# ARTIFICIAL INTELLIGENCE IN THE ENERGY SECTOR: ENHANCING BOILER PERFORMANCE WITH ADVANCED THERMAL SPRAY COATINGS

By

HARSHIT GARG * KESHAV GULATI ** DIVYANSHU MITTAL ***

*-*** Department of Computer Science and Engineering, CGC College Of Engineering, Punjab, India.

https://doi.org/10.26634/jme.15.3.22076

Date Received: 18/05/2025 Date Revised: 28/07/2025 Date Accepted: 09/08/2025

***ABSTRACT***

*The Energy Sector is experiencing a critical change with the integration of AI and progressed materials. This paper investigates the part of AI in upgrading the execution of evaporator businesses, especially in thermal power plants. Different thermal spray coatings utilized in evaporator applications, such as NiCrAlY and CoNiCrAlY, are examined for their benefits in enhancing erosion resistance, wear resistance, and overall effectiveness. The potential of AI in optimizing kettle operations, foreseeing support needs, and reducing energy utilization is also analyzed. By integrating AI with advanced thermal spray coatings in the energy sector, we can achieve higher efficiency, lower emissions, and greater sustainability.*

*Keywords: Artificial Intelligence, Energy Sector, Boiler Performance, Thermal Spray, Efficiency Optimization, Energy Reduction.*

## INTRODUCTION

The global energy sector is essential for economic growth and social development. However, the sector faces several challenges, including growing demand, aging infrastructure, volatile fuel costs, and the pressing need to reduce greenhouse gas emissions. As countries move toward sustainable development goals, there is increasing pressure to enhance the efficiency and reliability of energy systems, particularly within fossil-fuel-based power generation. Conventional energy systems, including thermal power plants, often struggle with inefficiencies caused by component degradation, maintenance delays, and limited adaptability to real-time conditions. These challenges generate a need for innovative technological interventions that can improve operational performance while meeting environmental regulations.

i-manager Publications

Member of: SDG Publishers Compact

This paper has objectives related to SDG

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

### 1. Role of Artificial Intelligence in the Energy Sector

Artificial Intelligence (AI) is rapidly transforming the landscape of the energy industry. By using data-driven models and machine learning algorithms, AI enables predictive analytics, fault detection, dynamic optimization, and energy forecasting (Bello et al., 2024; Hossain et al., 2019). In power generation and distribution, AI supports grid stability, reduces downtime through predictive maintenance, and enhances decision-making with real-time data analysis. AI plays a crucial role in the transition to smart energy systems by integrating renewable sources, automating plant operations, and improving resource management. The deployment of AI not only reduces costs but also enhances the sustainability and resilience of energy systems.

### 2. Boiler Performance in Thermal Power Plants

Boilers are the backbone of thermal power plants, responsible for producing steam by converting water using the heat generated from fuel combustion (Aruna & Mukasyan, 2008). Their performance significantly affects the overall efficiency, output, and emissions of the plant. Poorly maintained or inefficient boilers can cause major energy losses, higher operating costs, and increased emissions. Improving boiler performance through advanced materials and intelligent control systems is essential for ensuring reliable, safe, and environmentally friendly energy production. The use of thermal spray coatings and the integration of AI-driven monitoring systems are among the most promising solutions to these challenges, enabling longer component life, reduced wear and tear, and optimized fuel use (Kumar et al., 2021).

## 3. The Energy Sector: Advancing with AI and Thermal Coatings

The energy sector, particularly thermal power generation, is facing enormous pressure to reduce the emissions while maintaining high performance and reliability. As the global demand increases, the challenges also increase correspondingly. Aging infrastructure, inefficient combustion systems, and frequent equipment failures have become major concerns. To tackle these challenges, the industry is increasingly adopting two transformative technologies-artificial intelligence (AI) and advanced thermal spray coatings (Wijewardane, 2015). AI systems are transforming the operation of thermal power plants. By using algorithms that analyze real-time sensor data, AI can detect performance drops, predict potential equipment failures, and recommend adjustments to optimize fuel use. The intelligent control system reduces energy wastage, lowers maintenance costs, and helps stabilize operations under varying conditions.

## 4. Thermal Spray Coatings for Boiler Applications

### *4.1 Overview of thermal spray coatings*

Thermal spray coatings are a group of surface engineering processes in which molten or semi-molten materials are sprayed onto a substrate to improve its surface properties. These coatings are widely used in high-temperature and corrosive environments, such as boiler systems in thermal power plants. The primary purpose of thermal spraying is to provide a protective barrier against harsh conditions such as oxidation, corrosion, high thermal loads, and chemical erosions. When applied, these coatings extend the operational life of components such as boiler tubes and superheaters, while reducing maintenance needs and improving efficiency. Different thermal spray methods exist, such as plasma showering, high-velocity oxy-fuel (HVOF) showering, bend splashing, and fire showering. Each strategy has its preferences depending on the coating fabric and execution necessities. The choice of process and coating composition plays a critical role in determining the effectiveness of protection against tough boiler conditions.

