

PREVENTION OF AIR POLLUTION: CLEAN CARBON TECHNOLOGIES, FGD (FLUE GAS DESULFURIZATION) & ESP (ELECTROSTATIC PRECIPITATORS) FOR COAL BASED POWER PLANT

Parmar Kishan Dasharathlal ^{*1}, Tarun Prasad Sonwani²

¹(M.Tech Student, Health Safety and Environmental Engineering, Shri Rawatpura Sarkar
University Raipur, India.)

²(Assistant Professor, Mechanical Engineering, Shri Rawatpura Sarkar University Raipur
India.)

Article Received: 02 April 2026, Article Revised: 22 April 2026, Published on: 12 May 2026

*Corresponding Author: Parmar Kishan Dasharathlal

(M.Tech Student, Health Safety and Environmental Engineering, Shri Rawatpura Sarkar University Raipur, India.)

DOI: <https://doi-org/101555/ijarp.8409>

ABSTRACT:

Globally, air pollution from coal-based thermal power plants is a serious problem for the environment and human health, especially in nations like India that rely heavily on coal. Hazardous pollutants such sulphur dioxide (SO₂), nitrogen oxides (NO_x), particulate matter (PM), mercury (Hg), and carbon dioxide (CO₂) are released by these plants. With an emphasis on Electrostatic Precipitators (ESP), Flue Gas Desulfurization (FGD) systems, and clean carbon technologies, this study examines key technologies for preventing air pollution in coal-fired facilities. In addition to the effects of the Environment (Protection) Fourth Amendment Rules 2025 on compliance in the thermal power industry, it looks at these technologies' operational processes, regulatory frameworks, cost implications, health advantages, and implementation issues in India.

KEYWORDS: Electrostatic precipitator (ESP), Flue gas desulfurization (FGD), SO₂ and NO_x control.

INTRODUCTION

The global energy landscape relies significantly on coal, contributing about 37% to global electricity and 72% in India. Despite its economic advantages, coal combustion in thermal

power plants generates severe air pollutants, accounting for high proportions of particulate matter, sulphur dioxide, nitrogen oxides, and mercury emissions. Health risks associated with these emissions are profound, leading to substantial mortality rates and various respiratory and cardiovascular diseases, particularly affecting vulnerable populations. Recognizing these dangers, stringent emission standards have been adopted, notably in India, where revised regulations set limits on major pollutants. The primary pollutants from coal combustion include sulphur dioxide, nitrogen oxides, particulate matter, and mercury, each posing significant health and environmental hazards. Coal-based thermal power plants in India produced alarming emission levels in recent assessments, underscoring the need for effective emissions control technologies, such as Flue Gas Desulfurization, to mitigate their environmental impact.

LITERATURE REVIEW

Coal-based thermal power plants remain one of the largest contributors to global air pollution and greenhouse gas emissions. According to the International Energy Agency, coal continues to play a major role in electricity generation worldwide, particularly in developing countries such as India, where energy demand is rapidly increasing. The Global Coal Plant Tracker report highlights the continued expansion and operation of coal-fired plants despite increasing environmental concerns (International Energy Agency [IEA], 2025).

In India, thermal power dominates the electricity sector and contributes significantly to industrial emissions. The Ministry of Power (2024) reported that coal-based generation constitutes a major share of the country's total installed power capacity. However, the environmental consequences of this dependence are severe, particularly in relation to sulfur dioxide (SO₂), nitrogen oxides (NO_x), particulate matter (PM), mercury emissions, and carbon dioxide (CO₂).

Several studies have linked emissions from coal-fired power plants to serious public health impacts. National Institutes of Health (2023) observed that pollutants released from coal combustion are associated with respiratory diseases, cardiovascular disorders, and premature deaths. Similarly, Henneman L et al. (2023) found that exposure to emissions from coal-generated electricity substantially increases mortality risk in the United States. Supporting these findings, Cropper M et al. (2021) estimated that existing and proposed coal-fired plants contribute significantly to premature mortality due to air pollution exposure.

In the Indian context, the Comptroller and Auditor General of India (2021) identified inadequate pollution-control infrastructure and weak compliance mechanisms in thermal

power plants. The audit report emphasized that many facilities failed to install modern emission-control technologies within prescribed timelines, thereby increasing environmental and health risks.

