Thermal Power Plant Efficiency Improvement: Technologies, Performance Analysis, and Future Perspectives

Ravikiran.S[1], Hemanth kumar. R[2], Mohamed Aadhil.A[3], Brithivi raj. G[4], Vijayan Gopalsamy[5]
[1,2,3] *Students - Department of Mechanical Engineering, Meenakshi Sundararajan Engineering College*,
[4,5] *Faculties - Department of Mechanical Engineering, Meenakshi Sundararajan Engineering College*,
Kodambakkam, Chennai - 600 024, Tamil Nadu, India

***Abstract*—Thermal power plants continue to play a vital role in global electricity generation despite the growing adoption of renewable energy sources. Enhancing their efficiency is essential to reduce fuel consumption, operational costs, and environmental emissions while ensuring sustainable power production. This review presents recent advances in thermal power plant efficiency improvement, focusing on supercritical and ultra-supercritical technologies, waste heat recovery systems, advanced boiler and turbine designs, artificial intelligence, digital twin technology, predictive maintenance, advanced materials, and carbon capture solutions. The study critically examines the performance benefits, implementation challenges, and future prospects of these emerging technologies for developing cleaner, more reliable, and highly efficient thermal power generation systems.**

***Index Terms*—Digital Twin, Energy Efficiency, Supercritical Technology, Thermal Power Plant, Waste Heat Recovery**

I. INTRODUCTION

The increasing global demand for electricity, coupled with stringent environmental regulations and the depletion of conventional fossil fuel resources, has intensified the need for highly efficient and sustainable power generation systems. Although renewable energy technologies have experienced remarkable growth in recent years, thermal power plants continue to supply a major proportion of the world's electricity because of their ability to provide stable and continuous base-load power. According to **the** International Energy Agency (IEA, 2023)**,** coal- and natural gas-fired power plants remain indispensable in ensuring grid stability despite the increasing penetration of renewable energy sources. Consequently, improving the efficiency of existing thermal power plants has become one of the most effective approaches for reducing fuel consumption, minimizing greenhouse gas emissions, and lowering electricity generation costs.

Conventional steam power plants operate based on the Rankine cycle, where the thermal efficiency is primarily governed by boiler performance, steam cycle parameters, turbine efficiency, condenser effectiveness, and auxiliary power consumption. Typical subcritical coal-fired power plants achieve efficiencies in the range of 35–38%, with a significant fraction of the supplied energy being lost through flue gases, cooling systems, radiation, and auxiliary equipment. Beer (2007) emphasized that improving thermal efficiency not only reduces specific fuel consumption but also directly decreases carbon dioxide emissions and other pollutants, making efficiency enhancement an economically attractive and environmentally sustainable strategy for existing power generation infrastructure.

To overcome the limitations of conventional systems, significant progress has been achieved in advanced steam cycle technologies. Supercritical (SC) and ultra-supercritical (USC) thermal power plants operate at elevated steam pressures and temperatures, thereby increasing the average heat addition temperature and improving cycle efficiency. These advanced technologies have demonstrated net thermal efficiencies exceeding 45%, while simultaneously reducing coal consumption and greenhouse gas emissions compared with conventional subcritical units. The adoption of high-temperature ferritic steels, nickel-based superalloys, and advanced turbine materials has further enabled reliable operation under severe thermal conditions, making USC technology one of the most promising developments in modern thermal power generation.

Another important approach to efficiency enhancement involves recovering energy that would otherwise be rejected to the environment. Waste heat recovery technologies, including economizers, regenerative feedwater heaters, air preheaters, and Organic Rankine Cycle (ORC) systems, have attracted considerable attention owing to their ability to utilize low-grade thermal energy from exhaust gases. Nemade and Ponsankar (2020) demonstrated that integrating an ORC-based waste heat recovery system with a coal-fired thermal power plant could effectively convert low-temperature flue gas energy into useful electrical power, thereby increasing the overall plant efficiency and reducing fuel consumption.