### *4.2 Types of Coatings (NiCrAlY, CoNiCrAlY, etc.)*

Several alloy compositions have been developed specifically for boiler applications to withstand thermal fatigue, corrosion, and erosion (Mirzaee et al., 2023). Some of the most widely used are:

*4.2.1 NiCrAlY (Nickel-Chromium-Aluminum-Yttrium):*

This coating is well known for its excellent oxidation resistance at high temperatures. The presence of aluminum promotes the formation of a stable alumina ($Al_2O_3$) layer, while yttrium improves adhesion and enhances thermal cycling resistance. NiCrAlY coatings are commonly applied using plasma spray techniques and are widely used on boiler components exposed to high temperatures. Figure 1 shows Thermal Spray Deposition of NiCrAlY Coating.

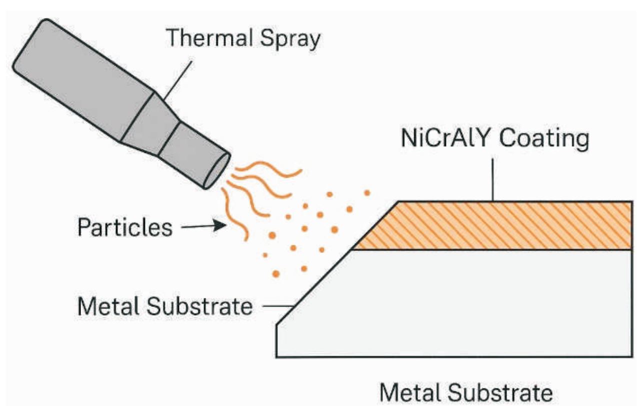


Figure 1. Thermal Spray Deposition of NiCrAlY Coating

*4.2.2 CoNiCrAlY (Cobalt-Nickel-Chromium-Aluminum-Yttrium)*

This combination provides a balance of oxidation and hot corrosion resistance along with mechanical strength. The cobalt content increases durability and resistance to thermal fatigue, making CoNiCrAlY suitable for high-stress boiler areas. It is commonly applied using HVOF or plasma spraying and performs effectively in environments exposed to both oxidation and sulfidation risks.

*4.2.3 FeCrAl Amalgams (Iron-Chromium-Aluminum)*

These coatings are cost-effective and exhibit great oxidation resistance. They are often used as alternatives in cases where nickel or cobalt-based coatings are not economically feasible.

*4.2.4 Ceramic-Based Coatings (e.g., YSZ – Yttria-Stabilized Zirconia)*

These are used as thermal barrier coatings (TBCs) to insulate boiler components and reduce thermal conductivity, thereby protecting the underlying metal from extreme heat

***4.3 Benefits of Coatings in Boiler Applications***

Thermal spray coatings offer several key advantages for components operating in boiler environments

*4.3.1 Erosion Resistance*

Boiler components are exposed to corrosive flue gases and moisture, which can result in rapid deterioration. Coatings such as NiCrAlY and CoNiCrAlY form stable oxide layers that act as protective barriers, significantly reducing corrosion rates.

*4.3.2 Wear Resistance*

Boilers often experience mechanical wear caused by ash impingement, soot blowing, and particle-laden flows. Coatings with hard phases provide enhanced resistance to erosion and abrasion, thereby protecting component geometry and function.

*4.3.3 Thermal Protection*

Some coatings, especially ceramic-based ones, act as insulators, protecting metal substrates from direct thermal stress. This improves thermal efficiency and prevents premature material failure

*4.3.4 Extended Service Life*

Coated boiler tubes and components show increased durability, resulting in fewer shutdowns, lower maintenance costs, and improved overall reliability.

*4.3.5 Natural and Financial Benefits*

By progressing the effectiveness and life span of warm control frameworks, these coatings offer assistance in diminishing fuel utilization and bringing down $CO_2$ emanations, adjusting with natural directions and maintainability objectives.

**5. Artificial Intelligence in Boiler Operations**

***5.1 Transforming Energy Management***

Modern power plants face increasing demands-not only to generate energy, but to do so with greater efficiency, lower emissions, and improved reliability (Ukoba et al., 2024; Zhao & Zhang, 2016). Conventional power systems, while effective, are limited by their reactive nature." Artificial Intelligence serves as a new kind of partner-learning from experience, responding in real time, and helping operators prevent issues rather than simply reacting to them.

