

An Integrated LCA and IEOM Framework for Coal Power Plants in Emerging Economies

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Abstract

This study aims to initiate a sustainability assessment of the Thar Coal Power Plant (TCPP) by collecting preliminary data for a future Life Cycle Assessment (LCA). The methodology involves benchmarking TCPP's operational and environmental performance against high-efficiency international coal plants, including Waigaoqiao (China), Niederaussem (Germany), and Boundary Dam (Canada). Key results show that TCPP emits substantially more CO₂ and has a lower thermal efficiency compared to international benchmarks. The study focuses on the potential of IEOM tools, such as Lean Six Sigma, predictive maintenance, blockchain technology, and capacity layout planning, to improve operational efficiency and reduce emissions. This research establishes a strategic foundation for sustainable coal energy in Pakistan. It also lays the groundwork for comprehensive Life Cycle Assessment (LCA) and effective environmental policies.

Keywords

Life Cycle Assessment (LCA), Thar Coal Power Plant (TCPP), Thermal Efficiency, Capacity Layout Planning, Lean Six Sigma.

1. Introduction

By 2050, the population growth of emerging economies is projected to significantly increase their consumption of coal-fired energy to meet increased energy demand. Such reliance indicates an increase in environmental concerns when planned without sustainable considerations. Mitigating these challenges, using methods tailored to localities, such as Life Cycle Assessment (LCA), can assess the environmental performance of alternative energy systems (Malode et al., 2022). Coal currently contributes around 5.4% of Pakistan's energy mix, with Thar Coal Reserves playing a major role (Abro et al., 2021). The Thar Block II provided by the Sindh Engro Coal Mining Company (SECMC) produces around 6.5 million tonnes of coal annually and is used by a 1,200 MW electricity power plant (Butt et al., 2023). The Thar coalfield possesses a low-sulfur content; however, the high moisture content of the coal poses combustion and efficiency difficulties. Technologies such as Clean Coal Technologies (CCTs) and Circulating Fluidized Bed Combustion (CFBC) are increasingly important for enhancing performance and reducing negative

impact (Butt et al., 2023). Regardless, Pakistan does not currently possess a single LCA of the Thar Coal Power Plant (TCPP), nor any benchmarking exercise that compared TCPP's efficiency, emissions intensity, or technology with leading coal power plants globally. The absence of these comparisons and the LCA methodology limits a fact-based decision-making process for enhancing the plant's performance, and sustainable approaches to be environmental stewards. While some individual studies have discussed emissions control technologies or separate combustion technologies, a basis for improvement at TCPP has not been developed from a single framework/methodology that includes LCA, benchmarking, and Industrial Engineering and Operations Management (IEOM) tools.

This research deals with these gaps by acquiring the first preliminary data for ISO-compliant LCA of TCPP, locating its performance in the context of best practices in international coal plants, and developing potentially viable improvements with IEOM methods. The goal is to lay the groundwork for a data-driven, sustainability-driven roadmap to improve the operational and environmental performance of coal-based power in Pakistan.

1.1 Objectives

This research aims to fill crucial gaps in TCPP environmental and operational assessment with three main objectives:

- 1. Preliminary Life Cycle Data Collection:**
Initiate cradle-to-gate data collection following ISO 14040 and ISO 14044 guidelines to support future comprehensive Life Cycle Assessment (LCA) of TCPP. This includes quantifying energy inputs, emissions, and resource consumption across key phases of the coal value chain.
- 2. Comparative Benchmarking:**
To identify best practices and gaps, TCPP's performance metrics—such as thermal efficiency, emissions intensity, and technology deployment—should be benchmarked against international coal-fired power plants, including Waigaoqiao (China), Boundary Dam (Canada), and Niederaussem (Germany).
- 3. Application of IEOM Strategies:**
Utilize Industrial Engineering and Operations Management (IEOM) tools—such as Lean Six Sigma, predictive maintenance, capacity layout optimization, and blockchain technologies—to propose targeted improvements in process efficiency, emissions control, and operational reliability.

