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Thermodynamic Analysis of Steam Power Plants: A Systematic Review of Efficiency Improvement Strategies

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ABSTRACT

This systematic review critically examines strategies for enhancing the thermodynamic efficiency of steam power plants, focusing on advanced cycle configurations, component-level optimizations, and waste heat recovery systems. While supercritical and ultra-supercritical cycles offer significant efficiency gains (up to 45-50%), they entail high capital costs and technical challenges due to extreme operating conditions. Component-level optimizations, such as improved boiler and turbine designs, present a more feasible and cost-effective approach, though with limited cumulative impact. Waste heat recovery systems, particularly Organic Rankine Cycles (ORCs), show promise but are highly context-dependent. The review underscores the environmental benefits of reduced fuel consumption and emissions but highlights the need for comprehensive life-cycle assessments. Emerging technologies like supercritical CO_2 cycles offer potential but face scalability challenges, emphasizing the need for further research and integration of multiple strategies.

Keywords: Steam Power Plants, Thermodynamic Efficiency, Efficiency Improvement Strategies

1. Introduction:

Steam power plants have been a cornerstone of global energy production for over a century, providing a reliable and scalable means of generating electricity (Mirandola et al., 2015; Martelli et al., 2021; Madu 2018). They account for a significant portion of the world's power supply, particularly in regions where coal, natural gas, or nuclear energy serves as the primary fuel source (Bakhtar, 2004). According to Mihai & Toma (2023) fossil fuel-based power plants, including steam power plants, contributed approximately 60% of global electricity generation in recent years, underscoring their continued relevance in the energy mix. However, the thermodynamic efficiency of conventional steam power plants, typically based on the Rankine cycle, remains a critical concern (Gülen, 2021). The average efficiency of coal-fired steam power plants, for instance, hovers around 33–40%, with older plants operating at even lower efficiencies (Termuehlen & Emsperger, 2003). This inefficiency not only leads to excessive fuel consumption but also results in higher greenhouse gas (GHG) emissions, exacerbating climate change and environmental degradation. As global energy demand continues to rise, projected to increase by nearly 50% by 2050 (Dorian et al., 2020), improving the efficiency of steam power plants has become a pressing priority to ensure energy security, reduce operational costs, and mitigate environmental impacts (Sharma, 2023; Ibrahim et al., 2010; Madu 2018).

Despite the extensive body of research on steam power plant efficiency, there remains a notable gap in the literature regarding a comprehensive and systematic analysis of efficiency improvement strategies. While numerous studies have explored individual approaches, such as advanced thermodynamic cycles, component-level optimizations, and waste heat recovery systems, these investigations are often fragmented and lack a holistic perspective. For example, studies on supercritical and ultra-supercritical cycles focus primarily on the benefits of higher operating temperatures and pressures (Tan, 2012), while research on waste heat recovery emphasizes the potential of Organic Rankine Cycles (ORCs) for low-grade heat utilization (Loni et al., 2021). However, there is limited integration of these strategies into a unified framework that evaluates their collective impact on overall plant efficiency. Furthermore, existing reviews often fail to address the practical challenges and trade-offs associated with implementing these strategies, such as high capital costs, technological limitations, and operational complexities. This fragmentation in the literature underscores the need for a systematic review that synthesizes and critically evaluates the diverse range of efficiency improvement strategies, providing a comprehensive understanding of their potential and limitations. However, the objective of this paper is to systematically review and analyze efficiency improvement strategies in steam power plants, with a focus on their thermodynamic principles, performance metrics, and practical applications. By employing a systematic literature review (SLR) methodology, this study aims to identify, evaluate, and synthesize the most effective strategies for enhancing the efficiency of steam power plants. The SLR approach ensures a rigorous and transparent process, minimizing bias and enhancing the reproducibility of the findings. This methodology involves a structured search of peer-reviewed literature, followed by a critical appraisal of the selected studies to extract relevant data and insights. The systematic nature of this review allows for a comprehensive assessment of both established and emerging strategies, providing a balanced perspective on their feasibility and effectiveness.

2. Methodology

The methodology employed in this systematic review follows a rigorous and transparent approach to ensure comprehensive coverage and minimize bias in the analysis of efficiency improvement strategies for steam power plants. The Scopus database was selected as the primary source for this review due to its extensive coverage of peer-reviewed literature in engineering and energy sciences. The systematic review process adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009). The search strategy was carefully designed to capture relevant studies published between 2015 and 2025, focusing on thermodynamic analysis and efficiency improvement in steam power plants. Key search terms included combinations of "steam power plant," "thermodynamic analysis," "efficiency improvement," and related synonyms. Boolean operators and wildcards were used to refine the search and ensure comprehensive coverage. The initial search yielded a substantial number of articles, which were then subjected to a multi-stage screening process. In the first stage, titles and abstracts were reviewed to exclude studies that did not meet the inclusion criteria. The inclusion criteria encompassed original research articles, review papers, and conference proceedings that specifically addressed thermodynamic efficiency improvements in steam power plants. Studies focusing solely on other types of power plants or those not presenting quantifiable efficiency improvements were excluded. In the second stage, full-text articles were assessed for eligibility based on predetermined quality criteria. These criteria included the clarity of methodology, robustness of data analysis, and relevance to the research question. However, data extraction from the selected studies was performed using a structured form to ensure consistency. Extracted information included study characteristics, efficiency improvement strategies, quantitative performance metrics, and implementation challenges. The extracted data were then synthesized to identify common themes, trends, and gaps in the literature. A critical aspect of the methodology was the evaluation of the identified efficiency improvement strategies across three key dimensions: technical feasibility, economic viability, and environmental impact. This multi-criteria assessment approach provides a holistic view of each strategy's potential and limitations (Ahmadi & Toghraie, 2016;(Ateekh-Ur-Rehman & Alkahtani, 2017). To enhance the reliability of the findings, a narrative synthesis approach was adopted, complemented by quantitative analysis where possible. This approach allowed for a nuanced interpretation of the diverse strategies and their contextual factors ((Rodgers et al., 2009). One limitation of this methodology is the exclusive use of the Scopus database, which may have led to the omission of relevant studies not indexed in this platform. Future reviews could benefit from including additional databases to ensure even broader coverage. Additionally, the rapid pace of technological advancements in the field necessitates regular updates to the review to maintain its relevance. Despite these limitations, the systematic and transparent nature of this methodology provides a solid foundation for synthesizing current knowledge on efficiency improvement strategies in steam power plants. The rigorous approach to study selection, data extraction, and analysis enhances the reliability and reproducibility of the findings, contributing valuable insights to both researchers and practitioners in the field of thermal power engineering.

