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# Efficiency analysis of nuclear power plants: A comprehensive review

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## Abstract

Nuclear power plants play a significant role in global electricity generation, offering a reliable and low-carbon energy source. Maximizing the efficiency of nuclear power plants is crucial for optimizing energy output and reducing operational costs while ensuring safety and environmental sustainability. This paper presents a comprehensive review of the efficiency analysis conducted on nuclear power plants, covering various aspects such as thermal efficiency, conversion efficiency, fuel utilization, and overall plant performance. The review synthesizes the existing literature, discusses key factors influencing efficiency, and highlights potential areas for future research and improvements. It is revealed from the present review that the efficiency of the Boiling Water Reactor (BWR) of the Nuclear Power Plant is 32% and which can be increased to 33% by using advanced BWR. Also, the efficiency of the Pressurized Water Reactor (PWR) of the Nuclear Power Plant is 33% and which can be increased to 36.5% by using the PWR with Gas Burner and Reheating. On the other hand, the efficiency of the Small Modular Reactor (SMR) of the Nuclear Power Plant is 33.4% and which can be increased to 35.5%, 37.4% and 45% by using SMR with Gas Burner, SMR with Reheating and SMR with CCGT, respectively. Therefore, it is predicted that the Small Modular Reactor (SMR) is the most economic Nuclear Power Plant as it has higher thermal efficiency when it is incorporated with Combined Cycle Gas Turbine (CCGT).

**Keywords:** Nuclear Power Plant; Heat Transfer; Efficiency; Enhancement; Performance

## 1. Introduction

Nuclear power plants have emerged as a vital component of the global energy landscape, providing a reliable and low-carbon source of electricity. In light of the increasing demand for clean and sustainable energy solutions, maximizing the efficiency of nuclear power plants has become paramount. Efficiency analysis plays a crucial role in evaluating and enhancing the performance of these plants, leading to improved energy output, reduced operational costs, and minimized environmental impact.

This paper presents a comprehensive review of the efficiency analysis conducted on nuclear power plants, aiming to provide a consolidated understanding of the subject matter. By synthesizing existing literature, exploring key factors influencing efficiency, and highlighting potential areas for improvement, this review contributes to the knowledge base surrounding nuclear power generation.

The efficiency analysis of nuclear power plants encompasses various aspects, including thermal efficiency, conversion efficiency, fuel utilization, and overall plant performance. Thermal efficiency focuses on the conversion of heat energy into electricity, while conversion efficiency evaluates the effectiveness of energy conversion processes within the plant. Fuel utilization analysis examines the efficiency of fuel consumption and the extraction of energy from nuclear fuel. Overall plant performance analysis considers the integrated efficiency of various plant components and systems.

While several studies have investigated specific aspects of efficiency analysis in nuclear power plants, there remains a need for a comprehensive and consolidated review of the subject. This paper aims to fill that gap by presenting a detailed

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examination of the existing research and analysis methods employed in the field. By synthesizing and analyzing the findings of previous studies, this paper aims to provide a holistic understanding of the efficiency analysis of nuclear power plants.

Furthermore, this review explores the interplay between efficiency, safety, and environmental considerations. It addresses the challenges of balancing efficiency improvements with stringent safety measures and regulatory requirements. By identifying the key factors influencing efficiency, highlighting best practices, and suggesting potential areas for future research and improvements, this paper aims to contribute to the ongoing efforts towards achieving efficient, safe, and sustainable nuclear power generation.

The following section deals with the various nuclear power plants in terms of their characteristics, safety, environmental considerations and performance analysis.

## 2. Nuclear Power Plant

A nuclear power plant operates as a thermal power plant, utilizing a nuclear reactor to produce a substantial amount of heat. This heat is then converted into steam, either directly or via a steam generator, which drives a steam turbine connected to a generator, resulting in the generation of electricity. The steam turbine is a standard component found in all thermal power plants and was first invented by Sir Charles Parsons in 1884. His initial model was linked to a dynamo, producing 7.5 kW (10 hp) of electricity. However, what sets nuclear power plants apart is the inclusion of the nuclear reactor and its intricate safety and auxiliary systems [1]. Initiating or altering the power output of nuclear power plants can be a time-consuming process, often taking many hours or even days. This prolonged duration is primarily due to the necessity of gradually heating the nuclear steam supply system and the turbine-generator to reach their required operating temperature. Although modern nuclear power plants can function as load-following power plants, adjusting their output to meet varying electricity demands, the most economically efficient and technically straightforward mode of operation is typically considered to be baseload operation.

