WAPRIME
https://welchacademy.com/index.php/prime
e-ISSN: 3062-2743

Efficiency and safety in nuclear power plants from a mechanical engineering perspective

Bilgehan Ucgan *1
[1] National Research Nuclear University MEPhI, Institute of Nuclear Physics and Technologies, Russia, bilgeucgan38@gmail.com

Cite this study: Ucgan, B. (2025). Efficiency and safety in nuclear power plants from a mechanical engineering perspective. WAPRIME, 2(1), 36-43.

https://doi.org/10.5281/zenodo.17049853

Keywords
Nuclear
Mechanical engineering
Safety systems
Nuclear power plant
Efficiency

Research Article
Received:20 May 2025
Revised: 05 June 2025
Accepted: 12 June 2025
Published: 27 August 2025

Abstract

Nuclear power plants (NPPs) are pivotal to low-carbon electricity generation, but their sustainability depends on advancing both thermodynamic efficiency and engineering-based safety. From a mechanical engineering perspective, the performance of turbines, pumps, heat exchangers, and structural materials directly dictates reliability. Conventional pressurized water reactors (PWRs) and boiling water reactors (BWRs) operate with thermal efficiencies of only 32–35%, constrained by coolant conditions, while advanced high-temperature gas-cooled reactors (HTGRs) and molten salt reactors (MSRs) can exceed 40%. Exergy analyses consistently identify steam generators, condensers, and turbines as the main sites of irreversibility, emphasizing the need for component-level optimization. Safety remains equally critical. Lessons from Three Mile Island, Chernobyl, and Fukushima underscore the vulnerability of active safety systems and the necessity for passive cooling, reliable pumps and valves, and radiation-resistant materials. Recent advances in computational fluid dynamics (CFD), additive manufacturing, and high-performance alloys are redefining both efficiency and safety margins. Furthermore, climate change—through heatwaves, droughts, and extreme events—poses growing risks to reactor cooling and resilience. This review concludes that integrating thermodynamic optimization, passive safety systems, advanced materials, and digital monitoring technologies is essential for next-generation NPPs. Key research gaps include hybrid thermodynamic cycles, AI-driven diagnostics, and climate adaptation strategies, offering critical directions for academia and industry alike.

1. Introduction

Energy supply security, climate change mitigation, and sustainable development goals necessitate a fundamental transformation of global energy systems. At the center of this transformation, nuclear energy holds a strategic position due to its low carbon emissions, high energy density, and reliable baseload generation capacity [1]. According to the International Energy Agency, approximately 10% of global electricity production is supplied by nuclear power [2]; in countries such as France, this share reaches up to 70%, illustrating the pivotal role of nuclear energy in national energy security and climate policy [3].

Nuclear power plants (NPPs) operate by converting the heat generated from nuclear fission into electricity through steam turbines based on the Rankine cycle [4]. The thermodynamic performance of these plants is closely tied to the efficiency of turbines, pumps, heat exchangers, and auxiliary systems. Recent studies evaluating thermodynamic trade-offs in nuclear-driven energy systems emphasize the importance of component-level optimization to enhance both power and cooling performance [5]. Similarly, advanced thermal-hydraulic analyses provide critical insights into fluid flow, heat transfer, and reactor cooling safety, making them indispensable tools for plant design and operation [6]. Moreover, research on industrial energy recovery systems also illustrates that efficiency optimization is a cross-sector engineering necessity [7].

From a safety perspective, historical accidents such as Three Mile Island (1979), Chernobyl (1986), and Fukushima Daiichi (2011) revealed that weaknesses in engineering design and failures in cooling systems can escalate into major disasters [8–10]. These events underscored the need for passive safety systems, radiation- and corrosion-resistant materials, and thermohydraulic improvements to ensure reactor reliability.

Nevertheless, a review of the existing literature indicates that research on NPPs has predominantly focused on reactor physics, nuclear fuel cycles, or energy policies [11]. Comprehensive studies addressing both efficiency and safety from a mechanical engineering perspective remain scarce. This article aims to fill this gap by presenting a broad literature review of nuclear power plants from the standpoint of mechanical engineering, with emphasis on thermodynamic efficiency and engineering-based safety approaches.

