Predictive Maintenance-Driven Digital Decarbonization in the Indian Cement Industry: An Equipment-Focused Framework

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Abstract

The cement sector is one of the most energy-intensive manufacturing industries and a significant contributor to greenhouse gas emissions. In India, the industry accounts for a considerable share of industrial carbon emissions due to its dependence on high-temperature processing equipment and energy-demanding grinding operations. While regulatory initiatives and cleaner fuel strategies have improved environmental performance, operational inefficiencies at the equipment level continue to impede deeper decarbonization. This paper examines the role of Artificial Intelligence (AI) and Industrial Internet of Things (IIoT)-enabled Predictive Maintenance (PdM) as a digital mechanism for reducing energy consumption and carbon emissions. An Equipment-Centric Predictive Maintenance and Decarbonization (ECPMD) framework is proposed to evaluate the influence of PdM on rotary kilns, pre-heaters, and grinding systems. Evidence synthesized from academic studies, industry reports, and sustainability disclosures indicates that predictive maintenance improves equipment reliability, stabilizes operations, lowers energy demand, and contributes to measurable emission reductions. The study highlights the strategic importance of predictive maintenance in supporting the Indian cement industry's transition toward sustainable and low-carbon production.

Keywords: Predictive Maintenance, Digital Transformation, Cement Industry, Decarbonization, Artificial Intelligence, Industrial Internet of Things, Sustainability.

1. Introduction

The global drive toward carbon neutrality has intensified pressure on energy-intensive industries to improve environmental performance. Among these industries, cement manufacturing remains particularly challenging because of its dependence on thermal processing and continuous mechanical operations. In India, rotary kilns, pre-heaters, and grinding units account for the majority of energy consumption and process-related emissions.

Traditional maintenance practices are generally preventive or reactive in nature, often resulting in unexpected failures, productivity losses, and inefficient energy utilization. Advances in AI, machine learning, and IIoT technologies have enabled the development of predictive maintenance systems capable of continuously assessing equipment condition and forecasting potential failures before they occur.

Although predictive maintenance has been widely investigated from reliability and productivity perspectives, its contribution to energy efficiency and carbon mitigation has received comparatively less attention. Furthermore, most existing studies evaluate outcomes at the organizational level rather than examining the performance of individual process equipment. This study addresses this gap by exploring predictive maintenance as a digital decarbonization strategy from an equipment-centric viewpoint.

Research Objectives

The objectives of this study are:

1. To assess the adoption of predictive maintenance technologies in key cement manufacturing equipment.
2. To investigate their contribution to energy efficiency and carbon emission reduction.
3. To develop a conceptual framework linking predictive maintenance maturity with decarbonization performance.

2. Equipment-Centric Predictive Maintenance and Decarbonization Framework

The proposed framework explains the relationship between predictive maintenance implementation and environmental performance through three interconnected dimensions.

1. Digital Maintenance Intelligence

The first dimension represents the deployment of advanced sensing technologies, AI-driven analytics, machine learning algorithms, and condition-monitoring systems across critical production equipment.

2. Operational Performance Stabilization

The second dimension focuses on operational outcomes including reduced downtime, improved combustion consistency, optimized material flow, minimized wear, and enhanced process control.

3. Sustainability Outcomes

The final dimension captures environmental benefits in the form of lower thermal and electrical energy consumption, reduced carbon emissions, and extended equipment service life.

This framework positions predictive maintenance as an enabling technology that connects digital transformation initiatives with industrial decarbonization goals.

3. Predictive Maintenance Applications in Cement Process Equipment

Rotary Kilns

Rotary kilns are responsible for the largest share of thermal energy consumption and direct carbon emissions in cement production. Their performance is strongly influenced by combustion efficiency, refractory condition, and mechanical stability.

Modern predictive maintenance systems employ thermal imaging, infrared monitoring, vibration diagnostics, and AI-supported flame analysis to identify abnormal operating conditions at an early stage. Literature indicates that these technologies can substantially improve kiln stability while reducing energy losses associated with combustion inefficiencies.

Reported benefits include reductions in heat consumption, lower emission intensity, fewer unplanned shutdowns, and longer refractory life. Consequently, rotary kilns offer the highest decarbonization potential among all major cement production assets.

3.2 Pre-Heater Systems

Pre-heaters play a critical role in heat recovery and material pre-calcination before kiln processing. Their efficiency can be affected by pressure imbalances, cyclone blockages, coating formation, and false air ingress.

Predictive maintenance solutions utilize temperature sensors, pressure monitoring systems, and machine-learning-based anomaly detection tools to identify performance deterioration before significant efficiency losses occur.

Studies show that improved thermal recovery and reduced process interruptions contribute to lower fuel requirements and indirect reductions in carbon emissions.

3.3 Grinding Operations

Grinding circuits represent the largest consumers of electrical energy within cement plants. Equipment wear, separator inefficiencies, vibration abnormalities, and load imbalances often lead to excessive power consumption.