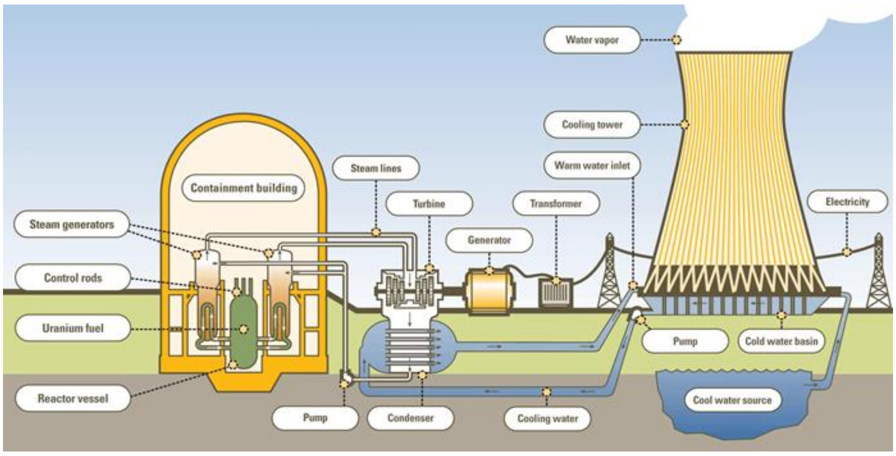


**Figure 1** Main features of nuclear power plants with PWR-type (Pressurized Water Reactor) [1].

The nuclear power plant consists of two main buildings: the containment building, which houses the nuclear reactor, pressurizer, reactor coolant pumps, steam generators, and other essential equipment in an air-tight structure. This containment building is crucial for preventing the release of fission products into the atmosphere during potential accidents, and it is often constructed using steel-reinforced concrete. The second building is the turbine building, housing the turbine, generator, condenser, and other necessary equipment responsible for converting pressurized steam's thermal energy into mechanical work to drive the generator. While some nuclear power plants may include cooling towers as part of their cooling system, they are not universally required. Coastal nuclear power plants, for instance, may use alternative cooling methods for their cooling water, rendering cooling towers unnecessary.

The fundamental working principle of a Nuclear Power Plant revolves around utilizing nuclear reactors solely for generating heat. This heat is then used to produce steam, which, in turn, drives a steam turbine connected to a generator, ultimately generating electricity. Typically, a nuclear reactor in these power plants has a nominal thermal power of around 3400 MW. The heat is generated through fission within the nuclear reactor and is transferred to the primary cooling water. In the case of Pressurized Water Reactors (PWRs), the coolant (water) is heated within the reactor core, raising its temperature from approximately 290°C (554°F) to about 325°C (617°F) as the water flows through the core. The hot coolant is then pumped through main coolant pumps and directed into steam generators. Inside the steam generators, the heat is transferred through the walls of tubes to the lower pressure secondary coolant located on the secondary side of the exchanger. Here, the coolant evaporates, resulting in pressurized steam at around 280°C (536°F) and 6.5 MPa. This pressurized steam is subsequently directed into the steam turbine, where it undergoes expansion from pressures of approximately 6 MPa to pressures of about 0.008 MPa. It is worth noting that steam turbines used in western nuclear power plants are among the largest steam turbines ever built. The steam turbine is connected to the main generator, which effectively converts the mechanical energy from the steam turbine into electricity, providing power for various applications. This process of nuclear heat generation, steam production, and electricity generation constitutes the core working principle of Nuclear Power Plants. Figure 1 shows the main features of nuclear power plants with PWR-type (Pressurized Water Reactor) [1].

Davor and Vedran [2] performed energy and exergy analysis of a nuclear power where the authors present a detailed analysis of the energy and exergy efficiency of a nuclear power plant, aiming to provide a baseline for future improvements and optimizations. The study focused on evaluating the efficiency and losses of various components of the power plant, including turbines, pumps, heat exchangers, condenser, deaerator, re-heater, moisture separator, and steam generator. By describing the schematic representation of a nuclear power plant, highlighting the differences between nuclear and conventional thermal power plants the authors explained the process of energy generation in nuclear reactors through fission and the subsequent use of steam to generate electricity using turbines. The analysis of the turbines reveals the power output, energy losses, and efficiency of both the high pressure turbine (HPT) and low pressure turbine (LPT). The energy efficiency of the HPT is reported as 71.10%, while the exergy efficiency is 84.45%. Similarly, the LPT demonstrates an energy efficiency of 71.9% and an exergy efficiency of 61.8%. The authors provided a detailed breakdown of energy and exergy efficiencies for each part of the turbine cylinders. The paper also examined the energy and exergy efficiencies of heat exchangers responsible for heating water from the condenser to the steam generator. The authors presented the efficiency values for various heat exchangers, indicating that HP1 (the first high-pressure heat exchanger) demonstrates an energy efficiency close to 100%, while other heat exchangers range from 84% to 97% in terms of energy efficiency. Exergy efficiency varies from 60% to 90% for different heat exchangers. The analysis extends to other components of the power plant, such as the condenser, deaerator, reheater, moisture separator, and steam generator. The condenser is found to have a high energy efficiency of 94% but experiences significant energy losses. The deaerator, reheater, moisture separator, and steam generator exhibit almost 100% energy efficiency, while their exergy efficiencies range from 78% to 98%.