2. Efficiency Approaches in Nuclear Power Plants

2.1. Thermodynamic Efficiency of Reactor Cycles

The thermal efficiency of conventional pressurized water reactors (PWRs) and boiling water reactors (BWRs) is typically limited to ≈32–35%, primarily due to coolant temperature and pressure constraints that cap the Rankine cycle performance [4, 12]. Advanced concepts—including high-temperature gas-cooled reactors (HTGRs) and molten-salt reactors (MSRs)—can push outlet temperatures higher, enabling ≈40–45% cycle efficiencies when paired with optimized heat-exchanger networks or hybrid layouts [5, 13, 14, 15]. Nuclear-driven hybrid cycles (e.g., sCO_2 Brayton integrated with organic Rankine for hydrogen cogeneration) further illustrate favorable power/cooling trade-offs at elevated source temperatures [5, 16].

Although these constraints are specific to nuclear systems, similar optimization logic applies across energy technologies. For instance, waste-heat recovery in industrial ovens demonstrably improves system performance (methodological analogy) [7], while geometric/configuration optimization in PV systems (e.g., tilt angle) underscores how seemingly simple design choices shift overall conversion efficiency (cross-sector insight) [17]. In addition, improvements in thermal efficiency are closely linked to materials engineering, since advanced alloys and coatings are required to tolerate higher coolant outlet temperatures and prevent corrosion under extreme conditions. Furthermore, studies emphasize that the economic viability of new reactor concepts is strongly dependent on these efficiency gains, as small percentage increases in thermal performance translate into substantial reductions in fuel usage and lifecycle costs. The comparative thermodynamic performance of these reactor types is summarized in Table 1 [4-5, 12-16].

Table 1. Thermodynamic performance of reactor types.

Reactor Type	Typical Outlet T (°C)	Thermal Efficiency (%)	Advantages	Limitations
PWR	280–320	32–34	Mature, reliable, widespread	Limited by coolant temperature/pressure
BWR	270–290	33–35	Direct steam generation	Radioactive steam reaches turbine path
HTGR	700–850	40–45	High efficiency; H_2 co-production potential	High-T materials and sealing challenges
MSR	600–700	40–44	Low-pressure primary loop; strong safety margins	Salt chemistry/corrosion management

2.2. Heat Transfer and Thermohydraulics

Heat-transfer performance governs efficiency (condensers, steam generators) and safety margins (fuel-cladding temperatures). A key limit is the critical heat flux (CHF); exceeding CHF triggers a boiling crisis, rapid wall temperature rise, and potential cladding damage. Consequently, enhanced cladding/coatings and surface engineering are prominent levers to extend the margin to CHF [6, 15].

Modern CFD and multi-scale thermo-hydraulic (TH) simulations are indispensable for capturing two-phase flow, subchannel mixing, and core-wide instabilities; Eulerian two-phase methods and coupled codes are now standard in BWR/PWR analyses and safety transients [12, 18-19]. These tools also quantify maldistribution losses that depress heat-exchange effectiveness (and thus overall cycle efficiency) [6, 19].

Methodologically, viscous heating and near-wall dissipation studies in canonical shear flows (e.g., parallel-plate Couette) provide transferable insight for localized overheating modeling in nuclear channels (analogy) [20]. Likewise, industrial systems' waste-heat recovery/transfer optimization illustrates the universal value of minimizing exergy destruction on the cold side of cycles [7]. The main thermohydraulic challenges and proposed engineering solutions are consolidated in Table 2 [6, 12-13, 15-16, 18-19].

Table 2. Thermohydraulic challenges and solutions.