To address these concerns, advanced air pollution control technologies have gained importance. Electrostatic Precipitators (ESP) are widely used for removing particulate matter from flue gases through electrically charged collection systems, while Flue Gas Desulfurization (FGD) systems reduce sulfur dioxide emissions using chemical absorption methods. According to Flue-gas desulfurization (2005), wet limestone FGD systems are among the most effective technologies for SO₂ removal in coal-fired power plants.

Research on improving FGD efficiency has also expanded in recent years. Koech L et al. (2023) conducted a comparative analysis of sorbents used in spray dry scrubbing systems and concluded that optimized sorbent selection can significantly enhance SO₂ removal efficiency while reducing operational costs.

Air pollution inventories further demonstrate the magnitude of emissions from India's thermal power sector. The Energy and Resources Institute (2021) developed a spatially resolved emission inventory showing that coal-based thermal plants are among the major contributors to ambient air pollution across industrial regions in India.

Recognizing the need for stricter regulation, the Ministry of Environment, Forest & Climate Change introduced the Environment (Protection) Fourth Amendment Rules, 2025, which mandate tighter emission standards and increased adoption of pollution-control technologies in thermal power plants. These amendments are expected to accelerate compliance with SO₂, NO_x, and particulate matter emission norms while encouraging cleaner and more sustainable power generation practices.

REGULATORY COMPLIANCE

The Environment (Protection) Fourth Amendment Rules, 2025, issued by the Ministry of Environment, Forest and Climate Change on July 11, 2025, revise SO₂ emissions regulations for coal and lignite-based thermal power plants. The new rules categorize plants into three groups based on location: Category A (near major cities), Category B (near Critically Polluted Areas), and Category C (all others). Compliance deadlines vary, with Category A plants required to meet SO₂ standards by December 31, 2027, while Category C plants are fully exempt. Plants retiring before

December 31, 2030, need to submit undertakings to avoid compliance. The policy revision is based on studies revealing that ambient SO₂ levels in India are typically below the National

Ambient Air Quality Standards, and most coal has low sulphur content. However, the decision to exempt roughly 79% of capacity from SO₂ standards, allowing significant non-compliance, has raised concerns regarding air quality in affected regions. Historical compliance efforts have faced multiple extensions, reflecting ongoing technical and operational challenges. Recent regulations impose financial penalties for non-compliance, yet these are viewed as inadequate to drive necessary pollution control upgrades. As of late 2024, only 8% of plants were compliant, with 42% at various installation stages, and half had yet to initiate upgrades, indicating a significant gap in achieving the intended environmental standards.

Emission Levels in India

Analysis of coal-based thermal power plant emissions in **India during 2016** revealed the following annual emission levels:

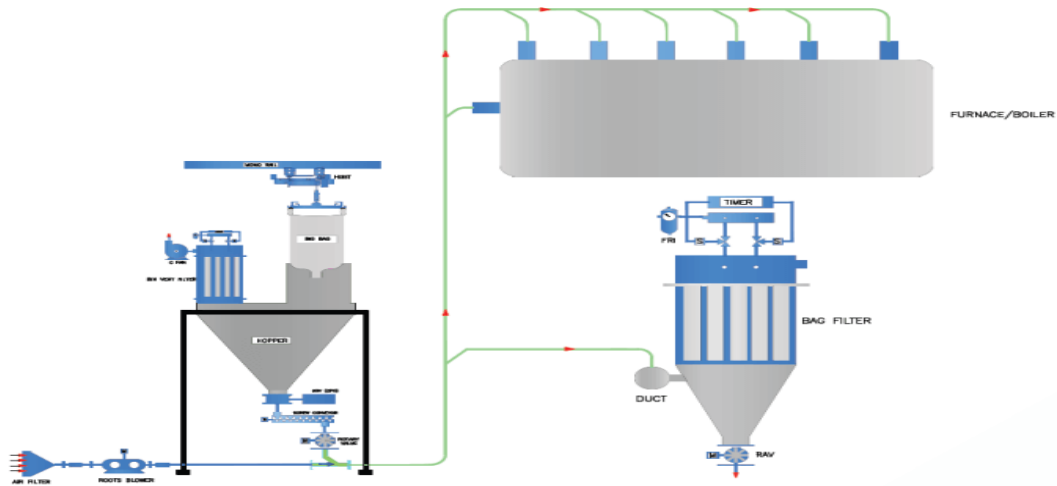
Table 1 Annual Emission Levels. (*Gg: Gigagrams)

PM ₁₀	572.5 Gg
PM _{2.5}	229 Gg
SO ₂	5437 Gg
NO _x	2509 Gg
CO	167 Gg
NMVOCs	80 g

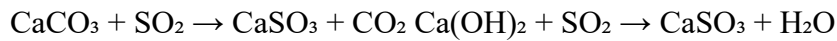
These substantial emission quantities underscore the critical importance of implementing effective emission control technologies across India's coal power fleet.