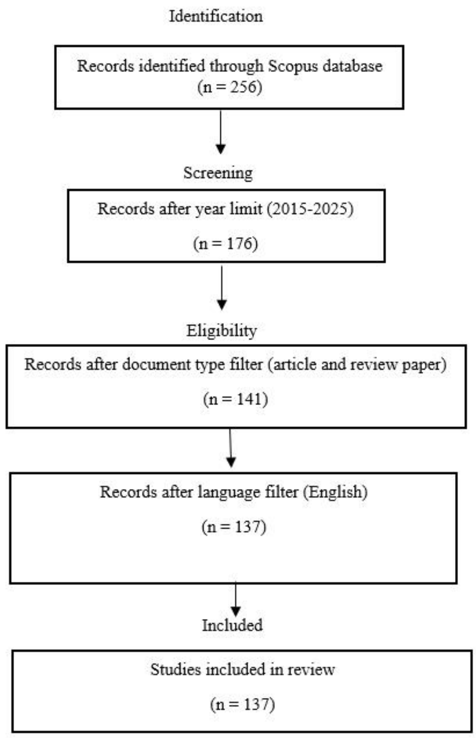

Figure 1: PRISMA Method Flow Representation

3.1 Results

3.1.1 Key Strategies for Improving thermodynamic efficiency

The systematic review of the literature reveals several key strategies for improving the thermodynamic efficiency of steam power plants. These strategies can be broadly categorized into advanced cycle configurations, component-level optimizations, and waste heat recovery systems. Advanced cycle configurations, such as supercritical and ultra-supercritical steam cycles, have emerged as promising approaches to enhance overall plant efficiency. By operating at higher temperatures and pressures, these cycles can achieve thermal efficiencies of up to 45-50%, significantly surpassing conventional subcritical cycles (Tan, 2012). However, the implementation of such cycles requires advanced materials capable of withstanding extreme conditions, which can increase capital costs and pose technical challenges (Gülen, 2021). Component-level optimizations focus on enhancing the performance of individual elements within the steam cycle. For instance, improvements in boiler design and combustion efficiency can lead to substantial gains in overall plant performance (Ahmadi & Toghraie, 2016). Advanced turbine designs, including multi-stage and reheat configurations, have also shown potential for increasing cycle efficiency (Rogalev et al., 2021). Waste heat recovery systems represent another critical area for efficiency improvement. The integration of Organic Rankine Cycles (ORCs) for low-grade heat utilization has gained significant attention, with studies reporting potential efficiency improvements of 2-5% (Loni et al., 2021). Additionally, the use of regenerative feedwater heating and steam extraction for district heating can further enhance overall energy utilization (Xu et al., 2015). Emerging technologies, such as supercritical CO2 cycles, show promise for future power plant designs. These cycles offer potential efficiency gains and reduced plant footprint compared to traditional steam cycles (Stamatellos & Stamatelos, 2022). However, their practical implementation at large scales remains a challenge. It is important to note that the effectiveness of these strategies can vary depending on factors such as plant size, fuel type, and local conditions. Furthermore, the synergistic effects of combining multiple strategies are not always well understood, highlighting the need for further research in this area (Martelli et al., 2021). While these strategies offer significant potential for efficiency improvements, their implementation often involves trade-offs between technical feasibility, economic viability, and environmental impact. A holistic approach that considers these factors is crucial for the successful adoption of efficiency improvement measures in steam power plants.

Table 1: Key Strategies for Improving Thermodynamic Efficiency

Theme	Subtheme	Code	Supporting Quote	Author(s)
Cycle Modification	Turbine Configuration	Multi-Stage Expansion	*"Single-stage turbines in a normal OTEC cycle is replaced with a two-stage turbine with reheating between stages"*	(Hoseinzadeh et al., 2024)
	Reheat and Regenerative Cycles	i. Reheat cycles ii. Regenerative feedwater heating iii. Interrupted regeneration	*"Reheat cycles did not show a remarkable increase in performance with respect to Simple Rankine cycles." "Regeneration process can be interrupted to provide cogeneration heat."*	(Xu et al., 2015)
	Supercritical and Ultra-Supercritical Cycles	High-pressure operation 9. High-temperature operation 10. Efficiency gains	*"For pressures above 25 MPa, efficiency increases are limited." "Supercritical cycle was found advantageous for the applications studied."*	
	Cycle Enhancements	Reheat	*"Recompression cycle versions, together with reheat, appear able to reach the SunShot target of 50% cycle efficiency, even with dry cooling." (This refers to sCO2 cycles, but reheat is also a strategy used in steam plants).*	(Stamatellos & Stamatelos, 2022)
		LP Turbine Size Reduction	*"However, the primary aim of this modification is to reduce the size of the power unit by decreasing the low-pressure*	