## 3. Water Based Nuclear Power Plant

Water-cooled reactors have been integral to the commercial nuclear industry since its inception and currently dominate over 95 percent of all operational civilian power reactors worldwide. Furthermore, the majority of nuclear reactors currently under development and construction are also water-cooled. These reactors, known as Water Cooled Reactors (WCRs), have been the cornerstone of the nuclear industry throughout the 20th century [3]. Out of the 442 reactors currently in operation, approximately 96 percent are water-cooled reactors. Initially licensed to operate for 40 years, advancements in knowledge and technology have allowed these plants to extend their operational lifespans to 60 years, and there is potential for even longer operation. As we move into the 21st century, it is evident that WCRs will continue to play a crucial role in meeting energy demands. Among WCRs, Light Water Reactors (LWRs) are the most widespread globally, and they come in two main types: Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs). PWRs produce steam for the turbine in separate steam generators, while BWRs utilize steam directly from the reactor core in the steam turbine. Both types of LWRs rely on enriched fuel containing the fissile isotope U-235.

### 3.1 Pressurized Water Reactors (PWR)

Ahmet and Oguz [4] studied about the influence of cooling water temperature on the efficiency of a pressurized-water reactor nuclear-power plant where they acknowledged that the cooling water temperature can vary due to seasonal changes in climatic conditions and can also affect the design process for selecting the plant site. The authors considered the variation in condenser vacuum with the temperature of the cooling water extracted from the environment. The main findings of the paper indicate that an 18°C increase in the temperature of the coolant extracted from the environment would result in a decrease of approximately 0.45% in power output and 0.12% in the thermal efficiency of the PWR nuclear power plant. The authors highlight the importance of considering environmental temperature in plant site selection and emphasize the need to evaluate plant performance under different climatic conditions.

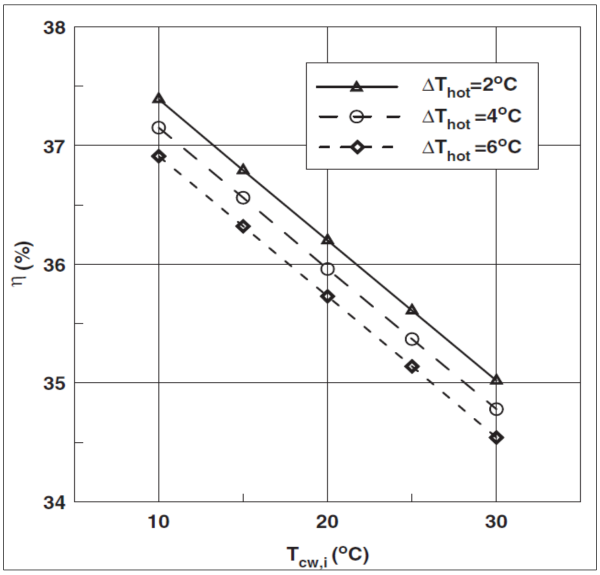


**Figure 2** Variation of thermal efficiency $\eta_{th}$ with cooling water inlet temperature $T_{cw,i}$ for $\Delta T_{hot}$ = 2 ℃, 4 ℃ and 6 ℃ [4].

Figure 2 depicts the variation of thermal efficiency $\eta_{th}$ with cooling water inlet temperature $T_{cw,i}$ for $\Delta T_{hot}$ = 2 ℃, 4 ℃ and 6 ℃ [4]. It is observed from Figure 2 that an increase from 20℃ to 30℃ in temperature of the coolant extracted from environment yields a decrease from 35.96 to 34.78% in thermal efficiency of the PWR NPP considered. The study developed a condenser heat balance model to determine the relationship between cooling water temperature and condenser pressure. Using this model, a cycle analysis was conducted to determine off-design heat balance conditions and corresponding power output and thermal efficiency for a range of cooling water temperatures.

Ahmet and Hasbi [5] performed an exergy analysis of a Pressurized-Water Reactor Nuclear-Power Plant where the authors focused on evaluating the irreversibility and exergy destruction within the plant and its subsystems, with a specific emphasis on identifying areas of work loss. The study considered a proposed PWR plant in Turkey and China, with a maximum thermal power of 4250 MW. The authors emphasized the differences between various nuclear-power plant designs, particularly comparing PWRs to other types like BWRs and CANDU reactors. They acknowledged that these differences can significantly affect exergy analysis results, as each design has distinct cooling and heat transport arrangements. Figure 3 shows the plant thermodynamic efficiency and percent rate of irreversibility for each group of components [5].