Dry Sorbent Injection (DSI)

Dry sorbent injection represents the simplest and most cost-effective FGD approach. In this method, finely powdered limestone (CaCO₃) or hydrated lime (Ca(OH)₂) is pneumatically injected directly into the flue gas duct upstream of a particulate matter collector (baghouse or ESP). The sorbent particles contact SO₂ in the flue gas, reacting to form calcium sulfite and sulfate. The particles are subsequently captured by the downstream PM collector along with fly ash.



Chemical reactions in DSI:



Advantages:

- Lowest capital cost (approximately ₹1-2 crore per MW in India)
- Simple operation and control
- No water consumption
- Easy retrofit to existing plants
- Rapid implementation

Disadvantages:

- Lower SO₂ removal efficiency (typically 50-60%)
- Requires significantly higher sorbent consumption per unit SO₂ removal
- No saleable byproduct
- Increases fly ash disposal costs
- May affect PM collector performance
- The ESP (Electrostatic Precipitator) operates through three sequential stages: ionization, transport, and collection.

Operating Principles of ESP

The ESP operates through three sequential stages: ionization (particle charging), transport, and collection.

Stage 1: Particle Charging (Corona Discharge) - A high voltage of 30,000-60,000 volts is applied between discharge and collection electrodes, generating a strong electric field that ionizes gas molecules, resulting in a corona discharge. This process produces negative ions that travel towards the collection electrodes. Dust particles in the flue gas are negatively charged through interactions with these ions, influenced by factors such as particle size, residence time, and corona current intensity.

Stage 2: Particle Transport - The negatively charged dust particles drift towards the positively charged collection electrodes. The drift velocity is determined by the electric field strength, particle charge, mass, and gas viscosity. Notably, smaller particles require longer residence times to reach the electrodes compared to larger particles.

Stage 3: Particle Collection - Charged particles hit the collection electrodes and adhere to their surface, forming a dust layer. Accumulated dust is periodically dislodged using mechanical rappers, which cause the dust to fall into hoppers for removal. In dry ESPs, this mechanical rapping is the primary method of collection, whereas in wet ESPs, a continuous water washing process is employed to remove collected particles.

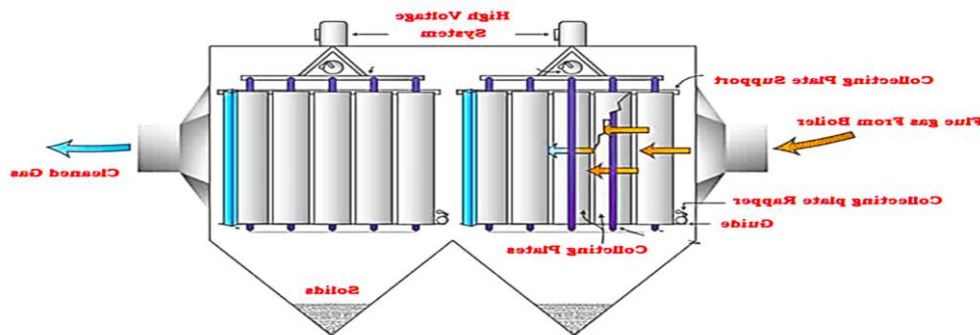


Figure 1. Electrostatic Precipitator – ESP – Process.

PROBLEM IDENTIFICATION

The Emission Paradox:

Coal-fired power stations continue to provide a significant portion of the world's baseload power despite the transition to renewable energy. The primary problem is the high emission intensity from burning coal, which releases large volumes of sulphur dioxide (SO₂), particulate matter (PM₁₀/PM_{2.5}), and carbon oxides (Cox), which are responsible for acid rain, respiratory illnesses, and global warming, respectively.

The Critical Challenge of Sulfur Dioxide (SO₂) Control:

Sulphur in coal causes SO₂ to be produced during combustion. The following are some issues with the current implementation of Flue Gas Desulfurization (FGD):

- a) Chemical Inefficiency: Low limestone utilization rates plague many wet FGD systems. The process $SO_2 + CaCO_3 \rightarrow CaSO_3 + CO_2$ becomes sluggish if the pH of the slurry is not precisely maintained, resulting in "slip" where sulphur escapes into the atmosphere.
- b) The Parasitic Load: FGD units are enormous industrial facilities in and of themselves. They need fans and high-pressure pumps, which use between 1% and 3% of the plant's total power output. This "energy penalty" lowers the facility's overall efficiency.