Together, these objectives support the development of a sustainability-driven framework for optimizing coal-fired power generation in Pakistan, informed by global best practices and data-driven decision-making

2. Literature Review

Another significant inefficiency impacting the optimization of lignite-based power generation is the supply chain. Recent studies show that supply chain-related inefficiencies are responsible for 18-25% of total plant emissions in an equivalent-size plant, with even lower emissions for the excavators and haulage trucks used alone (Tang & Pervukhin, n.d.). TCPP's diesel haulage system for its 6 km coal transport, versus the conveyor belt systems used at Germany's Niederaussem plant, also plays a clear role in the overall inefficiencies.

Furthermore, the high moisture content of Thar Lignite creates additional supply chain challenges not adequately addressed in existing literature. Where advanced plants like China's Waigaoqiao facility utilize AI-coordinated supply chains to reduce fuel waste by 15%, TCPP lacks similar optimization systems, representing a clear opportunity for improvement through Industrial Engineering and Operations Management (IEOM) approaches.

Technology adoption barriers constitute the third major gap in current research. While ultra-supercritical boilers have demonstrated the ability to improve efficiency to 46% at plants like Waigaoqiao, and carbon capture systems have reduced emissions to 150 kg CO₂/MWh at Boundary Dam, TCPP continues to operate with subcritical technology. This technology gap stems from multiple factors, including financial constraints (with CCS implementation costing approximately \$80 per ton of CO₂ according to Wang et al., 2022) knowledge gaps regarding return on investment for upgrades, and policy inertia that maintains less stringent emission standards. Pakistan's National Environmental

Quality Standards (NEQS) currently permit 500 mg/m³ of SO₂ emissions, which is significantly higher than the EU standard of 150 mg/m³, resulting in limited regulatory pressure for technological upgrades.

The research gap addressed by this study emerges from the intersection of these three themes. Prior studies have failed to examine TCPP's unique challenges through an integrated lens that combines behavioral, supply chain, and technological factors. No literature presents a full Life Cycle Assessment (LCA) of TCPP that utilizes primary operational data and includes other lignite plants (not only bituminous coal plants). There is also no literature available on context-specific, policy-relevant IEOM frameworks for the regulatory environment and resource constraints in Pakistan. This research fills these gaps in the knowledge by conducting TCPP's first cradle-to-grave LCA using direct operational data. Simultaneously, proposed targeted IEOM strategies such as Lean Six Sigma training programs to diminish behavioral inefficiencies, blockchain-enabled moisture monitoring for supply chain optimization, and an incremental approach to ultra-supercritical technology that considers the financial and infrastructure realities of Pakistan.

This method is unique because it addresses the integrated view of the contextual operational, logistics, and technological mechanisms associated with TCPP. Prior research has examined the contextual factors separately, but this study has designed a framework incorporating interdependence, i.e., how they combine to affect plant performance. By situating its analysis in direct comparison to global best practices while acknowledging local constraints, the research provides practical suggestions for action to improve efficiency and reduce emissions at TCPP, and potentially at other lignite-based power plants in developing countries that face the same challenges.

3. Methodology

This study utilizes a mixed-method approach using Life Cycle Assessment (LCA) and Industrial Engineering and Operations Management (IEOM) techniques to assess the environmental footprint and operational efficiency of the Thar Coal Power Plant (TCCP). The LCA follows ISO 14040 and ISO 14044 protocols and includes the three broad stages of the coal value chain: (1) Mining Operations: This includes analyzing diesel use (~60 million liters/year), electricity use (~72 million kWh/year) and machine performance; (2) Transportation: This would include the 60-ton haul trucks' emissions, driving at a distance of 6 km consuming 24 liters/hour of fuel; and (3) Combustion of the lignite (0.6 tons / MWh) including the amount of ash generated (~1.4 million tons/year), and wastewater produced (0.5 m³/MWh). By following the four-step LCA process, which includes defining the goal and scope, the life cycle inventory (LCI), impact assessment and interpretation, both emissions and resource inefficiencies can be pinpointed (Restrepo et al., 2015; Siddique, n.d.).

To complement the environmental analysis, IEOM strategies were applied to identify improvement opportunities. Benchmarking against international high-efficiency plants, including Waigaoqiao (China, 46% efficiency), Niederaussem (Germany), and Boundary Dam (Canada, CCS-equipped), enabled performance gap analysis. This benchmarking informed the application of Lean Six Sigma for waste minimization, AI-based predictive maintenance for reducing unplanned downtime, and blockchain technologies for emission transparency and compliance (Table 1-Table 2).