***5.2 Function of AI in Boilers***

In the case of boilers, AI functions as a digital brain that continuously monitors the system. Its contributions include:

*5.2.1 Spotting Inconvenience Early*

AI analyzes patterns in temperature, pressure, and other data to detect small changes that may signal larger issues. This enables earlier maintenance and reduces unexpected failures

*5.2.2 Keeping Effectiveness Tall*

Instead of relying on fixed settings, AI adjusts factors such as fuel input and airflow based on current conditions. This minimizes waste and keeps energy use optimized.

*5.2.3 Making Alterations Consequently*

Tasks that once required human intervention-such as adjusting heating levels or managing cleaning cycles-can now be handled by AI, reducing errors and improving consistency.

*5.2.4 Foreseeing Request*

With the factors such as weather, time of day, and usage history, AI can predict energy demand and adjust boiler settings accordingly.

*5.2.5 Learning over Time*

The longer the system operates, the more data it gathers. AI uses this data to continuously learn and improve its ability to make faster and more accurate decisions.

***5.3 Benefits of AI in Boiler Operations***

The use of AI in boiler operations delivers tangible improvements-not just in theory, but in daily performance:

- *Minimize Breakdowns:* Early alerts allow issues to be addressed before they escalate.
- *Improved Fuel Utilization:* Stringent control reduces energy waste, leading to lower operating costs and reduced carbon emissions.
- *Ecofriendly Operations:* More efficient combustion results in fewer harmful emissions released into the air.
- *Lower Costs:* Optimized processes lower fuel expenses, reduce repair costs, and minimize downtime.
- *High Secured Plants:* Continuous monitoring helps detect hazardous conditions early, improving safety for workers.

## 6. Enhancing Boiler Performance with AI and Thermal Spray Coatings

***6.1 Integration of AI with Thermal Spray Coatings***

Boilers in power plants face extreme conditions such as heat and corrosion, which gradually damage their components. Thermal spray coatings protect boiler components by forming a strong barrier against damage. However, simply applying coatings is not enough-it is equally important to detect when they begin to wear out or fail. This is where Artificial Intelligence becomes valuable. By analyzing data from sensors on boiler surfaces, AI can identify early signs of coating degradation. Such insights enable operators to plan maintenance more effectively and prevent costly breakdowns. In addition, AI helps optimize boiler operations to reduce stress on coated surfaces, thereby extending the lifespan of the coatings. The different governing criteria that fall under the performance metrics are listed in Table 1.

***6.2 Case Studies or Examples of Successful Implementation***

Several real-world projects demonstrate the successful integration of AI and thermal spray coatings. At a power station in Asia, sensors monitored the condition of coated components while AI predicted when recoating was necessary, preventing unexpected failures and reducing downtime. Researchers have also applied AI to optimize coating processes by analyzing data such as temperature and material flow, which improved coating adhesion and durability (Figure 2). In a pilot plant, AI simultaneously monitored coating health and boiler settings, adjusting fuel and air supply to maintain efficiency and lower emissions. These examples highlight the potential of combining AI's data-driven capabilities with protective coatings to ensure reliable and efficient boiler operations.

***6.3 Potential Challenges and Limitations***

Despite its potential, integrating AI with thermal spray coatings faces several challenges. Obtaining high-quality sensor data can be difficult, particularly in old plants that lack modern monitoring tools. Coating

| Performance Metric | Traditional Boiler Systems | AI-Integrated + Thermal Spray Enhanced Systems |
|---|---|---|
| Corrosion Resistance | Moderate | High |
| Wear and Tear Protection | Low | High |
| Component Lifespan | 3–5 years (critical components) | 6–10 years with coatings and AI alerts |
| Emission Levels | High | Low |
| Cost Over Time | Increasing – Rising due to parts replacement | Stabilized – Upfront investment, and lower long-term costs |
| Operational Downtime | Frequent due to failures | Rare – AI detects anomalies early |
| Energy Efficiency | ~78–82% | ~90–93% |

Table. 1 Boilers with and without AI and Thermal Sprays

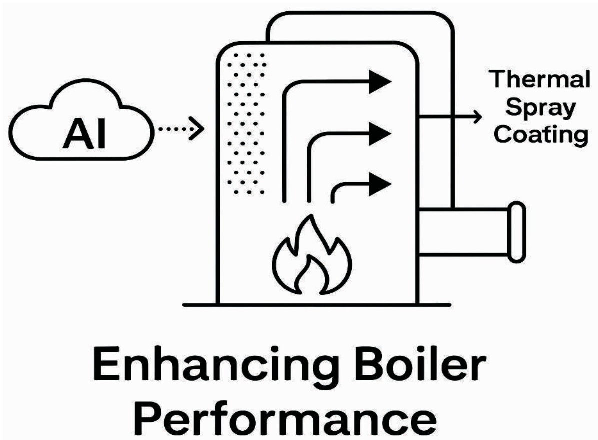


Figure 2. AI-Assisted Boiler System with Thermal Spray Coating Enhancement (Conceptual Illustration)

degradation occurs in complex ways that are not easy to predict, requiring continuous updates of AI models. Legacy boilers may also have compatibility issues with advanced AI systems, necessitating technical upgrades. In addition, personnel may need specialized training to operate and maintain AI tools effectively. The initial cost of installing sensors and AI systems can also be high, slowing adoption. Addressing these challenges requires balancing technology, cost, and training to achieve the best outcomes.