Visualizing the Problem Hierarchy:

Table 2 Visualizing the Problem Hierarchy.

System	Primary Problem	Secondary Consequence
Coal Combustion	Carbon / Sulfur / Ash released	Global warming and acid rain
ESP	High resistivity ash	PM2.5 escape / plume opacity
FGD	Reagent consumption/Slurry pH	SO ₂ slip and high-water usage
Integration	Parasitic energy load	Lowered net plant efficiency
Lifecycle	Solid waste (Gypsum/Ash)	Landfill saturation and leaching

POLLUTION CONTROL SYSTEM & WASTE / BYPRODUCT MANAGEMENT

The document discusses mercury control and trace metal emissions from coal combustion, detailing their significance and control technologies. It begins with an overview of mercury emissions from coal, noting that Indian coal-based thermal power plants emit controllable quantities of mercury, currently regulated at $\leq 0.03 \text{ mg/Nm}^3$ as per 2015 standards.

Key mercury control technologies involve sorbent injection into flue gas, with types including activated carbon, brominated sorbents, rice husk char, and trona-based sorbents, achieving varying efficiencies due to factors like coal halogen content. Integrated control strategies are outlined, linking systems such as Selective Catalytic Reduction (SCR) and Flue Gas Desulfurization (FGD) to improve mercury capture.

The document emphasizes the importance of multi-pollutant control systems that optimize the interaction between different pollutants. Case studies from NTPC demonstrate the successful implementation of emission controls, showcasing reductions in coal consumption and CO₂ emissions.

Additionally, the document addresses by-product management, highlighting fly ash and FGD gypsum. The Ministry of Environment mandates 100% fly ash utilization to mitigate waste, showing multiple pathways for its effective use in construction, agriculture, and land

reclamation. FGD gypsum, produced with high purity, is economically significant, with applications in drywall manufacturing and agriculture.

In summary, comprehensive pollution control and by-product utilization strategies illustrate the ongoing efforts to enhance environmental performance in coal-fired power plants.

COST-BENEFIT ANALYSIS AND HEALTH IMPACTS

Premature mortality, morbidity, and environmental destruction are only a few of the effects that coal power pollution has on the economy. Approximately 24,000 premature deaths and over \$240 billion in economic losses are caused by coal plant air pollution in the United States each year. Despite a lesser value of life due to income disparities, an estimated 112,000 deaths per year from coal-fired facilities in India show comparably high costs. Asthma flare-ups, hospital stays, and missed workdays are examples of morbidity expenses, which are estimated to be two to three times higher than mortality costs. According to benefit-cost evaluations, pollution control technologies offer large health and environmental advantages that greatly exceed their costs.

Cost Components for FGD Installation

A typical 500 MW coal power unit installing wet limestone FGD incurs the following costs:

Table 3 Cost Components.

Capital Costs	₹210-265 crore (₹4.2-5.3 crore/MW)
Annual O&M Costs	₹2.5-3 crore
Limestone reagent	₹1.2 crore
Electricity for pumps/fans	₹1.0 crore
Maintenance and labour	₹0.3 crore
Levelized Cost	Increases electricity cost by approximately 15-16 paise/kWh

According to analysis, installing Flue Gas Desulfurization (FGD) systems in coal-fired power stations has a benefit-cost ratio of 2–4:1, highlighting a compelling economic case based only on health and environmental benefits. Geographically, the effects of coal pollution on health differ greatly; highly populated areas are more vulnerable, especially those with poor air quality and pre-existing medical issues. By reducing sulphur dioxide (SO₂) emissions by more than 90%, FGD systems can lessen cardiovascular risks and the prevalence of chronic obstructive pulmonary disease (COPD). Furthermore, especially in high-risk areas, Electrostatic Precipitators (ESPs) efficiently absorb particulate matter (PM) emissions, minimizing deep lung penetration and related health hazards such neurological disorders and early mortality.

CASE STUDIES & PERFORMANCE EXAMPLES

The document presents three case studies on thermal power plants, focusing on environmental pollution challenges and control measures.