	Szewalski Cycle Rationale: Addressing Steam Turbine Limitations		*steam turbine cylinder and the steam condenser. The reduction of the "cold end" of the turbine is desirable from economic and technical standpoints."*	(Kowalczyk et al., 2015)
		Economic Benefits of Size Reduction	*"This process leads to an increased gross efficiency of the power plant gross and a decreased specific investment and maintenance costs"*	
	High-Temperature Steam Cycle Benefits	Supercritical Steam Cycle	*"According to Szewalski, a supercritical steam cycle is preferred due to its high efficiency in the primary part of the cycle." (This highlights the existing advantages of supercritical steam plants relative to subcritical ones.)*	
	Configuration of components significantly impacts the efficiency	Configuration of components	*Khan proposed and investigated the energy and exergy analysis of five different configurations of the combined cycle plant. Result proves that the performance of the combined cycle is significantly affected by the configuration achieved by combination of plant components.*	(Khan, 2021)
Control and Optimisation	Advanced Control Systems	1) Real-time monitoring 2) Predictive maintenance	*"Advanced control systems for optimizing plant performance." "AI and machine learning for predictive maintenance."*	(Xu et al., 2015)
	Sensitivity Analysis	3) Parameter optimization 4) LCOE reduction	*"Sensitivity analysis results enabled quantifying the impact on economic viability of key factors such as cycle temperatures, efficiencies, and capital costs."*	
	Alternative Heat Sources	Condenser Outlet Water	*"Using the output warm water from the condenser of the thermal power plant instead of sea level water lead to improving the performance of the OTEC cycle"*	(Hoseinzadeh et al., 2024)
	Air Management	Reduce excess air	*"decreasing combustion excess air from the fraction 0.4–0.15, energy and exergy efficiencies respectively increase to 0.19% and 0.37%"*	(Ahmadi & Toghraie, 2016)

	Load Management	Maintain nominal load	*"it is better that power plant always works in its nominal load in order to increase the efficiencies"*	
	Thermodynamic Cycle Analysis	Performance Parameters	*"Thermodynamic cycle analysis and optimizing its parameters" can enhance system efficiency*	(Hoseinzadeh et al., 2024)
	Recuperator Optimization: Importance of Recuperator Effectiveness	Recuperator Impact on Efficiency;	*"As revealed by the energy and exergy analysis of a realizable version of a recompression Brayton cycle with sCO2 in the current work, the exergy loss associated with the recuperators practically sets the limits of the attainable efficiency of the cycle and the power plant."*	(Stamatellos & Stamatelos, 2022)
	Component-Level Improvements: Boiler Optimisation	Boiler Exergy Losses High	*"...the maximum exergy losses of 68.27% happen in the boiler." This implicitly suggests boiler optimization as a key target.*	
	Load Management	Efficiency varies with load	*"The evaluation shows an improvement in overall energy efficiency with load percentage increase and reduced exergy efficiency…the operation of the plant below 56 percent of the designed capacity outcomes in a substantial rise in the effectiveness of the exergy..."*	(Sairamkrishna et al., 2019)
	Minimizing Part-Load Operation (Below 56% Design)	Avoid Low-Load Operation	*(Implied: Operating at higher load factors, above 56% of design capacity, improves energy efficiency, even though exergy efficiency decreases).*	
	Optimization of Thermodynamic Processes: Minimizing Irreversibilities	Minimizing Temperature and pressure Differentials	*"Respecting these constraints in the design of physical equipment, optimization of the thermodynamic cycle for the TES installation must: (i) minimize temperature differences for heat transfer during storage and recovery, (ii) minimize temperature and pressure differentials for mixing processes, and (iii) to a lesser extent, minimize pressure drop for considered process paths."*	(Kluba & Field, 2019)
Energy	Heat Recovery	Waste Heat Utilization	*"Reclaiming energy losses"*	(Hoseinzadeh et al., 2024)

Reclamation/ Waste Heat Utilization				
	Organic Rankine Cycle (ORC)	• Low-grade heat recovery • ORC integration	*"Organic Rankine Cycle (ORC) for low-grade waste heat recovery."*	(Xu et al., 2015)
	Feed Water Heating	Preheat air entering boiler	*"preheating the air entering the boiler causes an increase in efficiency"*	(Ahmadi & Toghraie, 2016)
	Thermal Energy Storage (TES): Enabling Flexible Power Generation	NPP Flexibility	*"Thus, capital-intensive nuclear facilities may need to adopt innovative technologies that permit maximum thermal output while modulating electrical output to match market-driven pricing."*	(Kluba & Field, 2019)
	Decoupling Thermal and Electrical Output	Maintain Thermal Power	*"An integrated TES installation enables an NPP to efficiently vary generator output while full reactor (thermal) power is maintained."*	
	Economic Benefits of TES	Market Opportunities	*"During periods of reduced demand or excessive green production, thermal energy may be stored to be recovered when dictated by demand or pricing."*	
Temperature Management	Source Temperature Modification	Temperature Increase	"*Increasing the temperature of sources... raising the temperature of the heat source beyond the operating temperature of the cycle"*	(Hoseinzadeh et al., 2024)
	Alternative Heat Sources	Condenser Outlet Water	*"Using the output warm water from the condenser of the thermal power plant instead of sea level water lead to improving the performance of the OTEC cycle"*	
	Temperature Control	Lower exhaust/smoke temperature	*"reducing the temperature of the smoke leaving the chimney from 137 °C to 90 °C, the above efficiencies respectively increase to 0.84% and 2.3%"*	(Ahmadi & Toghraie, 2016)
Working Fluid Selection	Fluid Optimisation	Fluid Properties	*"Choosing suitable working fluids with decent thermodynamic properties like ammonia... could significantly improve the efficiency of the system"*	(Hoseinzadeh et al., 2024)