Recent developments in digital technologies have introduced a new paradigm for thermal power plant operation and maintenance. Artificial intelligence (AI), machine learning (ML), Industrial Internet of Things (IIoT), predictive maintenance, and digital twin technologies are increasingly being adopted to improve operational efficiency and equipment reliability. Among these, digital twin technology has emerged as a powerful tool capable of creating real-time virtual representations of physical assets, enabling continuous monitoring, fault diagnosis, performance optimization, and predictive maintenance. Tao et al. (2019) highlighted that digital twins facilitate data-driven decision-making by integrating physics-based models with real-time operational data, thereby improving manufacturing and industrial system performance.

Recent industrial implementations have demonstrated the practical benefits of digital twin technology in thermal power plants. A digital twin can continuously monitor boiler performance, optimize combustion parameters, predict equipment degradation, and recommend optimal operating conditions under varying load demands. Studies have reported that digital twin-assisted optimization can improve thermal efficiency by approximately 0.4–0.6%, reduce nitrogen oxide emissions, minimize auxiliary power consumption, and significantly lower maintenance costs through predictive fault detection. Furthermore, optimized operation of flue gas desulfurization units and air preheaters using digital twins has resulted in considerable reductions in operating expenditure while maintaining stringent environmental compliance.

In parallel with digitalization, advances in computational techniques have transformed the analysis and optimization of thermal power plants. Computational Fluid Dynamics (CFD), finite element analysis (FEA), thermodynamic simulation, exergy analysis, and multi-objective optimization have become indispensable tools for evaluating combustion characteristics, heat transfer behavior, steam flow distribution, turbine aerodynamics, and thermal losses within plant components. These numerical approaches enable researchers to investigate complex thermo-fluid phenomena while substantially reducing the cost and time associated with large-scale experimental investigations.

Despite substantial progress in individual technologies, existing literature predominantly focuses on isolated approaches such as supercritical steam cycles, waste heat recovery, advanced materials, digital twins, artificial intelligence, or emission control technologies. Comprehensive review studies that systematically integrate these emerging technologies and critically assess their collective impact on thermal efficiency, operational reliability, economic feasibility, and environmental sustainability remain relatively limited. Moreover, the combined application of Industry 4.0 technologies with advanced thermodynamic systems has not yet been comprehensively discussed from the perspective of next-generation intelligent thermal power plants.

Therefore, this review presents a comprehensive assessment of recent advances in thermal power plant efficiency improvement by critically examining developments in advanced steam cycles, waste heat recovery systems, digital twin technology, artificial intelligence, predictive maintenance, advanced engineering materials, computational modeling, and emerging low-carbon technologies. The review further identifies current technological challenges, research gaps, and future opportunities that may contribute to the development of highly efficient, intelligent, and environmentally sustainable thermal power generation systems.

II. RELATED LITERATURE

Recent research has increasingly focused on improving the thermodynamic performance of thermal power plants through the adoption of advanced steam cycles. The transition from conventional subcritical units to supercritical (SC), ultra-supercritical (USC), and advanced ultra-supercritical (A-USC) technologies has significantly improved cycle efficiency by increasing the operating pressure and steam temperature. Advanced USC plants operating at steam conditions of approximately 300 bar and 600–620 °C have demonstrated net plant efficiencies approaching 46–48%, while simultaneously reducing specific coal consumption and carbon dioxide emissions compared with conventional units. These developments have been made possible by the use of high-temperature nickel-based superalloys, ferritic steels, and advanced creep-resistant materials capable of withstanding severe operating conditions.

Besides steam cycle improvement, waste heat recovery has become one of the most effective methods for increasing overall plant efficiency. A considerable amount of thermal energy leaves conventional power plants through stack gases, condenser cooling water, and auxiliary systems. Recovering this low-grade heat using technologies such as economizers, regenerative feedwater heaters, air preheaters, and Organic Rankine Cycle (ORC) systems can significantly improve energy utilization. Nemade and Ponsankar (2020) demonstrated that integrating an ORC with a 2 × 250 MW coal-fired thermal power plant effectively recovered flue-gas waste heat and enhanced the overall cycle efficiency while reducing fuel consumption. Similar studies have confirmed that waste heat recovery systems contribute to improved plant economics and lower greenhouse gas emissions by converting otherwise unused thermal energy into useful power.

