) based on domestic low-Sulfur coal, (ii) designed with High-efficiency ESPs, and (iii) located more than 10 km away from any city with +1 million population, FGDs to be avoided in TPPs awarded from January 2024 onwards.
- Implementation of these decisions will reduce PM pollution without the adverse impacts of FGDs (higher levels of water consumption & CO_2 emissions), while limiting the financial burden on the power sector thereby minimizing electricity tariff hikes on account of FGD installations.
- The impact on global warming by installing FGDs in all TPPs in India must be assessed.
- The effect on India's NDCs if FGDs are installed in all TPPs must be quantified.
- Since coal supplied from domestic coal mines accounts for 92% of the power generated in India, and this reliance is going to increase in future, there should be a greater thrust on the enablers required to use high-ash, low-Sulfur Indian coal more efficiently.
- Using coal washed at the pithead will not only reduce air pollution from TPPs & coal transportation but will also enhance ESP performance as well as boiler efficiency thereby reducing CO_2 emissions. Using washed coal will also reduce water consumption in TPPs.
- An integrated cost-benefit analysis of using washed coal in TPPs in India must be conducted since the dependence on high-ash domestic coal for power generation will continue in India.
- CO_2 emissions from TPPs can be minimized by burning coal more efficiently compared to the current levels of efficiency achieved in the super-critical power plants of India. Integrated Gasification Combined Cycle (IGCC) power plants use coal and water more efficiently and enable CO2 capture in an efficient manner. Coal gasification projects are being pursued by the Ministry of Coal (MOC). Integrated Gasification Combined Cycle (IGCC) technology should be mandated for TPPs applying for Environmental Clearance from 2027 onwards, as this technology is CO_2 capture-ready and utilizes both coal and water more efficiently.
- Escalating demands for freshwater use in all industries in general and TPPs in particular is a cause of great concern for India when large parts of India face water stress. To address this concern, the Ministry of Power (MOP, 2020) mandated all TPPs located within 50 km of a municipality or any Urban Local Body (ULB) to use the treated sewage water produced by the municipality/ULB with the "associated cost to be allowed as pass-through in the tariff." However, the cost of the Sewage Treatment Plant (STP) as well as the sewage water supply system are to be borne by the ULB as per MOP (2020).
- Even before this mandate was issued, the Koradi TPP of MAHAGENCO started procuring 130 million liters per day (MLD) of sewage water from the Nagpur Municipal Corporation (NMC) and using it in the TPP after secondary and tertiary treatment in a dedicated STP. This STP was constructed, operated, and maintained by MAHEGENCO for which the land was provided by the NMC who also passed through (to MAHAGENCO) a GOI grant to cover about 50% of the capital cost of the STP (MOP, 2019; Sharma, 2013).
- However, very few TPPs are complying with this mandate because most ULBs in India lack the expertise and financial strength to construct such large & modern STPs which require several synergies between the TPP and the ULB as well as the State Government (World Bank, 2020).

Therefore, Das et al. (2024) have recommended that the STP for secondary & tertiary treatment should also be constructed and operated by the TPP at its own cost (to be passed through in the tariff) while the ULB is responsible for constructing and maintaining the underground sewage system. MOP may like to amend their mandate (MOP, 2020) accordingly since this will enhance the sustainability of the thermal power sector and enable the achievement of SDG 6 ("Clean water & sanitation)" in ULBs.

- Finally, to provide reliable base load power at an affordable cost, India's nuclear power capacity should be increased to at least 100 GW by 2050. This is critical to reduce India's dependence on coal for baseload power and achieve Net Zero emissions by 2070.

In conclusion, the strategic implementation of FGDs, coupled with advancements in cleaner coal technologies and a balanced energy mix including a higher share for clean & firm non-fossil fuel energy source like atomic energy, will enable India to address the environmental impacts of coal-based TPPs without compromising on energy security and economic growth.

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11 **Abstract:**

India's Nationally Determined Contributions (NDCs) submitted to the United Nations Framework Convention on Climate Change in November 2022 include a commitment to reduce the emissions intensity of the country's GDP by 45 percent by 2030 from the 2005 level. Since coal-fired Thermal Power Plants (TPPs) produce ~50% of India's CO_2 emissions, it is critical to enhance the efficiency of TPPs and reduce their emissions to achieve India's NDCs.

However, installing Flue Gas Desulfurizers (FGDs) in all TPPs by 2030 will increase the Auxiliary Power Consumption (APC) of the TPPs and add approximately 272 Mt of CO2 emissions to the atmosphere between now and 2040. While CO_2 accumulations in the atmosphere contribute to global warming, the Intergovernmental Panel on Climate Change (IPCC) report (AR 6) states that anthropogenic SO_2 emissions have masked global warming by ~0.5^{0}C in the 2010-2019 period relative to the 1850-1900 period. Therefore, adding long-lived CO_2 emissions while removing short-lived SO_2 emissions by installing FGDs indiscriminately in all TPPs in India despite the very low Sulfur content of Indian coal and the low ambient SO_2 concentrations around the TPPs will enhance global warming.

Considering the low-sulfur Indian coals, the 220-275 m tall TPP stacks, and the tropical climate around TPPs in India, future FGD installations must be postponed till impact assessment studies of the FGDs installed (or to be installed) in 32 TPPs located within 10 km of cities are completed. For TPPs in other areas, the Ministry of Environment, Forest and Climate Change (MOEFCC) can exempt the TPPs using Indian coal with less than 0.5% Sulfur content from complying with the SO_2 stack emission norms while limiting PM emissions from the stacks to 50 mg per Normal m^3.

Particulate Matter (PM) pollution is the major problem attributed to TPPs using high-ash Indian coal. PM pollution from TPP stacks can be addressed quickly and cost-effectively by retrofitting indigenous High-efficiency Electrostatic Precipitators (ESPs) in all TPPs to reduce the stack emissions of PM by 99.97%. This will enable TPPs using low-sulfur Indian coal to minimize ambient air pollution even without FGDs. This will also eliminate the incremental requirements of freshwater and limestone required to operate the FGDs.

12 **Keywords:**

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