	Subcritical, Supercritical and Ultra-Supercritical Vapour Conditions	Improve Effectiveness of Coal-Fired Steam Power Plants by Advance Steam Parameters	*"...examined to improve the effectiveness of coal-fired steam power plants by advance steam parameters. This article introduces heat energy plant-based coal research using subcritical, supercritical and ultra-supercritical vapour circumstances."*	(Sairamkrishna et al., 2019)
	Low-Pressure Steam Replacement	ORC Working Fluid Properties	*"In the second part of the cycle, the ORC provides a working fluid with a low specific volume. The objective of this concept is to significantly reduce the LP turbine sizes..."*	(Kowalczyk et al., 2015)
	Nanofluid Advantages	Higher Energetic and Exergetic Efficiencies	*"It is observed that the nanofluids have higher energetic and exergetic efficiencies in comparison to molten salts for the both operating parameters."*	(Abid et al., 2016)
Exergy and Performance Analysis	Loss Identification	Exergy Analysis Importance	*"Exergy analysis is essential in spotting the main system's irreversibilities and optimizing operating conditions to reduce energy and environmental impacts of the energy systems"*	(Stamatellos & Stamatelos, 2022)
	Identifying Loss Locations	Exergy Analysis Importance	*"Exergy assessment can be particularly efficient in defining methods to optimize the efficiency of current activities and plant design while energy equilibrium transfers heat between the device and its environment."*	` (Sairamkrishna et al., 2019)
	Quantifying Irreversibilities	Irreversibility Measurement	*"The loss of exergy, or irreversibility, usually offers quantitative inefficiency measurement of processes."*	
	Targeted Improvements	Component-Specific Analysis	*"Analysis of plant multiple parts shows the general distribution of plant irreversibility among plant parts, identifying those that contribute most too general plant inefficiency."*	
	Loss Quantification and Optimization	Exergy Analysis for Improvement	*"Exergy analysis is an important tool for the optimization of complex thermodynamic processes because energy balance alone does not include entropy generation and therefore*	(Kowalczyk et al., 2015)

			energy quality degradation."	
	Identifying Work Potential Losses	Lost Work Potential Reduction	*"Evaluating exergy at each particular part would improve the performance of the system by reducing the lost work potential."*	(Abid et al., 2016)
	Loss Identification and Minimization	Exergy Destruction Analysis	(The paper uses exergy analysis to identify areas of high irreversibility, implicitly suggesting that reducing exergy destruction improves overall performance.)	(Khan, 2021)
Component improvements	Turbine Efficiency	○ Turbine design ○ Advanced materials ○ Isentropic efficiency	*"For every 10% increase in turbine efficiency, the LCOE is reduced by 9.5%."* *"Turbine efficiency stands out as a promising area for improvement."*	(Xu et al., 2015)
	Heat Exchanger Innovations	1) Printed Circuit Heat Exchangers (PCHE) 2) Shell and tube heat exchangers	*"All high-temperature heat exchangers for CO2 must be printed circuit heat exchangers (PCHE)."* *"Condenser and waste heat recovery exchanger are shell and tube type."*	
	Boiler Optimization	Boiler Exergy Losses High	*"...the maximum exergy losses of 68.27% happen in the boiler."* This implicitly suggests boiler optimization as a key target.	(Sairamkrishna et al., 2019)
	Condenser Optimization	Condenser Energy Losses High	*"...the highest power losses of 49.92% happen in the condenser..."* While this refers to *energy* losses, reducing these losses would improve overall efficiency and suggests focusing on condenser performance.	

`3.1.2 The key strategies for improving the thermodynamics efficiency of a steam power plant perform in terms of technical feasibility, *economic viability, and environmental impact*

The key strategies for improving the thermodynamic efficiency of steam power plants demonstrate varying levels of performance across technical feasibility, economic viability, and environmental impact dimensions. From a technical feasibility standpoint, advanced cycle configurations such as supercritical and ultra-supercritical steam cycles have shown significant potential, achieving thermal efficiencies of up to 45-50% (Tan, 2012). However, these cycles require advanced materials capable of withstanding extreme temperatures and pressures, presenting engineering challenges (Gülen, 2021). Component-level optimizations, including improved boiler designs and advanced turbine configurations, generally offer high technical feasibility and can be implemented in existing plants with varying degrees of modification (Ahmadi & Toghraie, 2016).Waste heat recovery systems, particularly Organic Rankine Cycles (ORCs), demonstrate promising technical feasibility for low-grade heat utilization, though their integration into existing plant designs may require significant modifications (Loni et al., 2021). Emerging technologies like supercritical CO2 cycles show high potential but face challenges in scaling up to commercial applications (Stamatellos & Stamatelos, 2022). Economic viability varies considerably among these strategies. Advanced cycle configurations often require substantial initial investments due to specialized materials and equipment needs. However, their higher efficiencies can lead to long-term fuel savings and reduced operational costs (Rogalev et al., 2021). Component-level optimizations generally offer a more favorable cost-benefit ratio, as they can be implemented incrementally and often have shorter payback periods (Martelli et al., 2021). Waste heat recovery systems, while potentially cost-effective in the long run, may require significant upfront investments. Their economic viability is highly dependent on factors such as fuel prices and the potential for utilizing recovered heat (Xu et al., 2015). The economic feasibility of emerging technologies like supercritical CO2 cycles remains uncertain due to their early stage of development and potentially high initial costs. Environmentally, most efficiency improvement strategies demonstrate positive impacts through reduced fuel consumption and lower greenhouse gas emissions per unit of electricity generated. Advanced cycle configurations and waste heat recovery systems can significantly reduce the carbon footprint of steam power plants (Mirandola et al., 2015). Component-level optimizations also contribute to emissions reduction, albeit to a lesser extent. However, it's crucial to consider the life-cycle environmental impacts of these strategies, including the production and disposal of advanced materials required for high-efficiency cycles (Gülen, 2021). Additionally, the environmental benefits of these improvements may be offset if they lead to increased reliance on fossil fuels due to improved economic competitiveness. The performance of these strategies is further influenced by factors such as plant size, fuel type, and local conditions. For instance, the effectiveness of waste heat recovery systems may vary depending on the availability of suitable heat sinks or district heating networks (Xu et al., 2015). Similarly, the economic viability of advanced cycle configurations may be more favorable in regions with high fuel costs or stringent emissions regulations.