Table 1. Comparative Analysis of Global Coal-Fired Power Plants

Power Plant	Location	Capacity (MW)	Fuel Type	Technology	Key Features
TCCP	Pakistan	1,200	Lignite	Circulating Fluidized Bed Combustion (CFBC)	High moisture coal, moderate sulfur, No CCUS
Ghatampur	India	1,980	Bituminous	Supercritical Technology	High efficiency, controlled emissions
Waigaoqiao	China	5,000	Hard Coal	Ultra-Supercritical	Industry-leading efficiency (46%), low emissions
Niederaussem	Germany	3,864	Lignite	Ultra-Supercritical	Advanced emissions control with lignite
Boundary Dam	Canada	824	Lignite	Carbon Capture & Storage (CCS)	Near-zero CO ₂ emissions, CCS integration

4. Data Collection and Processing:

The study draws on both primary and secondary data sources. Primary data was collected on-site at Thar Block II through operational logs, Continuous Emission Monitoring Systems (CEMS), and structured interviews with plant engineers and environmental officers. To assure accuracy, this raw data was verified for completeness and consistency through triangulation across various sources, including weekly and monthly reports. Discrepancies and outliers were resolved through cross-validation, utilizing internal reports as a source of truth.

Secondary data was obtained from peer-reviewed literature, national energy reports, and environmental assessments. Relevant literature included Masih., (2018), Raza et al., (2022), Siddiqui et al., (2018) and Hagler Bailly Pakistan, n.d. These were used to provide baseline emission factors, technology benchmarks, and lifecycle parameters for benchmarking. All data was standardized into consistent measurement units, and the datasets were checked for duplicate data, missing values, and formatting errors using Microsoft Excel and Power Query.

By using multiple sources of information, the data integration approach ensures that the team forges the LCA and benchmarking assessments with sound, validated, and contextualized knowledge. It also allows for the strong application of IEOM principles to inform both design and operations decisions to move TCCP towards more sustainable practices.

5. Results

This section examines the emissions performance, efficiency, water use, and waste production of the Thar Coal Power Plant (TCCP) to a selection of global coal-fired power plants. The discussion explores the implications of the environmental aspects described, as well as how the performance of TCCP has been previously reported in studies, to emphasize areas of improvement at TCCP, which can be achieved through benchmarking comparisons, and any considerations from the IEOM frameworks can also be applied to the data.

A performance comparison of globally famous plants—Ghatampur, Waigaoqiao, Niederaussem, and Boundary Dam—was conducted. A comprehensive performance, emissions, and environmental impact assessment found some significant performance, emissions, and environmental impact differences between the plants. The most noteworthy

case was the Thar Coal Power Plant, which showed elevated emissions of CO₂, SO₂, and NO_x, in addition to thermal efficiency (mostly 30-35%) due to combustion properties associated with lignite. The Thar plant also has moderate daily water consumption (2.2 m³/MWh) and low waste (an average of approximately 256000 tons/year).

- **Emissions:** Thar has higher CO₂ (935 kg/MWh), SO₂ (5.2 kg/MWh), and NO_x (3.5 kg/MWh) emissions compared to global plants.
- **Efficiency:** Thar's thermal efficiency (30-35%) is lower than Waigaoqiao (46%) and Niederaussem (43%).
- **Moderate Water Consumption:** Thar uses 2.2 m³/MWh, higher than Waigaoqiao (1.5 m³/MWh) but lower than Ghatampur (2.5 m³/MWh)
- **Waste Generation:** Thar produces 256,000 tons/year of coal ash, lower than Ghatampur (2 million tons/year) but higher than Boundary Dam (100,000 tons/year).

Table 2. Benchmarking Thar Against Global Coal-Fired Power Plant

Parameter	Thar	Ghatampur	Waigaoqiao	Niederaussem	Boundary Dam
Location	Sindh, Pakistan	UP, India	Shanghai, China	Niederaussem, Germany	Saskatchewan, Canada
Capacity (MW)	1,200	1,980	5,000	3,864	824
Fuel Type	Lignite	Bituminous coal	Bituminous coal	Lignite (brown coal)	Sub-bituminous coal
CO ₂ Emissions (~kg CO ₂ /MWh)	935	800	750	800	150 (with CCS)
SO ₂ Emissions (~kg CO ₂ /MWh)	5.2	1.8	1.8	2.0	1.8
NO _x Emissions (~kg CO ₂ /MWh)	3.5	1.2	1.2	1.5	1.2
Particulate Matter (PM) (~kg CO ₂ /MWh)	0.15	0.1	0.1	0.12	0.1
Water Consumption (m ³ /MWh)	2.2	2.5	1.5	1.8	2.0
Thermal Efficiency	30-35%	38%	46%	43%	30% (with CCS), 35% (without CSS)