Challenge	Risk/Impact	Engineering Solutions
Critical Heat Flux (CHF)	Boiling crisis → cladding overheat	Advanced claddings; surface enhancement; improved coolant distribution
Coolant/Working Fluid Choice	Lower T/pressure → capped efficiency	Helium (HTGR), molten salts (MSR), sCO_2 in secondary/hybrid cycles
Two-Phase CFD & Coupled TH	Uncertainty in boiling & instabilities	Eulerian two-phase CFD; multi-scale coupled codes; validation vs. experiments

2.3. Turbine and Pump Performance

Because nuclear steam conditions are typically cooler than those in ultrasupercritical fossil plants, steam-turbine sections in NPPs suffer larger moisture fractions, causing aerodynamic losses and wet-steam erosion that can dominate exergy destruction in the turbine train [5, 21-22]. Documented mitigations include last-stage blade redesign, moisture separators/reheaters, and improved low-pressure path aerodynamics [21-22].

On the primary side, reactor coolant pumps (RCPs) operate under demanding hydraulic and seismic environments; cavitation, vibration/fatigue, and off-design transients reduce reliability and efficiency [6, 22-23]. Proven strategies include condition monitoring, reliability-centered maintenance, optimized impeller/hub geometries, and (for specific designs) bearing/shaft innovations to maintain margin against instabilities [23], with seismic qualification and dynamic response modeling integral to AP-PWR architectures [22]. Cross-sector evidence also shows how working-fluid choice and evaporator architecture shift compressor/pump loads and overall COP—an analogy supportive of coolant/pump co-optimization in NPP balance-of-plant [14]. Key efficiency-impacting issues in turbines and pumps are summarized in Table 3 [5-6, 21-23].

Table 3. Efficiency factors in turbines and pumps.

Component	Dominant Losses/Issues	Engineering Solutions
Steam Turbine (LP path)	Wet-steam erosion; last-stage aero losses	Blade profile redesign; moisture separation/reheat; optimized exhaust
Reactor Coolant Pumps	Cavitation; vibration/fatigue; seismic response	Condition monitoring; hydraulic redesign; dynamic qualification

3. Safety Approaches in Nuclear Power Plants

3.1. Historical Lessons and Core Safety Challenges

The safety of nuclear power plants (NPPs) has been significantly shaped by major historical accidents—Three Mile Island (1979) [8], Chernobyl (1986) [9], and Fukushima Daiichi (2011) [10]. These events revealed that cooling-system failures, insufficient redundancy, and inadequate operator support can escalate to catastrophic outcomes. Mechanical engineering aspects, including pump reliability, valve actuation, and passive heat removal, played critical roles in accident progression [6].

Additionally, the emergence of Small Modular Reactors (SMRs) has introduced a design philosophy where safety is integrated through modularity and inherent passive features [24]. However, challenges such as seismic qualification, coolant stability, and containment scaling remain prominent [22, 23]. The main engineering lessons from these accidents are summarized in Table 4 [6, 8–10, 22–24].

Table 4. Major nuclear accidents and engineering lessons.

Accident	Year	Key Failure	Mechanical Engineering Lessons
Three Mile Island	1979	Cooling system malfunction; operator error	Need for automated control; pump/valve redundancy
Chernobyl	1986	Positive void coefficient; design flaws	Importance of inherent stability and reactivity feedbacks
Fukushima Daiichi	2011	Loss of off-site power; tsunami flooding	Passive heat removal, seawater pump resilience

3.2. Passive Systems and Mechanical Reliability

Post-Fukushima reactor designs emphasize passive safety systems—gravity-driven cooling, natural circulation loops, and air-cooled heat exchangers—as essential complements to active systems [6, 13]. Experimental and computational studies confirm that such systems can extend coping time significantly without operator intervention [15, 19].

From a mechanical reliability perspective, reactor coolant pumps (RCPs) remain vital for safe operation. Seismic analyses demonstrate how earthquake loads can destabilize shafts and bearings [22], while hydraulic evaluations highlight cavitation and vibration as long-term risks [23]. Engineering responses include dynamic seismic qualification, impeller redesign, and advanced online monitoring [6]. These improvements are synthesized in Table 5 [6, 13, 15, 19, 22-23].

Table 5. Key Safety Enhancements in Modern NPPs.