Table 2. Ways the key strategies for improving the thermodynamics efficiency of a steam power plant perform in terms of technical feasibility, economic viability, and environmental impact.

<table>
<tr><th>Theme</th><th>Subtheme</th><th>Code</th><th>Quote</th><th>Citation</th></tr>
<tr><td rowspan="6">Technical Feasibility</td><td>Cycle Modifications</td><td>Use of two-stage turbine with reheating</td><td>"In the proposed cycle, the average output power is increased by 552 kWh per month, and energy and exergy efficiencies are improved by 0.048 % and 0.31 %, respectively."</td><td rowspan="2">(Hoseinzadeh et al., 2024)</td></tr>
<tr><td>Integration with OTEC</td><td>Using warm water from thermal power plant condenser</td><td>"Using the warm water outlet of the thermal power plant condenser, in addition to increasing the thermal efficiency and improving the performance of the OTEC cycle, increased the efficiency of the main thermal power plant."</td></tr>
<tr><td>Optimization of Parameters</td><td>Optimization of pressure ratio, mass flow rate, and temperature difference</td><td>"Optimization of parameters in the proposed cycle, including pressure ratio in the HP turbine, mass flow rate in the LP evaporator, and temperature difference between output ammonia of the LP evaporator."</td><td></td></tr>
<tr><td>Cycle Modifications</td><td>Use of a supplementary steam cycle with an R-turbine</td><td>"In the proposed LPDPP configuration, the super heat of the steam bleeds for the dryer and RH3–RH5 can be reduced aggressively and the net power plant efficiency can be enhanced by using a supplementary steam cycle."</td><td rowspan="3">(Xu et al., 2015)</td></tr>
<tr><td>Integration with Lignite Drying</td><td>Redirecting steam bleeds through a regenerative turbine (R-turbine)</td><td>"The major change is the redirection of the steam bleeds for the dryer and RH3–RH5 from the IPT and LPT through a separate turbine named the Regenerative-turbine (R-turbine)."</td></tr>
<tr><td>Optimization of Parameters</td><td>Reduction of super-heating in steam bleeds</td><td>"The degree of super-heating of the steam bleeds for the dryer and RH3–RH5 decreases dramatically, leading to a reduction in the heat transfer temperature difference and exergy destruction rate."</td></tr>
</table>

	Cycle Configurations	Use of transcritical, recompression, and supercritical CO_2 cycles	*"A thermodynamic analysis helped identify the different power cycle configurations that were of interest due to applicability and potential economic benefits, namely: transcritical, recompression, and supercritical cycle configurations."*	(Alvarez et al., 2025)
	Regeneration and Reheating	Implementation of regeneration and reheating strategies	*"One of the strategies that improves cycle efficiency is regeneration, which is the use of the recovered heat from the high temperature turbine exhaust to pre-heat the compressed CO_2 right before inputting the heat from the heat source."*	
	Optimization of Parameters	Optimization of maximum pressure and temperature	*"For every maximum temperature under fixed cycle conditions, there is a maximum pressure that maximizes the thermal efficiency."*	
	Energy and Exergy Analysis	Identification of energy and exergy losses in boiler components	*"The investigation identifies the chimney as the primary locus of energy dissipation, responsible for a substantial 18% of the total energy input into the steam generator."*	(Abuelnuor et al., 2024)
	Optimization of Combustor	Reduction of exergy destruction in the combustion chamber	*"The combustion chamber exhibits the highest loss rate for exergy, reaching 39.8%."*	
	Heat Exchanger Efficiency	Improving heat exchanger performance	*"The evaporator, contributing to the second-highest exergy loss rate, registers at 12.7% of the entire exergy entering the steam generator at a Boiler Maximum Continuous Rate (BMCR) of 90%."*	
	Energy and Exergy Analysis	Identification of energy and exergy losses in key components	*"The results from the energy analysis show that 69.8% of the total lost energy in the cycle occurs in the condenser as the main equipment wasting energy, while exergy analysis introduces the boiler as the main equipment wasting exergy where 85.66% of the total exergy entering the cycle is lost."*	(Ahmadi & Toghraie, 2016)
	Optimization of the Boiler	Reducing exergy destruction in the boiler	*"The boiler, the main equipment destroying the exergy in the whole cycle, has low exergy efficiency due to reasons such as incomplete combustion process and high temperature difference in the heat transfer process."*	
	Heat Exchanger Efficiency	Improving heat exchanger performance	*"To reduce heat transfer exergy losses in the boiler, temperature difference should be reduced as much as possible and heat transfer area should be increased."*	
	Energy and Exergy Analysis	Identification of energy and exergy losses in key	*"Exergy analysis shows that the exergy loss mainly comes from the throttling process and temperature difference in the phase-changer heat transfer*	