Rapid advances in digital technologies have further transformed thermal power plant operation from conventional supervisory control to intelligent, data-driven optimization. Industry 4.0 technologies—including Artificial Intelligence (AI), Machine Learning (ML), Industrial Internet of Things (IIoT), cloud computing, and Digital Twin (DT) technology—are increasingly employed for real-time performance monitoring, combustion optimization, predictive maintenance, and operational decision-making. Tao et al. introduced the concept of Digital Twin-driven smart manufacturing, demonstrating how virtual replicas of physical assets can improve process optimization and equipment reliability. More recently, systematic reviews have highlighted the growing adoption of digital twin technology across the power generation sector, particularly for condition monitoring, predictive diagnostics, and efficiency enhancement of thermal power plants.

Digital twin technology enables continuous synchronization between physical equipment and numerical models using real-time sensor data. Such systems allow operators to evaluate multiple operating scenarios, optimize combustion parameters, predict component degradation, and schedule maintenance before failures occur. Industrial implementations have shown that digital twin-assisted optimization can improve thermal efficiency by approximately 0.4–0.6%, reduce auxiliary power consumption, minimize NO_x emissions, and lower maintenance costs through predictive analytics. The integration of AI algorithms with digital twins further enhances operational flexibility under varying load conditions, making them valuable tools for next-generation intelligent thermal power plants.

In addition to digitalization, Computational Fluid Dynamics (CFD), finite element analysis, and exergy analysis have become indispensable numerical tools for analyzing the thermo-fluid behavior of boilers, turbines, condensers, and heat exchangers. These techniques enable detailed visualization of combustion processes, heat transfer mechanisms, fluid flow, and irreversibility distribution within power plant components. Numerical simulations provide valuable information for design optimization while substantially reducing experimental cost and development time. Consequently, CFD-assisted optimization has become an integral part of boiler redesign, combustion enhancement, and thermal management studies.

Environmental sustainability has also become a major driver for technological innovation in thermal power generation. Carbon Capture, Utilization and Storage (CCUS), biomass co-firing, hydrogen blending, ammonia co-firing, and supercritical carbon dioxide (sCO_2) Brayton cycles are being actively investigated to reduce greenhouse gas emissions while maintaining reliable electricity generation.

Among these technologies, CCUS is considered one of the most promising pathways for decarbonizing existing fossil fuel-based power plants, whereas hydrogen and ammonia co-firing provide practical transition strategies toward low-carbon energy systems. Furthermore, the integration of renewable energy sources with conventional thermal plants is promoting the development of flexible operating strategies capable of supporting future smart electrical grids.

Although significant advances have been achieved in individual research areas, most published studies concentrate on specific technologies independently, such as supercritical steam cycles, waste heat recovery, digital twins, artificial intelligence, or carbon capture. Comprehensive reviews that systematically evaluate these technologies from a unified perspective and examine their combined influence on thermal efficiency, operational reliability, economic feasibility, and environmental sustainability remain relatively scarce. In addition, limited attention has been devoted to the synergistic integration of advanced materials, intelligent digital technologies, thermodynamic optimization, and low-carbon solutions for the development of next-generation smart thermal power plants. These gaps highlight the need for a comprehensive review that consolidates recent technological developments and identifies future research directions for improving thermal power plant efficiency.

III. RESEARCH GAP

Substantial research has been carried out on improving thermal power plant performance through advanced steam cycles, waste heat recovery systems, computational modeling, digitalization, and carbon mitigation technologies. However, most existing studies investigate these technologies independently and focus on specific components or operational strategies. Comprehensive review articles that critically integrate recent developments in supercritical and ultra-supercritical technologies, Industry 4.0 applications, digital twin technology, artificial intelligence, advanced engineering materials, waste heat recovery, and low-carbon technologies are relatively limited. Furthermore, the synergistic implementation of these technologies for achieving highly efficient, intelligent, and environmentally sustainable thermal power plants has not been comprehensively discussed. Therefore, a systematic review integrating these emerging technologies is required to provide a holistic understanding of current developments, technological challenges, and future research opportunities.