Waste Generation tons/year	Coal ash 256,000	Coal ash 2 million	Coal ash 1.5 million	Coal ash 1.2 million	Coal ash 100,000
CCS Technology	None	None	None	None	Post-combustion CCS (Unit 3)

5.1 Emissions and Efficiency Comparison

Thar Coal Power Plant's emissions are much higher, and efficiency is much lower compared to worldwide averages. For instance, the Thar CO₂ emissions are 935 kg/MWh, whilst Waigaoqiao's CO₂ emissions are 750 kg/MWh and Boundary Dams are 150 kg/MWh (with CCS). Thar SO₂ emissions are 5.2 kg/MWh and NO_x emissions are 3.5 kg/MWh, whilst global averages are 1.8 kg/MWh and 1.2 kg/MWh, respectively (Fig. 1). The higher emissions values per MWh of electricity generated at the TCPP depends on the Lignite's low calorific values and high moisture content and these observations are consistent with the findings by the Wu et al., 2022.

The thermal efficiency of TCPP (30-35%) is well below that of Waigaoqiao's (46%) and Niederaussem's (43%) because TCPP lacks Ultra-Supercritical technologies. Such Ultra-Supercritical technologies enhance thermal efficiency by operating at a higher temperature and greater pressure, and can improve overall heat rate and fuel consumption of the TCPP (Kharub et al., 2018).

5.2 Water Use and Waste Generation

The TCPP shows moderate water consumption (2.2 m³/MWh), which is slightly less than Ghatampur (2.5 m³/MWh) but exceeds Waigaoqiao's benchmark (1.5 m³/MWh). Case studies demonstrate that dry cooling and wastewater recycling enable 30% reductions in water consumption at similar facilities. On the other hand, Thar produces 256,000 tons of coal ash per year, less than Ghatampur (2 million tons) but still a lot. Boundary Dam has had success with reusing ash to make construction materials, demonstrating the potential circular economy of materials that Thar has yet to consider.

5.3 Interpreting the Gaps: Technological and Operational Deficiencies

The increased emissions and decreased efficiency at Thar can be attributed to three key features: (1) the fuel quality of the lignite, (2) the use of old subcritical combustion technology, and (3) the lack of post-combustion emission controls, including Flue Gas Desulfurization (FGD), Selective Catalytic Reduction (SCR), and Carbon Capture and Storage (CCS). And those gaps are like what has been reported at Boundary Dam, which has achieved an over 80% reduction in CO₂ emissions, through CCS. If implemented at Thar, similar reductions could have reduced emissions from 935 to about 150 kg/MWh.

Furthermore, global plants apply Lean Six Sigma and predictive maintenance systems to reduce downtime and optimize combustion. The lack of these approaches in TCPP creates operational inefficiencies, resulting in increased per-unit emissions (Figure 1, Figure 2 and Figure 3).