		components	*process."*	(Fu et al., 2020)
	Optimization of MSES	Reducing exergy destruction in the MSES system	*"With optimized Molten-salt energy storage plans, the storage efficiencies increase to 72.6% and 78% via leading the exhaust drains or steam into higher pressure points."*	
	Heat Exchanger Efficiency	Improving heat exchanger performance	*"The heat transfer exergy loss is reduced with multistage heat exchangers and buffer storage tanks, increasing storage efficiency."*	
	Energy and Exergy Analysis	Identification of energy and exergy losses in cogeneration units	*"The thermal economy and exergy efficiency of the condensing unit and the high back pressure unit are analyzed during the heating period, to obtain the advantages of the high back pressure unit."*	(Luan et al., 2024)
	Optimization of Extraction Load	Adjusting steam extraction distribution to optimize operation	*"The study presents the high back pressure unit extracts steam distribution method is adjusted to optimize the operation strategy during the heating period."*	
	Heat Exchanger Efficiency	Improving heat exchanger performance	*"The high back pressure condensers of the two units are connected in series to the heating network and operated in a quality control manner, improving heating efficiency."*	
	Energy and Exergy Analysis	Identification of energy and exergy losses in the cogeneration system	*"The main purpose of the research was to evaluate the effectiveness of the system considered and to assess whether such a three cycle cogeneration system is reasonable."*	(Fic et al., 2015)
	Optimization of Heat Pump Cycle	Reducing exergy destruction through temperature optimization	*"Diminishing temperature difference in the regenerative exchanger causes rapid increase in both efficiencies but also results in increasing heat transfer area."*	
	Heat Exchanger Efficiency	Improving heat exchanger performance	*"The system is equipped with a high-temperature argon heat pump to obtain the temperature level of a heat carrier required by a high-temperature process."*	
Economic Viability	Cost of Implementation	High initial cost of OTEC systems	*"Considering the present shortcomings and its high initial cost required, this system is superior to wind and solar energy stability."*	(Hoseinzadeh et al., 2024)
	Economic Analysis	Need for economic analysis of proposed cycle	*"Performing economic analysis for the proposed cycle."*	
	Revenue from Freshwater Production	Sale of freshwater as a source of revenue	*"Using this high volume of freshwater produced in the proposed cycle, in addition to eliminating the need for water consumption of the entire power plant, the surplus sale of fresh water can*	

			also be a significant source of revenue for the power plant."	
	Cost of Implementation	Increased fixed capital investment (FCI) for auxiliary equipment	*"The fixed capital investment (FCI) of the proposed LPDPP increases by $5.4 M as compared to the reference power plant, but the FCI of the proposed LPDPP only increases by 1.1%."*	(Xu et al., 2015)
	Economic Benefits	Higher net economic benefits due to increased efficiency	*"The net annual economic benefit of the proposed LPDPP reaches $47.6 M, which is $0.9 M greater than that of the conventional one."*	
	Revenue from Efficiency Gains	Increased electricity sales income	*"The proposed LPDPP with greater net electric power output leads to the annual electricity sales income increase from $197.7 M to $199.1 M."*	
	Cost of Implementation	High capital costs for solar field and power block	*"The costs of the solar field and the power block are the largest capital costs. Efficiency increases result in reduction of these costs for the same output power."*	(Alvarez et al., 2025)
	Levelized Cost of Energy (LCOE)	Reduction of LCOE through efficiency improvements	*"For every 10 % increase in the turbine efficiency, the LCOE is reduced by 9.5 %, while reductions in the largest capital costs of the power plant, i.e., the solar field and the power block, could potentially reduce the LCOE by 20 %."*	
	Economic Benefits of Scale	Larger-scale electricity production reduces LCOE	*"As observed in Alternative B, larger-scale electricity production is strongly beneficial for economic viability with increased efficiencies and decreased capital cost to capacity ratios."*	
	Cost of Implementation	Focus on reducing fuel consumption and operational costs	*"Efforts to optimize power generation plants have emerged as crucial strategies to reduce fuel consumption and minimize environmental impact."*	(Abuelnuor et al., 2024)
	Efficiency Improvements	Enhancing boiler efficiency to reduce fuel costs	*"Boiler energy efficiencies are determined at 61.4% at 27% BMCR, 66.4% at 55% BMCR, and 72.4% at 90% BMCR."*	
	Economic Benefits of Scale	Larger-scale operation improves efficiency and reduces costs	*"At 90% BMCR, the energy efficiency increases to 72.4%, demonstrating the influence of boiler load on energy utilization and efficiency."*	
	Cost of Implementation	Focus on reducing fuel consumption and operational costs	*"Combustion process optimization through enough combustion air preheating, creating suitable fuel and air mixing operation, and controlling the amount of combustion excess air at optimal level can reduce exergy loss."*	(Ahmadi & Toghraie, 2016)
	Efficiency Improvements	Enhancing boiler efficiency to reduce	*"Exergy efficiency calculated for the cycle is 35.2%, which is a relatively appropriate efficiency for the steam*	