Safety Area	Engineering Focus	Example Solutions
Passive Decay Heat Removal	Gravity-driven coolant flow, natural convection	Passive residual heat removal systems
Seismic Safety (RCPs)	Structural dynamics under earthquakes	Shaft alignment models; seismic qualification
Long-term Reliability	Reducing cavitation, vibration	Advanced impeller design; online monitoring

4. Conclusion

This review has shown that the future of nuclear power plants (NPPs) as a sustainable low-carbon energy source directly depends on achieving a dual objective: high thermodynamic efficiency and uncompromised safety. From a mechanical engineering standpoint, both goals are tightly interlinked through the design, performance, and long-term reliability of key components.

On the efficiency side, conventional PWRs and BWRs operate with cycle efficiencies limited to ≈32–35%, largely constrained by coolant temperatures and pressures. However, advanced reactor designs such as HTGRs and MSRs demonstrate the potential to raise cycle efficiencies to ≈45%, while hybrid Brayton–Rankine cycles enable even higher performance and cogeneration opportunities (e.g., hydrogen production). Exergy analyses consistently identify turbines, condensers, and steam generators as the primary sites of irreversibility, highlighting the necessity for equipment-level innovations including improved turbine blade aerodynamics, advanced condensers, and optimized coolant circulation. Efficiency is therefore not simply a thermodynamic problem, but a mechanical engineering challenge involving system integration, materials, and operational strategies.

On the safety side, the historical accidents at Three Mile Island, Chernobyl, and Fukushima revealed the vulnerabilities of active safety reliance, insufficient redundancy, and mechanical system fragilities. These lessons have driven a paradigm shift in modern reactor designs toward passive safety systems, including gravity-driven cooling, natural circulation, and air-cooled emergency heat exchangers. Simultaneously, the reliability of reactor coolant pumps, valves, and structural components has become central to ensuring stable operation under both normal and extreme conditions. Post-Fukushima innovations demonstrate that safety and efficiency are not mutually exclusive, but rather complementary imperatives where passive designs can extend coping times without significantly compromising performance.

Importantly, the review highlights that both efficiency and safety are increasingly shaped by mechanical reliability, materials engineering, and advanced diagnostics. Cavitation-resistant pump designs, irradiation-tolerant alloys, and AI-driven monitoring systems illustrate how modern mechanical engineering directly influences reactor resilience. In addition, small modular reactors (SMRs) introduce new opportunities for inherently safe designs and raise questions on seismic reliability, scaling laws, and passive system validation that require rigorous mechanical and thermal-hydraulic evaluation.

Taken together, the findings underscore that mechanical engineering will remain a cornerstone of nuclear sustainability, ensuring that reactors are designed not only to produce more power with fewer losses but also to resist the most severe external hazards. By integrating advances in thermodynamics, thermohydraulics, and safety systems, nuclear power can strengthen its role as a reliable pillar of the global energy transition and climate mitigation strategies.

5. Discussion

The results of this review confirm that the future role of nuclear energy is contingent upon striking a balance between thermodynamic efficiency and engineering-based safety. While advanced reactor concepts (e.g., HTGRs, MSRs, hybrid Brayton–Rankine systems) can increase efficiency to above 40% [5, 13], they simultaneously demand new materials, enhanced thermal-hydraulic modeling, and reconfigured safety margins [6, 15, 19]. Thus, improving efficiency cannot be decoupled from safety considerations.

A key insight from the mechanical engineering perspective is that most efficiency losses and safety vulnerabilities converge on a few critical components—turbines, steam generators, condensers, and reactor coolant pumps. Exergy analyses show that irreversibilities in turbines and condensers dominate efficiency deficits [5, 21], while cavitation, vibration, and seismic sensitivity in pumps dictate long-term reliability [6, 22-23]. These findings illustrate that solutions such as blade redesign, moisture separation, hydraulic optimization, and seismic qualification are not minor engineering details but core enablers of sustainable nuclear energy.

The safety lessons from historical accidents reinforce this view. The Three Mile Island, Chernobyl, and Fukushima disasters [8–10] demonstrated how cooling-system failures and insufficient passive measures could escalate into systemic crises. Today, the global nuclear industry has responded with passive safety systems, natural convection cooling, and modular reactor designs [13, 24]. However, these advances must be continuously validated against real-world scenarios such as long-duration station blackouts, seismic events, and climate-induced hazards. Mechanical reliability—particularly of pumps, valves, and containment structures—remains the frontline defense.