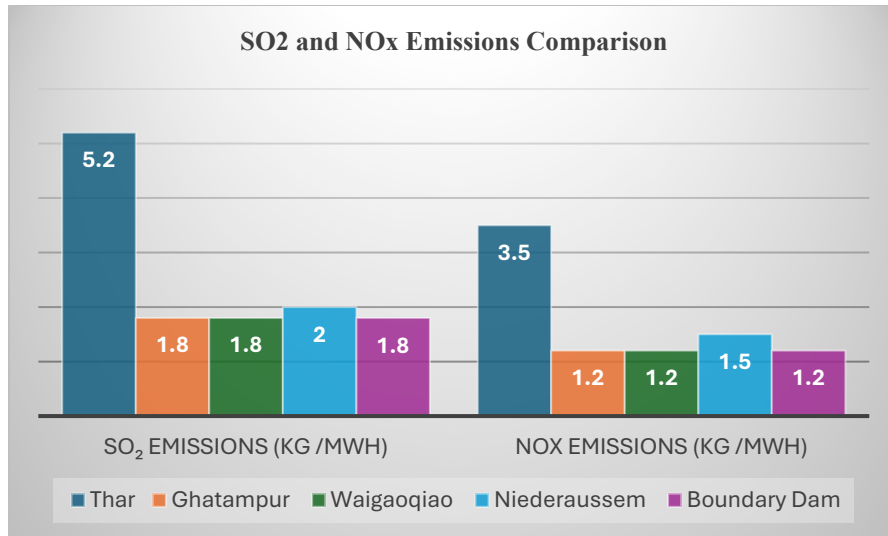


Figure 1. Cross-Plant Comparison of SO₂ and NO_x (Kg/MWh) Emission Profiles of Thar, Ghatampur, Waigaoqiao, Niederaussem, and Boundary Dam

5.4 Proposed Improvements

This section provides policy recommendations based on the implementation of IEOM strategies to improve efficiency, reduce emissions, and incorporate sustainable operations into the Thar coal power plant while keeping costs down. Best practices, driven by IEOM, from internationally well-known coal-fired plants provide a better understanding of how to maximize efficiency, minimize emissions, and increase reliability at the Thar facility (Table 3). This portion deals specifically with a potential application of the IEOM principles concerning the Thar Coal Power Plant, with the intention of improving its efficiency and sustainability. Although Thar has not yet used similar technologies, there are other coal mining and electricity-producing companies throughout the world that have used similar technologies effectively. The following IEOM-related measures are how we can help improve Thar:

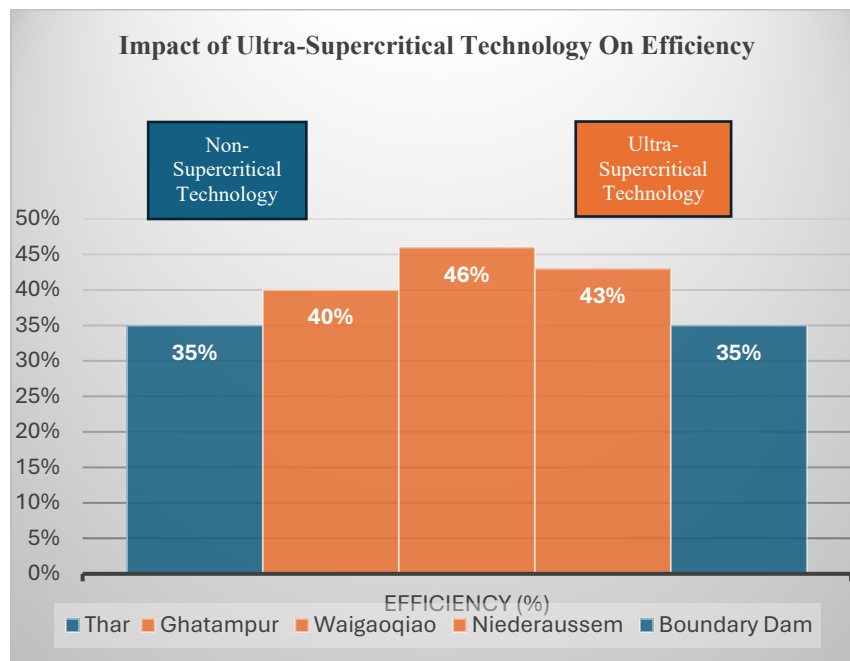


Figure 2. Operational Efficiency (%) of Ultra-Supercritical Technology Across Global Coal Power Plants