		fuel costs	*cycle. This is due to designing proper number of feed water preheating heaters and combustion air preheating."*	
	Economic Benefits of Scale	Larger-scale operation improves efficiency and reduces costs	*"Repowering of steam cycle of the power plant can also be an effective and efficient suggestion for increasing production capacity and total efficiency of the units."*	
	Cost of Implementation	Focus on reducing fuel consumption and operational costs	*"Integrating MSES system with the steam cycle in the CFPP is feasible to reduce the MOL, and by optimizing the MSES system scheme, it is possible to achieve higher efficiency with higher investment cost."*	(Fu et al., 2020)
	Efficiency Improvements	Enhancing storage efficiency to reduce fuel costs	*"With the coupled plan including both optimized main steam and re-heat steam energy storage system, the minimum operation load decreases by 80.7 MW, and storage efficiency is 75.1%."*	
	Economic Benefits of Scale	Larger-scale operation improves efficiency and reduces costs	*"The maximum MOL reduction potential of the MSES system was analyzed, with the coupled plan, MOL decreases by 80.7 MW, and storage efficiency is 75.1%."*	
	Cost of Implementation	Focus on reducing fuel consumption and operational costs	*"After adopting high back pressure operation during the heating period, the average reduction in coal consumption for power generation is 97.5 g/kWh."*	(Luan et al., 2024)
	Efficiency Improvements	Enhancing exergy efficiency to reduce fuel costs	*"Exergy efficiency increased by an average of 9.4%, and exergy efficiency of the unit's heating network increased by an average of 19.2%."*	
	Economic Benefits of Scale	Larger-scale operation improves efficiency and reduces costs	*"After the unit adopts optimized allocation of extraction load, the average coal consumption for power generation is reduced by 0.69 g/kWh on the basis of high back pressure heating operation."*	
	Reduction of Thermal Waste	Use of warm water from condenser reduces thermal waste	*"Using the warm water outlet of the thermal power plant condenser, in addition to increasing the thermal efficiency and improving the performance of the OTEC cycle, increased the efficiency of the main thermal power plant and elimination of the environmental problems caused by the discharge of high-volume warm water into sea."*	(Hoseinzadeh et al., 2024)
	Reduction of Carbon Footprint	Integration with renewable energy sources	*"Integration of OTEC systems with other power sources or other technologies like solar power, fossil fuel systems, wind turbines, and membranes are methods that lead to improving the efficiency and*	

Environmental Impact			*performance of the system."*	
	Freshwater Production	Production of freshwater reduces environmental impact	*"Using this volume of fresh water produced, the need to use chemical units in the power plant to produce fresh water also imposes high costs on the power plant. It will also eliminate the use of wells currently used to supply raw water to chemical units."*	
	Reduction of Exergy Destruction	Minimizing exergy destruction in dryers and regenerative heaters	*"The exergy destruction of the dryer is reduced from 14.23 MWth in the conventional LPDPP to 13.25 MWth in the proposed design."*	(Xu et al., 2015)
	Reduction of Greenhouse Gas (GHG) Emissions	Lower coal consumption due to increased efficiency	*"Improving the energy utilization efficiency in lignite fired power plants will play an important role in both reducing coal consumption rate and lessening the immediate impact of the GHG emissions."*	
	Reduction of Thermal Waste	Lower exhaust flue gas temperature and reduced heat loss	*"After the pre-drying process, the evaporated coal-inherent water of flue gas is reduced, and the corresponding acid dew point temperature decreases, leading to lower exhaust flue gas temperature."*	
	Reduction of Carbon Footprint	Integration with renewable solar-thermal energy	*"By integrating two technologies, solar-thermal energy and CO_2 thermodynamic cycles, this investigation strives to provide new knowledge and conclusions that will initiate further research and innovations in these technologies."*	(Alvarez et al., 2025)
	Efficiency Improvements	Higher efficiency reduces fuel consumption and emissions	*"Higher temperatures would make the CO_2 cycle more economically competitive by increasing its efficiency, as solar to electric performance was observed to be slightly lower than that of the conventional steam cycle for the studied temperatures."*	
	Cogeneration Benefits	Combined heat and power (CHP) applications	*"Supercritical cycle technology is advantageous with respect to transcritical cycle technology due to the reduction in cooling equipment costs without a large impact on cycle efficiency."*	
	Reduction of Carbon Footprint	Minimizing environmental impact through efficiency improvements	*"The study emphasizes the importance of implementing targeted strategies to enhance the efficiency of power generation processes, thereby contributing to reduced energy losses and improved environmental sustainability."*	(Abuelnuor et al., 2024)
	Reduction of Exergy Destruction	Reducing exergy destruction in key	*"The combustor system emerges as the primary source of exergy destruction, with losses of 52.8%, 45.7%, and 39.8%*	