## 7. Future Directions and Conclusion

### *7.1 Future Trends in AI and Thermal Spray Coatings*

Future works include the integration of AI and thermal spray coatings, which are expected to play an increasingly important role in energy generation. New sensor technologies will provide detailed, real-time data on boiler conditions, enabling AI to detect minor issues before they develop into major problems. Advanced AI methods, such as deep learning, will further improve the precision of boiler control, helping to save energy and protect coatings. Researchers are also developing improved coatings with self-healing properties or greater durability in harsh environments. When combined with AI, these advancements could significantly reduce repair time and costs. Additionally, virtual models of boilers-known as digital twins-will allow operators to test different scenarios without physical risk, enhancing maintenance planning and system reliability.

## Conclusion

The integration of AI with advanced thermal spray coatings can make boilers more reliable, efficient, and environmentally friendly. These technologies help extended equipment life, reduce costs, and minimize emissions. For the energy industry to fully realize these benefits, several steps should be considered: upgrading equipment with smart sensors and data systems to support AI, fostering collaboration between AI specialists and coating developers, training personnel to operate new AI-based tools, and implementing pilot programs to demonstrate the effectiveness of these technologies in real plants. By adopting these measures, power plants can achieve cleaner and more dependable operations.

*Acknowledgments*

We would like to thank our mentors and academic advisors for their guidance and valuable insights throughout this research.

## References

[1]. **Aruna, S. T., & Mukasyan, A. S. (2008).** Combustion synthesis and nanomaterials. *Current Opinion in Solid State and Materials Science,* 12(3-4), 44-50.

https://doi.org/10.1016/j.cossms.2008.12.002

[2]. **Bello, S., Wada, I., Ige, O., Chianumba, E., & Adebayo, S. (2024).** AI-driven predictive maintenance and optimization of renewable energy systems for enhanced operational efficiency and longevity. *International Journal of Science and Research Archive,* 13(1), 2823-2837.

https://doi.org/10.30574/ijsra.2024.13.1.1992

[3]. **Hossain, E., Khan, I., Un-Noor, F., Sikander, S. S., & Sunny, M. S. H. (2019).** Application of big data and machine learning in smart grid, and associated security concerns: A review. *IEEE Access,* 7, 13960-13988.

https://doi.org/10.1109/ACCESS.2019.2894819

[4]. **Kumar, S., Handa, A., Chawla, V., Grover, N. K., & Kumar, R. (2021).** Performance of thermal-sprayed coatings to combat hot corrosion of coal-fired boiler tube and effect of process parameters and post-coating heat treatment on coating performance: A review. *Surface*

*Engineering,* 37(7), 833-860.

https://doi.org/10.1080/02670844.2021.1924506

**[5]. Mirzaee, M., Mohebbi, T., & Rezakhani, D. (2023).** A comprehensive review of the corrosion and erosion resistant coating on the fireside in power plant boilers. *Farayandno,* 18(82), 73-93.

https://doi.org/10.22034/farayandno.2023.2001252.1920

**[6]. Ukoba, K., Olatunji, K. O., Adeoye, E., Jen, T. C., & Madyira, D. M. (2024).** Optimizing renewable energy systems through artificial intelligence: Review and future prospects. *Energy & Environment,* 35(7), 3833-3879.

https://doi.org/10.1177/0958305X241256293

**[7]. Wijewardane, S. (2015).** Thermal spray coatings in renewable energy applications. In *Future Development of Thermal Spray Coatings* (pp. 241-257). Woodhead Publishing.

https://doi.org/10.1016/B978-0-85709-769-9.00010-5

**[8]. Zhao, X., & Zhang, X. (2016).** Artificial intelligence applications in power system. In 2016 *2nd International Conference on Artificial Intelligence and Industrial Engineering (AIIE 2016)* (pp. 158-161). Atlantis Press.

https://doi.org/10.2991/aiie-16.2016.36

## ABOUT THE AUTHORS

*Harshit Garg, Department of Computer Science and Engineering, CGC College Of Engineering, Punjab, India.*

*Keshav Gulati, Department of Computer Science and Engineering, CGC College Of Engineering, Punjab, India.*

*Divyanshu Mittal, Department of Computer Science and Engineering, CGC College Of Engineering, Punjab, India.*