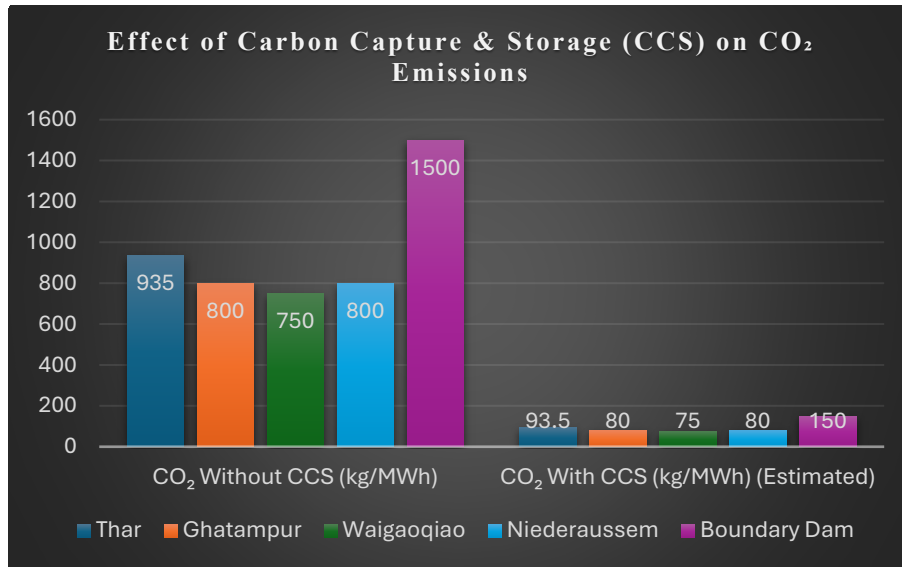


Figure 3. Comparative Analysis of CO₂ Emissions (Kg/MWh) With and Without Carbon Capture & Storage (CCS) at Thar, Ghatampur, Waigaoqiao, Niederaussem, and Boundary Dam

Table 3. Best Practices for Cleaner and More Efficient Thar Coal Power Plant

<i>Parameter</i>	Current Thar Value	Recommended Best Practice	Expected Improvement Calculation
CO₂ Emissions (kg/MWh)	935	500	If Thar adopts ultra-supercritical technology (43-46% efficiency), emissions could drop by 40% (based on efficiency gains from Waigaoqiao & Niederaussem). Adding CCS could reduce CO ₂ by 80%, potentially bringing it as low as 150 kg/MWh. Without CCS, 500 kg/MWh is realistic.
SO₂ Emissions (kg/MWh)	5.2	1.8	Limestone Injection + FGD (Flue Gas Desulfurization) can reduce SO ₂ emissions by 65% (like Niederaussem & Ghatampur plants).
NO_x Emissions (kg/MWh)	3.5	1.2	Low NO _x Burners and selective Catalytic Reduction (SCR) can reduce NO _x by 65%, aligning with global benchmarks.
Thermal Efficiency (%)	30-35%	42-46%	Ultra-supercritical boilers can improve efficiency to 46% (Waigaoqiao level) or 43% (Niederaussem level).

Water Consumption (m ³ /MWh)	2.2	1.5	Dry Cooling Systems and water Recycling can reduce water use by 30%, aligning with global plants.
Waste Generation (tons/year)	256,000	100,000 - 150,000	Coal ash utilization for bricks/cement and efficiency improvements can cut waste by 40%.

5.4.1 Lean Six Sigma

The Six Sigma DMAIC framework has been used successfully to identify performance inefficiencies in thermal power plants, and it was found that low availability of equipment is a major cause of capacity loss (Kharub et al., 2018). To mitigate this performance loss inefficiency, recommended solutions include modern technologies such as supercritical combustion systems, improvements in maintenance practices; and reducing distribution losses. These enhancements can collectively provide significant improvements in the plant's overall efficiency. Additionally, combining simulation methods, optimization models, and Pareto analysis has been suggested to optimize capacity use, cut operating costs, and maximize profitability; value stream mapping (VSM) from Lean Six Sigma tools, has also been shown to give significant applications to the mining and energy sector. Research demonstrates that VSM can help reduce cycle time by 23.4% and lead time by 56.1%, as it aids in smoothing and improving workflow and removing waste (Bhat & Venkitaraman, 2024). In relation to the context of the Thar Coal Power Plant, VSM can provide a visualized perspective of the flow of materials and energy in relation to the value chain. The application of VSM would be advantageous for optimizing the use of resources and minimizing waste and inefficiency in the processes, which effectively improves the operational productivity of the plant.

5.4.2 Predictive Maintenance

Advanced digital technologies such as Artificial Intelligence, Internet of Things, and edge computing present valuable opportunities to modernize the TCPP's operations. Thar can potentially improve its equipment reliability and plant efficiency using these cutting-edge technologies. This framework enables a network of smart sensors and edge computing devices that process operational data at the source. This architecture permits immediate insights into machinery health and allows predictive maintenance measures to optimize plant uptime. Such predictive maintenance systems have been shown to reduce unplanned downtime, lower maintenance costs, and prevent critical equipment failures, ultimately enhancing plant reliability and operational stability. Research shows that implementation of these predictive systems has proven operational benefits in terms of reduced downtimes and maintenance costs while improving overall facility reliability (Tang & Pervukhin, n.d.).