		components	*at 27%, 55%, and 90% BMCR, respectively."*	
	Chemical Reaction Optimization	Optimizing chemical reactions to reduce exergy loss	*"The study underscores the pivotal role of chemical reactions as the primary driver of exergy loss within the system."*	
	Reduction of Carbon Footprint	Minimizing environmental impact through efficiency improvements	*"Combustion process optimization and reducing temperature difference of combustion products and steam can reduce exergy loss, contributing to environmental sustainability."*	(Ahmadi & Toghraie, 2016)
	Reduction of Exergy Destruction	Reducing exergy destruction in key components	*"The boiler has the highest potential for optimization, with 85.66% of the total lost exergy in the cycle."*	
	Chemical Reaction Optimization	Optimizing chemical reactions to reduce exergy loss	*"Combustion process is another major factor of exergy loss in the boiler. Optimizing combustion can significantly reduce exergy destruction."*	
	Reduction of Carbon Footprint	Minimizing environmental impact through efficiency improvements	*"Integrating MSES system with CFPP is a promising way to reduce the minimum load and avoid overnight shutdowns, so as that the renewable energy consumption ability could be increased."*	(Fu et al., 2020)
	Reduction of Exergy Destruction	Reducing exergy destruction in key components	*"The exergy analysis of the MSES system reveals a larger exergy loss in the throttling process when exhaust steam out of the reloading heat exchanger mixes with the low pressure steam in the Rankine cycle."*	
	Chemical Reaction Optimization	Optimizing chemical reactions to reduce exergy loss	*"By avoiding energy level downgrade in the storage system, the storage efficiency increases up to 78%."*	
	Reduction of Carbon Footprint	Minimizing environmental impact through efficiency improvements	*"High back pressure cogeneration units can make full use of the waste heat of the spent steam to reduce the unit's cold-end losses, improving the field utilization rate and heating efficiency."*	(Luan et al., 2024)
	Reduction of Exergy Destruction	Reducing exergy destruction in key components	*"Exergy efficiency of steam-water exergy increased by 9.4% on average, while exergy efficiency of the heat network increased by 19.2% on average."*	
	Chemical Reaction Optimization	Optimizing chemical reactions to reduce exergy loss	*"The optimized extraction steam distribution method improves the exergy efficiency of the unit, reducing exergy losses in the heating network."*	

3.2 Discussion

The systematic review of efficiency improvement strategies for steam power plants reveals a complex landscape of technological advancements, economic considerations, and environmental impacts. The key strategies identified, including advanced cycle configurations, component-level optimizations, and waste heat recovery systems, demonstrate varying degrees of effectiveness and applicability across different plant types and operational contexts. Advanced cycle configurations, such as supercritical and ultra-supercritical steam cycles, have shown significant potential for improving thermodynamic efficiency, with reported thermal efficiencies of up to 45-50% (Tan, 2012). However, these advancements come with increased technical complexity and capital costs, primarily due to the need for advanced materials capable of withstanding extreme temperatures and pressures (Gülen, 2021). This trade-off between efficiency gains and implementation challenges highlights the importance of considering both short-term feasibility and long-term benefits in plant upgrade decisions. Component-level optimizations, including improvements in boiler design and turbine configurations, offer a more incremental approach to efficiency enhancement. These strategies often present a favorable balance between technical feasibility and economic viability, as they can be implemented in existing plants with relatively lower upfront costs (Ahmadi & Toghraie, 2016). However, the cumulative impact of these optimizations may be limited compared to more comprehensive plant overhauls. Waste heat recovery systems, particularly Organic Rankine Cycles (ORCs), have emerged as promising solutions for capturing low-grade heat and improving overall plant efficiency. Studies have reported potential efficiency improvements of 2-5% through ORC integration (Loni et al., 2021). However, the effectiveness of these systems is highly dependent on plant-specific factors and the availability of suitable heat sinks or district heating networks (Xu et al., 2015). The environmental impact of these efficiency improvement strategies is generally positive, with reduced fuel consumption leading to lower greenhouse gas emissions per unit of electricity generated (Mirandola et al., 2015). However, the life-cycle environmental impacts, including the production and disposal of advanced materials required for high-efficiency cycles, must be carefully considered (Gülen, 2021). Emerging technologies, such as supercritical CO2 cycles, present intriguing possibilities for future power plant designs but face significant challenges in scaling up to commercial applications (Stamatellos & Stamatelos, 2022). The potential benefits of these technologies, including higher efficiencies and reduced plant footprints, must be weighed against the uncertainties and risks associated with their implementation. The review also highlights the importance of considering the interplay between different efficiency improvement strategies. While individual technologies may offer modest gains, the synergistic effects of combining multiple approaches could lead to more substantial efficiency improvements. However, the complexities of integrating various technologies and optimizing their collective performance remain areas requiring further research and practical demonstration (Martelli et al., 2021).

4. Conclusion

This systematic review of efficiency improvement strategies for steam power plants reveals a complex landscape of technological advancements, economic considerations, and environmental impacts. The study highlights several key strategies, including advanced cycle configurations, component-level optimizations, and waste heat recovery systems, each with varying degrees of effectiveness and applicability. The findings underscore the significant potential for improving thermodynamic efficiency in steam power plants, with advanced cycle configurations demonstrating thermal efficiencies of up to 45-50% (Elwardany et al., 2024). However, these improvements often come at the cost of increased technical complexity and higher capital investments (Gülen, 2021). The review also emphasizes the importance of considering both short-term feasibility and long-term benefits when implementing efficiency enhancement strategies. Component-level optimizations emerge as a more incremental yet economically viable approach, offering a favorable balance between technical feasibility and cost-effectiveness (Ahmadi & Toghraie, 2016). Waste heat recovery systems, particularly Organic Rankine Cycles, show promise for capturing low-grade heat and improving overall plant efficiency, though their effectiveness is highly dependent on plant-specific factors (Loni et al., 2021; Xu et al., 2015). The environmental impact of these strategies is generally positive, with reduced fuel consumption leading to lower greenhouse gas emissions (Mirandola et al., 2015). However, the study highlights the need for a more comprehensive life-cycle assessment of these technologies, considering factors such as the production and disposal of advanced materials. Emerging technologies like supercritical CO_2 cycles present intriguing possibilities for future power plant designs but face significant challenges in scaling up to commercial applications (Stamatellos & Stamatelos, 2022). The review also points to the potential synergistic effects of combining multiple efficiency improvement strategies, an area that requires further research and practical demonstration.

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