IV. MOTIVATION

Growing environmental concerns, stringent emission regulations, increasing fuel costs, and the global transition toward sustainable energy systems have accelerated the need for highly efficient thermal power generation technologies. Although renewable energy sources are expanding rapidly, thermal power plants will continue to play a significant role in ensuring reliable base-load electricity generation for the foreseeable future. Consequently, improving plant efficiency through advanced technologies remains an important research priority for reducing fuel consumption, minimizing greenhouse gas emissions, and enhancing operational reliability.

V. OBJECTIVES OF THE WORK

The primary objectives of this review are:

1. To comprehensively review recent technological advancements for improving thermal power plant efficiency.
2. To critically evaluate the performance of advanced steam cycles, waste heat recovery systems, digital technologies, and advanced engineering materials.
3. To analyze the role of computational techniques, artificial intelligence, and digital twin technology in modern thermal power plants.
4. To identify current research gaps, technological challenges, and future directions for developing intelligent, efficient, and environmentally sustainable thermal power generation systems.

VI. COMPARATIVE ANALYSIS AND CRITICAL DISCUSSION

6.1 Performance Improvement through Advanced Steam Cycle Technologies.

The reviewed studies consistently demonstrate that advanced steam cycle technologies significantly improve the thermal efficiency of thermal power plants. Conventional subcritical power plants generally operate at efficiencies ranging from 35% to 38%, whereas supercritical (SC) and ultra-supercritical (USC) plants achieve efficiencies of approximately 42–48% due to higher steam pressure and temperature. The adoption of advanced nickel-based alloys and creep-resistant ferritic steels enables reliable operation under severe thermal conditions, thereby increasing power output while reducing specific coal consumption and greenhouse gas emissions. (Tab.1). The comparative analysis indicates that USC technology provides approximately 20–25% lower specific fuel consumption than conventional subcritical plants while substantially reducing CO_2 emissions.

6.2 Effect of Waste Heat Recovery

Waste heat recovery remains one of the most economical approaches for improving overall plant efficiency. Technologies such as economizers, regenerative feed water heaters, air preheaters, and Organic Rankine Cycle (ORC) systems effectively recover thermal energy from exhaust gases that would otherwise be lost to the environment. Published studies report that waste heat recovery systems can improve plant efficiency by 3–7%, depending on flue gas temperature, plant capacity, (Tab.2) and operating conditions. Besides improving efficiency, these systems reduce auxiliary fuel consumption and contribute to lower operating costs.

The literature confirms that integrating multiple heat recovery devices provides greater efficiency gains than individual technologies operating independently.

6.3 Impact of Artificial Intelligence and Digital Twin Technology

Recent advancements in Industry 4.0 technologies have transformed thermal power plant operation through intelligent monitoring and predictive optimization. Artificial Intelligence (AI), Machine Learning (ML), Industrial Internet of Things (IIoT), and Digital Twin (DT) technologies enable continuous monitoring of plant performance, combustion optimization, equipment fault diagnosis, and predictive maintenance. Digital twin technology allows real-time synchronization between physical equipment and numerical models, enabling operators to optimize combustion, predict component degradation, and minimize maintenance downtime. AI-assisted optimization has been reported to reduce heat rate, improve boiler efficiency, and increase equipment availability through continuous operational adjustments (Tab.3). The integration of intelligent monitoring systems has resulted in improved operational reliability, reduced maintenance costs, and enhanced overall plant performance.

Table 1. Thermal Efficiency of Various Technologies

Technology	Steam Pressure (bar)	Steam Temperature	Thermal Efficiency (%)
Subcritical	170–180	540	35–38
Supercritic	240–250	565	40–43
Ultra-	280–300	600–620	44–48

Table 2. Efficiency Enhancement Techniques

Techniques	Enhancement
Waste Heat Recovery Technique	Efficiency Improvement (%)
Economizer	1–2
Air Preheater	1–3
Feed water Heater	2–4
Organic Rankine	3–7

Table 3. Technology Materialization

Technology	Efficiency Improvement	Technology Maturity
Supercritical	High	Commercial
Ultra-	Very High	Commercial
Waste	Moderate	Commercial
AI-Based	Moderate	Emerging
Digital Twin	Moderate	Emerging
Advanced	High	Commercial
Carbon	Moderate	Developing
Hydrogen	High	Pilot Scale

6.4 Advanced Materials and Component Performance

Material development has played a crucial role in increasing steam temperature and pressure in modern thermal power plants. Advanced ferritic steels, nickel-based superalloys, ceramic coatings, and thermal barrier coatings have significantly enhanced the durability and reliability of boilers, steam turbines, and heat exchangers operating under extreme conditions. Improved material properties have enabled higher operating temperatures without compromising structural integrity, thereby directly contributing to increased thermal efficiency and extended component life. Recent investigations also highlight the growing use of nanostructured coatings to improve heat transfer while minimizing corrosion and oxidation.