Predictive maintenance approaches based on vibration analysis, acoustic monitoring, and AI-assisted diagnostics facilitate early fault detection and process optimization. As a result, grinding systems can achieve noticeable reductions in electricity usage while improving equipment reliability and operational continuity.

4. Decarbonization Benefits of Predictive Maintenance

Energy Efficiency Improvements

A review of published studies suggests that predictive maintenance contributes significantly to energy optimization by preventing operational degradation before it affects production efficiency.

The most prominent benefits include:

- Improved thermal efficiency in kiln and pre-heater systems.
- Reduced electricity consumption in grinding operations.

- Lower energy losses resulting from process instability.
- Enhanced utilization of production assets.

Overall, equipment-level energy savings reported in the literature range from approximately 4% to 9%, depending on technology maturity and implementation scope.

Carbon Emission Reduction

Predictive maintenance supports emission mitigation primarily through improved process stability rather than direct carbon capture or fuel substitution.

Stable combustion, efficient heat transfer, reduced over-grinding, and fewer production interruptions collectively lower the carbon intensity of cement manufacturing. When integrated with broader sustainability initiatives such as alternative fuels and process optimization programs, predictive maintenance can further enhance environmental performance.

Reliability and Asset Sustainability

Another important contribution of predictive maintenance is the extension of equipment lifespan. Reduced wear rates, fewer catastrophic failures, and optimized maintenance schedules lower the demand for replacement components and associated embodied carbon emissions. Improved reliability also minimizes production disruptions that often result in inefficient energy utilization.

5. Implementation Challenges and Strategic Enablers

Critical Success Factors

Successful deployment of predictive maintenance requires:

- High-quality industrial sensors capable of operating in harsh environments.
- Robust AI and machine-learning algorithms.
- Real-time data acquisition and analytics platforms.
- Integration with existing process control and maintenance management systems.
- Skilled personnel capable of interpreting predictive insights.

Existing Barriers

Despite growing adoption, several challenges continue to hinder implementation:

- Legacy infrastructure and fragmented data systems.
- High initial investment requirements.
- Limited digital capabilities among maintenance personnel.
- Difficulties in integrating third-party software platforms.
- Increasing cyber-security concerns associated with connected industrial systems.

Addressing these barriers will be essential for maximizing the environmental and economic benefits of predictive maintenance.

6. Conclusion

This study presents an equipment-focused perspective on predictive maintenance as a driver of digital decarbonization within the Indian cement industry. The findings indicate that AI- and IIoT-enabled maintenance systems can generate substantial benefits in terms of energy efficiency, operational reliability, and carbon emission reduction.

Among the equipment categories analyzed, rotary kilns demonstrate the greatest potential for decarbonization due to their significant contribution to thermal energy consumption and direct emissions. Pre-heaters and grinding systems also provide meaningful sustainability benefits through improved heat utilization and electrical efficiency.

The proposed Equipment-Centric Predictive Maintenance and Decarbonization framework illustrates how digital maintenance technologies can bridge the gap between operational excellence and environmental sustainability. As India advances toward its Net Zero 2070 commitment, predictive maintenance should be recognized not merely as a maintenance practice but as a strategic enabler of industrial decarbonization.

References

1. Bolson, N. F., et al. (2025). Assessing minimum energy requirements and emissions for different raw material compositions in clinker production. *Environmental Research: Infrastructure and Sustainability*, 5(3), 035005.
2. Ghosh, A., & Abawajy, J. (2025). Optimising industrial equipment operations using artificial intelligence and reliability-based approaches. *Expert Systems with Applications*, 271, 126672.
3. Jena, M. C., Mishra, S. K., & Moharana, H. S. (2024). Integration of Industry 4.0 technologies with reliability-centred maintenance for sustainable manufacturing. *Environmental Progress & Sustainable Energy*, 43(2), e14321.
4. Kumar, K., & Chatterjee, A. K. (2021). Developments in sensor applications for sustainable cement manufacturing. In *Intelligent and Sustainable Cement Production*. CRC Press.
5. Priya, G. K., Gundre, R., Bandyopadhyay, S., & Seethamraju, S. (2024). Decarbonization pathways for the Indian cement sector. *Journal of Environmental Management*, 358, 120860.
6. Sahoo, N., & Kumar, A. (2022). Energy conservation and emission reduction opportunities in the cement industry. *Environmental Development*, 44, 100767.
7. Sakhamuru, D. R. (2022). *Techno-Economic Analysis and Strategic Decarbonization of the Indian Cement Industry*. Massachusetts Institute of Technology.
8. Tsallis, C., Papageorgas, P., Piromalis, D., & Munteanu, R. A. (2025). Machine-learning-based predictive maintenance: Applications, challenges and future directions. *Applied Sciences*, 15(9), 4898.
9. Verma, Y. K., Ghime, D., Mazumdar, B., & Ghosh, P. (2023). Process integration and emission reduction strategies for sustainable clinker production. *International Journal of Environmental Science and Technology*, 20(12), 13329–13346.
10. Bureau of Energy Efficiency (2024). *Annual Report 2023–24*. Ministry of Power, Government of India.