Furthermore, the application of machine learning and deep learning has significantly enhanced the accuracy of predictive analytics. Techniques such as MLP, LSTM, LightGBM, and SGD regression are now playing a critical role to estimate emissions and optimize plant operations (Tang & Pervukhin, n.d.). Applying these advanced analytics at Thar can deliver more precise forecasts of environmental performance. They would also improve combustion and emissions control. Therefore, AI-driven predictive maintenance offers a valuable opportunity to increase both reliability and sustainability outcomes.

5.4.3 Capacity Layout Optimization

Advanced technologies, including AI, Big Data, and GIS, provide powerful solutions for power generation. For the TCPP and similar plants, these technologies could revolutionize resource management and plant efficiency. These advanced technologies provide real-time data processing and predictive analytics, enabling plant operators to make more informed and cost-effective decisions. More specifically, they have overcome challenges associated with determining facility layouts and routing logistics by analyzing extensive datasets for patterns and inefficiencies that would not be as easily identified using traditional methodologies (Tang & Pervukhin, n.d.).

These technologies have the potential to greatly improve operations at Thar by optimizing capacity layout and minimizing material handling times, reducing fuel waste, and potentially assisting in the coalescing of the coal supply,

storage, and burn systems. The use of AI, Big Data, and GIS applications provides greater spatial planning and resource allocation capabilities, and the eventual goal is a reduction in operational cost with improvements to throughput and reliability; all significant objectives for a plant looking to improve both economic and environmental performance.

5.4.4 Blockchain Technology

Challenges in combined inefficiency and transparency hamper the successful integration of renewable energy within the electrical energy sector and existing frameworks, primarily due to the complexity and centralization. Blockchain technology has been put forward as a path to solve these inefficiencies, transparent systems, and data management issues across the energy value chain in a distributed, transparent, and secure manner. I. U. Rakhmonov et al., 2024 suggested that blockchain aids the integration of renewable energy and peer-to-peer (P2P) energy transactions through supply chain transparency and improves the efficient operation of the grid. In addition, Restrepo et al., 2015; and Siddique, n.d. see blockchain as the technology stack used to create trust and a mechanism for improving interactions amongst energy producers, consumers, and stakeholders of the energy ecosystem.

There are various strategic advantages that blockchain technology can offer to the Thar Coal Power Plant. The real-time tracking of coal sources, logistics, and emissions captures data that would improve transparency and compliance with regulations. Blockchain would also allow for the combination of renewable energy components with Thar operations since blockchain offers a transparent accounting framework for hybrid energy systems. Blockchain would also enhance supply chain efficiency and help the plant meet global decarbonization and sustainability goals.

5.3.5 Policy and Technology Recommendations

This study introduces an integrated approach that combines policy interventions with IEOM strategies. The objective of this framework is to enhance the sustainability and operational efficiency of the TCPP. Long-term environmental and economic sustainability demands top-down policy reforms and bottom-up technological solutions. To improve the thermal efficiency of the TCPP, legislation supporting modern combustion technologies (Ultra-Supercritical boilers) is essential for this purpose. To address major air pollutants (SO₂ and NO_x), Pakistan must revise its National Environmental Quality Standards (NEQS) with globally recognized benchmarks set by the EU and the US. Economic tools like carbon pricing and clean-tech subsidies can accelerate Carbon Capture and Storage adoption. These technologies have reduced CO₂ emissions from 935 to 150 Kg/MWh at Canada's Boundary Dam.

While policy alignment sets important standards, IEOM frameworks provide real-world operational solutions. These frameworks turn standards into measurable indicators at the plant level. Lean Six Sigma methods can be used to improve coal handling, fuel combustion, and auxiliary processes, which might lead to efficiency gains of 5-10%. By combining AI and IoT, predictive maintenance solutions may reduce unexpected downtime up to 20%. This makes the system more reliable and lowers emissions per unit of electricity generation. Blockchain technology offers a transparent, tamper-proof tracking of emissions and compliance with environmental best practices. Integrating blockchain technologies can ensure real-time monitoring, emissions tracking, and transparent compliance with environmental standards. Benchmarking supports the effectiveness of these interventions, like China's Waigaoqiao and Canada's Boundary Dam, which provide practical models for the Thar to follow.