6.5 Environmental Performance and Carbon Reduction

Improving thermal efficiency directly reduces greenhouse gas emissions by lowering specific fuel consumption. Emerging technologies such as Carbon Capture, Utilization and Storage (CCUS), hydrogen co-firing, ammonia co-firing, and supercritical carbon dioxide (sCO_2) power cycles further enhance the environmental sustainability of thermal power generation. Among these technologies, CCUS offers substantial potential for reducing carbon emissions from existing coal-fired power plants, whereas hydrogen and ammonia blending provide promising transition pathways toward carbon-neutral electricity generation.

6.6 Comparative Analysis of Recent Technologies

A comparative evaluation of the reviewed technologies indicates that no single technology alone can maximize plant efficiency. Instead, the integration of advanced steam cycles, waste heat recovery, intelligent digital technologies, advanced materials, and emission control systems provides the greatest improvement in overall plant performance. The literature suggests that integrating these technologies can increase the overall thermal efficiency of modern thermal power plants from approximately 38% to nearly 47%, while significantly reducing fuel consumption and carbon emissions. The convergence of advanced thermodynamic cycles, computational modeling, and intelligent digital technologies is expected to play a decisive role in the development of next-generation smart thermal power plants.

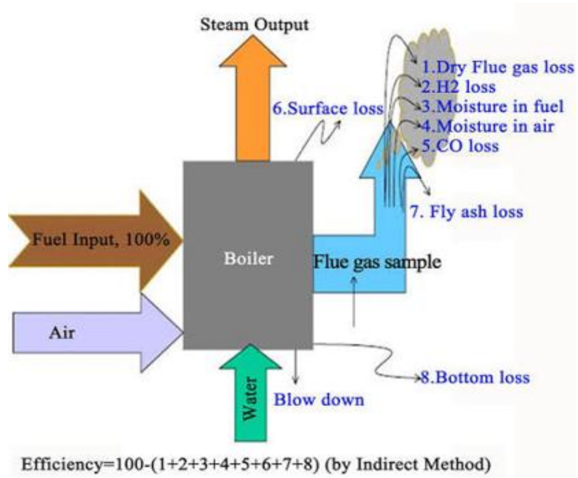

Figure 1. Efficiency calculation of Boiler

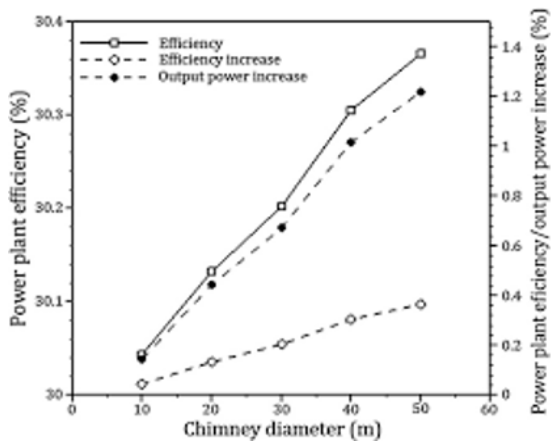

Figure 2. Efficiency enhancement of power plant

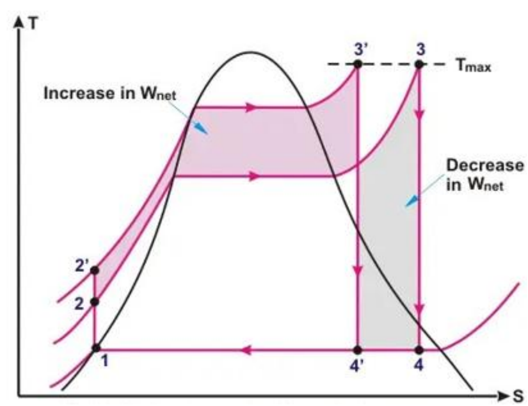

Figure 3. Variation of work output

V. CONCLUSION

Thermal power plants continue to play a significant role in meeting the growing global electricity demand despite the rapid expansion of renewable energy technologies. Improving their thermal efficiency has become essential to reduce fuel consumption, operating costs, and greenhouse gas emissions while ensuring reliable and sustainable power generation. This review comprehensively examined recent technological developments aimed at enhancing thermal power plant performance, including advanced supercritical and ultra-supercritical steam cycles, waste heat recovery systems, advanced boiler and turbine technologies, Computational Fluid Dynamics (CFD), artificial intelligence, digital twin technology, predictive maintenance, advanced engineering materials, and carbon capture and utilization strategies.

The reviewed literature demonstrates that significant improvements in plant efficiency can be achieved through the integration of advanced thermodynamic cycles, intelligent monitoring systems, and optimized heat recovery techniques. Furthermore, the adoption of Industry 4.0 technologies, such as artificial intelligence, machine learning, Industrial Internet of Things (IIoT), and digital twins, has transformed conventional thermal power plants into intelligent systems capable of real-time performance monitoring, predictive maintenance, and operational optimization. Emerging low-carbon technologies, including carbon capture, hydrogen co-firing, ammonia co-firing, and supercritical carbon dioxide power cycles, further contribute to improving environmental sustainability while maintaining reliable power generation.