Another critical discussion point concerns trade-offs versus synergies between efficiency and safety. Traditionally, measures to improve safety (e.g., redundant systems, passive cooling) were viewed as adding cost and reducing efficiency. Yet, emerging evidence suggests that integrated design approaches can yield synergistic benefits: passive systems extend coping times without requiring external power, while advanced heat exchangers improve both safety margins and efficiency. This reinforces the central argument of this review: efficiency and safety are not competing, but converging objectives when analyzed through a mechanical engineering lens.

6. Recommendations

The review findings suggest that efficiency and safety in nuclear power plants (NPPs) can only be improved through an integrated approach combining engineering innovation, advanced modeling, operational strategies, and supportive policies. From a mechanical engineering perspective, several concrete directions for future work can be highlighted.

First, component-level optimization remains essential. Turbines, condensers, steam generators, and reactor coolant pumps are responsible for most of the observed irreversibilities and reliability challenges. Their redesign, supported by new materials and advanced monitoring, should be prioritized to maximize cycle efficiency and operational safety.

Second, passive safety must be embedded into every new generation of reactor designs. Gravity-driven coolant flow, natural circulation loops, and passive residual heat removal systems have proven effective in extending coping times during accidents. Their wider adoption would simultaneously increase safety margins and reduce reliance on external power.

Third, modern analysis and digital tools open new opportunities. High-fidelity CFD and multi-scale thermal–hydraulic simulations can improve predictions of CHF, flow instabilities, and pump hydraulics. Digital twin approaches and AI-based diagnostics will make it possible to detect and prevent failures before they occur, providing real-time resilience to both efficiency losses and safety threats.

Finally, long-term sustainability requires organizational and policy-level action. Condition-based maintenance regimes, accident scenario training, and resilience against external hazards such as earthquakes and flooding should become standard practices. At the same time, cross-disciplinary collaboration and updated international safety standards are vital to ensure that small modular reactors (SMRs) and Generation IV systems achieve both efficiency and inherent safety.

In summary, the following recommendations can be formulated:

- Optimize turbines, condensers, steam generators, and pumps through redesign, new materials, and improved monitoring.
- Integrate passive safety features such as gravity-driven cooling, natural circulation, and air-cooled exchangers as standard practice.
- Expand the use of CFD, multi-scale thermal–hydraulic codes, and digital twin technologies for predictive safety and efficiency management.
- Implement AI-driven, condition-based maintenance strategies to improve reliability and minimize downtime.
- Strengthen training and preparedness for severe accident scenarios, including external hazards like tsunamis and earthquakes.
- Foster cross-disciplinary collaboration between mechanical engineers, nuclear physicists, and materials scientists.
- Update international safety standards and support SMR deployment pathways to ensure reactors are both efficient and intrinsically safe.

Ultimately, achieving high efficiency and uncompromised safety in nuclear power plants is not only a technical necessity but also a global responsibility. By applying mechanical engineering innovations alongside robust safety strategies, nuclear energy can consolidate its role as a cornerstone of the worldwide energy transition and contribute decisively to climate change mitigation.

Author contributions

Bilgehan Ucgan: Conceptualization, Methodology, Data curation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