Case Study 01: Mundra Thermal Power Complex, Gujarat - This facility has a total capacity of 8,620 MW from 14 coal-based units, making it a significant coastal thermal power complex. Initially commissioned from 2009 to 2013, it faces notable pollution challenges, being identified as a SO₂ and NO_x hotspot through various analyses, including NASA satellite imagery and Tropomi data. The Kachchh coast's pollution capacity is notably strained, showing saturation limits for pollutants like SPM, SO₂, and NO_x. In response, pollution control measures including SEA-based Flue Gas Desulfurization (FGD) systems have been implemented or are planned, with a coastal location aiding in seawater-based FGD deployment, thereby mitigating freshwater needs and waste issues. However, ongoing environmental compliance efforts face documentation challenges.

Case Study 02: North Eastern Coalfields Region- This area, covering parts of Chhattisgarh, Odisha, and Jharkhand, has a high concentration of coal power plants. Ambient SO₂ levels are low (3-10 µg/m³), significantly below national standards, but PM_{2.5} pollution remains problematic due to coal combustion and household solid fuel use. Limited implementation of FGD systems is concerning given the classification as critically polluted. Health impacts are exacerbated by concurrent exposure to pollutants, leading to cumulative PM_{2.5} levels above 150 µg/m³, with emphasis on controlling PM rather than SO₂ to address health risks.

Case Study 03: The Anqing Power Plant, China - As part of an initiative to achieve ultra-low emissions, the Anqing plant underwent substantial retrofitting. The adoption of advanced technologies like high-efficiency Electrostatic Precipitators (ESPs) and a unique "Spin-Exchange Coupling" Wet FGD system was critical. The objective was strict pollutant limits of PM below 3 mg/Nm³ and SO₂ below 35 mg/Nm³. The results were impressive, with the ESP achieving a 99.9% removal rate, and secondary treatments reducing PM levels further. A key takeaway is that modern "Clean Carbon" strategies require a comprehensive, multi-stage approach integrating advanced technologies for effective pollution control.

CONCLUSION

Coal-based thermal power plants are vital to India's energy framework, generating about 72% of the country's electricity. However, their operation leads to significant air pollution, including SO₂, NO_x, PM_{2.5}, mercury, and CO₂, adversely affecting air quality, health, and the

environment. Between 1999 and 2020, coal emissions in the U.S. resulted in roughly 460,000 premature deaths, highlighting a larger potential risk in India's dense population and weaker emission controls. Effective emission control technologies, such as flue gas desulfurization and electrostatic precipitators, can remove over 90% of pollutants. These technologies are mature and cost-effective, offering health and environmental benefits that justify their implementation costs.

Despite regulatory mandates from 2015 requiring full compliance by 2022, only 8% of India's targeted plants met these standards by 2024, with about half having not started installation. A recent regulatory revision in July 2025 exempted 79% of thermal power capacity from SO₂ compliance, acknowledging economic and logistical challenges but potentially exacerbating air quality issues in already polluted regions.

Future strategies must recognize regional differences. In urban and critically polluted areas, the deployment of flue gas desulfurization and advanced particulate matter control is crucial. In less populated coal areas, alternative methods like enhanced electrostatic precipitators, washed coal, and limestone injection may be more cost-effective. Long-term solutions involve transitioning to supercritical/ultra-supercritical technologies and renewable resources, yet due to existing infrastructure and rising demand, coal will likely remain a major energy source for decades. Therefore, maximizing the use of emission control technologies within financial and technical limits is critical for safeguarding public health and air quality during this transition.

REFERENCES

1. International Energy Agency. Global Coal Plant Tracker. July 2025.
2. Ministry of Power, Government of India. Executive Summary on Power Sector. 2024.
3. Comptroller and Auditor General of India. Air Pollution due to Thermal Power Plants. Performance Audit Report Chapter 7. 2021.
4. Henneman L, et al. Mortality risk from United States coal electricity generation. *Science*. 2023;382(6675).
5. Cropper M, Gamkhar S, Malik A, et al. The mortality impacts of current and planned coal-fired power plants. *PNAS*. 2021;118(5).
6. Ministry of Environment, Forest & Climate Change. Environment (Protection) Fourth Amendment Rules, 2025. Official Gazette. July 11, 2025.

7. National Institutes of Health. Deaths associated with pollution from coal power plants. National Institute of Environmental Health Sciences. 2023.
8. The Energy and Resources Institute. Development of Spatially Resolved Air Pollution Emission Inventory of India, 2021.
9. Wikipedia. Flue-gas desulfurization. February 2005.
10. Koech L, et al. Comparative Study of Sorbents for Spray Dry Scrubbing of SO₂ from Coal Flue Gas. ACS Environmental Au. June 2023.