Although considerable progress has been achieved, challenges related to high capital investment, material durability under extreme operating conditions, system integration, cyber security, and large-scale commercial implementation remain significant. Future research should therefore focus on the synergistic integration of advanced materials, digital technologies, intelligent optimization algorithms, and low-carbon energy systems to maximize plant efficiency and operational flexibility. Overall, the convergence of advanced thermal engineering, computational modeling, and smart digital technologies provides a promising pathway toward the development of highly efficient, economically viable, and environmentally sustainable next-generation thermal power plants.

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REFERENCES

[1] Beer, J. M. (2007). High efficiency electric power generation: The environmental role. *Progress in Energy and Combustion Science*, 33(2), 107–134. https://doi.org/10.1016/j.pecs.2006.09.001

[2] International Energy Agency (IEA). (2023). *World Energy Outlook 2023*. Paris: International Energy Agency.

[3] International Energy Agency (IEA). (2024). *Electricity 2024: Analysis and Forecast to 2026*. Paris: International Energy Agency.

[4] El-Emam, R. S., & Dincer, I. (2013). Energy and exergy analyses of integrated steam power plants: A review. *Renewable and Sustainable Energy Reviews*, 21, 152–173.

[5] Bianchi, M., & De Pascale, A. (2011). Bottoming cycles for electric energy generation: Organic Rankine Cycle applications. *Applied Energy*, 88(5), 1500–1509.

[6] Nemade, A. C., & Ponsankar, S. (2020). Efficiency improvement in thermal power plants using waste heat recovery of flue gas – Simulation study. *IOP Conference Series: Materials Science and Engineering*, 912, 042015.

[7] Tao, F., Zhang, M., Liu, Y., & Nee, A. Y. C. (2019). Digital Twin driven smart manufacturing. *Journal of Manufacturing Systems*, 48, 157–169.

[8] Pan, S. Y., Du, M. A., Huang, I. T., Liu, I. H., Chang, E. E., & Chiang, P. C. (2018). Strategies on implementation of carbon capture, utilization and storage (CCUS). *Journal of Cleaner Production*, 183, 608–621.

[9] Cengel, Y. A., & Boles, M. A. (2019). *Thermodynamics: An Engineering Approach* (9th ed.). McGraw-Hill Education.
[10] Nag, P. K. (2021). *Power Plant Engineering* (5th ed.). McGraw-Hill Education.
[11] Moran, M. J., Shapiro, H. N., Boettner, D. D., & Bailey, M. (2018). *Fundamentals of Engineering Thermodynamics* (9th ed.). John Wiley & Sons.
[12] Boyce, M. P. (2021). *Gas Turbine Engineering Handbook* (5th ed.). Elsevier.