References

1. International Atomic Energy Agency (IAEA). (2022). *Energy, electricity and nuclear power estimates for the period up to 2050.* IAEA.
2. International Energy Agency (IEA). (2021). *Net zero by 2050: A roadmap for the global energy sector.* IEA. https://www.iea.org/reports/net-zero-by-2050
3. Schneider, M., Froggatt, A., Hazemann, J., Katsuta, T., Ramana, M. V., Rodriguez, J. C., ... & Stienne, A. (2016). The world nuclear industry. *Status Report.*
4. Dincer, I., & Rosen, M. A. (2012). *Exergy: energy, environment and sustainable development*. Newnes.
5. Lou, J., Wang, J., Li, M., Chen, L., Wang, Y., Du, Y., & Zhao, P. (2023). Thermodynamic performance evaluation and power/cooling energy trade-off estimation of an isolated system driven by nuclear energy. *Applied Thermal Engineering*, *234*, 121263.
6. Zohuri, B., & Fathi, N. (2017). *Thermal-hydraulic analysis of nuclear reactors* (pp. 1-835). New York: Springer.
7. Erdoğan, M., & Acar, M. Ş. (2024). Thermodynamic analysis of a tunnel biscuit oven and heat recovery system. *WAPRIME, 1*(1), 1–15.
8. Kemeny, J. G. (1979). Reprot of the President's Commission on the Accident at Three Mile Island. *The need for change: The Legacy of TMI*.
9. Medvedev, Z. (1992). *The legacy of Chernobyl*. WW Norton & Company.
10. International Atomic Energy Agency (IAEA). (2015). *The Fukushima Daiichi accident: Report by the Director General.* IAEA.
11. Adamantiades, A., & Kessides, I. (2009). Nuclear power for sustainable development: current status and future prospects. *Energy Policy*, *37*(12), 5149-5166.

12. Rahman, M. W., Abedin, M. Z., & Chowdhury, M. S. (2023). Efficiency analysis of nuclear power plants: A comprehensive review. *World J. Adv. Res. Rev*, *19*, 527-540.
13. Paydar, A. Z., Balgehshiri, S. K. M., & Zohuri, B. (2023). *Advanced reactor concepts (ARC): a new nuclear power plant perspective producing energy*. Elsevier.
14. Çelik, C. (2024). Performance analysis of DX and flooded evaporators with eco-friendly refrigerants in medium-scale food storage systems. *WAPRIME, 1*(1), 16–25.
15. Lu, D., Su, Q., Ju, P., & Lv, L. (2021). Overview on critical heat flux experiment for the reactor fuel assemblies. *Annals of Nuclear Energy*, *163*, 108585.
16. Wang, Q., Liu, C., Luo, R., Li, D., & Macián-Juan, R. (2022). Thermodynamic analysis and optimization of the combined supercritical carbon dioxide Brayton cycle and organic Rankine cycle-based nuclear hydrogen production system. *International Journal of Energy Research*, *46*(2), 832-859.
17. Tirogo, I. (2024). Effect of different tilt angles on the performance of the different PV panels in Pouytenga, Burkina Faso. *WAPRIME, 1*(1), 45–56.
18. Pointer, W. D., Tentner, A., Sofu, T., Weber, D., Lo, S., & Splawski, A. (2007, April). Eulerian two-phase computational fluid dynamics for boiling water reactor core analysis. In *Joint International Topical Meeting on Mathematics & Computation and Supercomputing in Nuclear Applications (M&C+ SNA 2007), Monterey, California*.
19. Zhang, K. (2020). The multiscale thermal-hydraulic simulation for nuclear reactors: A classification of the coupling approaches and a review of the coupled codes. *International Journal of Energy Research*, *44*(5), 3295-3315.
20. Ünal, E. K. (2024). Analytical and numerical investigation of viscous heating in parallel-plate Couette flow. *WAPRIME, 1*(1), 57–69.
21. Álvarez-Fernández, M., del Portillo-Valdés, L., & Alonso-Tristán, C. (2016). Thermal balance of wet-steam turbines in nuclear power plants: a case study. *Applied Thermal Engineering*, *93*, 598-605.
22. De, C., Zhen-Qiang, Y., Ya-Bo, X., & Hong, S. (2014). Numerical study on seismic response of the reactor coolant pump in Advanced Passive Pressurized Water Reactor. *Nuclear Engineering and Design*, *278*, 39-49.
23. Oh, H. W., Yoon, E. S., & Park, S. J. (2006). Hydraulic performance analysis of an axial-flow main coolant pump for the system-integrated nuclear reactor. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, *220*(6), 635-640.
24. Cooper, M. (2014). Small modular reactors and the future of nuclear power in the United States. *Energy Research & Social Science*, *3*, 161-177.