Technological advancements alone can not ensure sustainability without strong regulatory frameworks. It demands rigorous environmental laws, penalties, and performance-based incentives. A coal-renewable hybrid strategy offers an effective solution to sustainable power generation. Successful examples include the Boundary Dam Canada and the Ghatampur India.

This integrated approach ensures that cleaner thermal power generation is both technically viable and economically sound. The study also outlines potential research directions, including.

- Life cycle assessment of water and solid waste.
- Feasibility studies of hybrid coal-renewable models.
- Economic evaluation of CCS deployment.

By implementing these interventions, the TCPP could serve as a reference point for sustainable thermal power generation in emerging economies.

6. Conclusion

This report discusses a notable gap in the literature by presenting the first Life Cycle Assessment (LCA) of the TCPP and benchmarking its performance against the international standards. Compared to its global counterparts, the TCPP reports higher emissions and reduced efficiency. Water savings at TCPP are also possible through dry cooling and wastewater recycling. This work emphasizes a range of IEOM-based technologies, such as Lean Six Sigma, predictive maintenance, capacity layout planning, and blockchain technology. The goal is to improve system performance and environmental sustainability.

The combination of application methods improves the reliability and operation of the plant and further builds on the importance of transparent data for decision-making within the plant to ensure compliance with regulations and sustainable development.

This study adds to the academic literature by starting a region-specific LCA data collection, which is a largely omitted component in previous assessments. For policymakers and institutional stakeholders, it provides actionable recommendations, including the adoption of ultra-supercritical boiler technologies, aligning national emission standards with EU and U.S. benchmarks, introducing incentive-based policies for emission reduction technologies such as carbon capture and storage (CCS), and exploring hybrid renewable-coal energy models for long-term sustainability. Future research should focus on evaluating the economic viability of CCS implementation at TCPP and developing predictive models to assess the policy impact on emission reduction and energy security.

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Biographies

Sharfuddin Ahmed Khan is currently an Associate Professor and Associate Program Chair of Industrial Systems Engineering at the University of Regina, Saskatchewan, Canada. Prior to this role, he served as a Lecturer (September 2009 – August 2019) and later as an Assistant Professor (September 2019 – December 2021) at the University of Sharjah, United Arab Emirates. He then joined the University of Regina as an Assistant Professor (January 2022 – June 2025) before being promoted to his current position. Dr. Khan has contributed extensively to top-tier academic journals and Scopus-indexed conferences in areas such as supply chain management, sustainability, and engineering management. His research has been published in renowned journals, including *Business Strategy and the Environment*, *Supply Chain Management: An International Journal*, *IEEE Transactions on Engineering Management, Production Planning and Control*, *International Journal of Production Research*, and *Operations Management Research*, among others. He has also authored book chapters and published books with leading academic publishers such as Taylor & Francis and Emerald Publishing. Dr. Khan has successfully secured significant research funding and has supervised and co-supervised numerous graduate students at the master's and doctoral levels. His research continues to make a strong academic impact. A detailed overview of his scholarly work is available on his [Sharfuddin Ahmed Khan - Google Scholar](#).

Atif Nasim Khan is currently a MASc student of Industrial Systems Engineering at the University of Regina, Saskatchewan, Canada. His research focus is the Life Cycle Assessment of the Coal Value Chain in emerging economies. Leveraging professional experience in Pakistan's coal mining sector, his research combines environmental and professional metrics to support sustainability in coal-intensive regions. During his graduate studies, Mr. Khan produced scholarly term papers on Digital Transformation in Inventory Management (85.5%) and CO₂ sequestration (90%), showcasing his interdisciplinary research strength. Before his graduate studies, he earned a Bachelor of Science in Mining Engineering from the University of Engineering & Technology, Lahore, Pakistan, in 2008. Mr. Khan has over 8 years of professional experience in technical sales and business development of specialty and construction chemicals, as well as industrial raw materials, within the coatings and construction industry. In his technical sales role, he played a key role in industry advancements, including the pioneering use of nano calcium oxide in hydropower projects and the development of eco-friendly coating technologies. He also has served as a Graduate Teaching Assistant at the University of Regina, supporting courses in Risk Assessment and Simulation & Modelling.