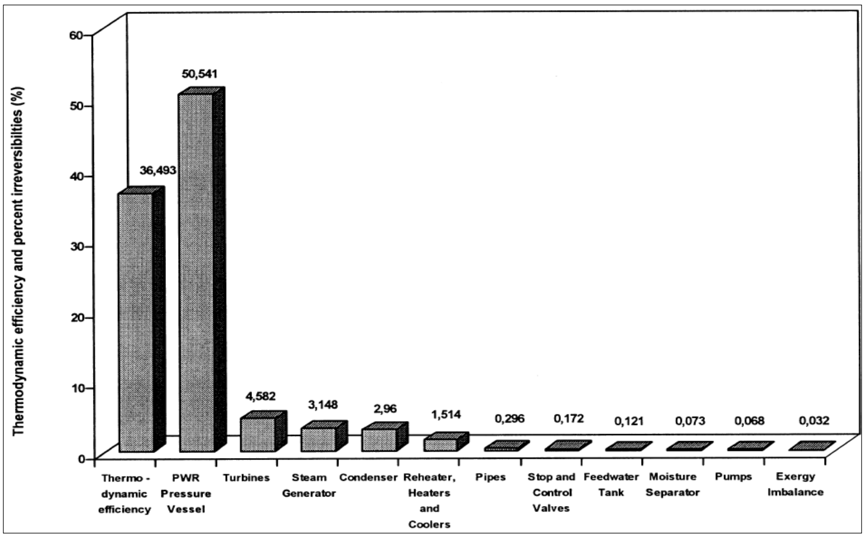


**Figure 3** Plant thermodynamic efficiency and percent rate of irreversibility for each group of components [5].

The results indicated that the reactor pressure vessel, including the PWR, is the most inefficient component in terms of exergy destruction. Turbines, steam generators, and condensers follow the PWR in the exergy destruction rank. The authors suggested that improving the efficiency of the PWR would have the greatest impact on enhancing the overall plant efficiency.

Sami studied the influence of condenser cooling water temperature on the thermal efficiency of a nuclear power plant [6]. The main findings of the study indicated that even a small increase in the coolant temperature can lead to a decrease in power output and thermal efficiency of the nuclear power plant. Specifically, the study suggests that an increase of one degree Celsius in the temperature of the cooling water extracted from the environment is projected to result in a decrease of 0.44% in power output and a decrease of 0.15% in the thermal efficiency of the nuclear power plant under consideration.

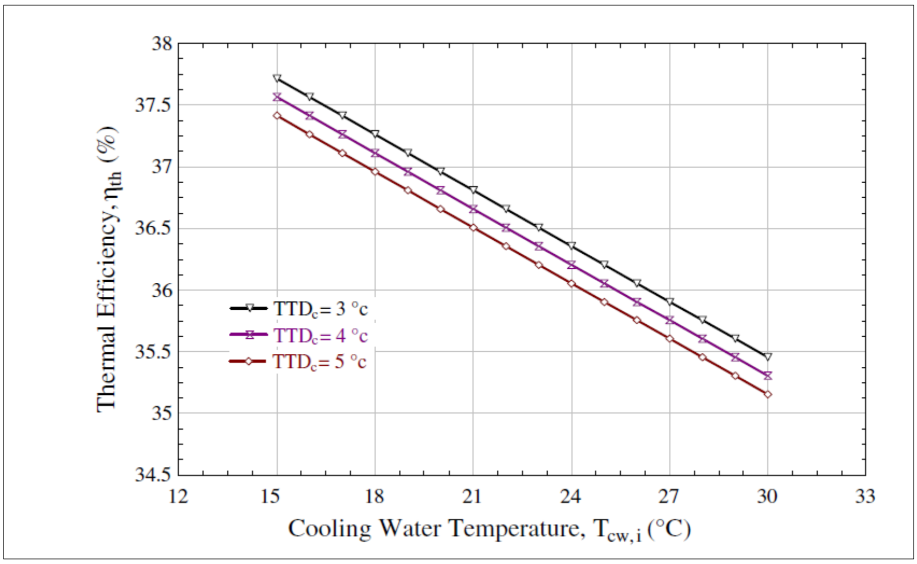


**Figure 4** Variation of thermal efficiency $\eta_{th}$ with cooling water inlet temperature $T_{cw,i}$ [6].

Figure 4 demonstrate the variation of thermal efficiency $\eta_{th}$ with cooling water inlet temperature $T_{cw,i}$ [6]. It is seen in Figure 4 that with increase of cooling water temperature the thermal efficiency decreased. Additionally, the authors emphasized the need to develop methods to compensate for the loss in plant efficiency caused by changes in cooling water temperature. The study also mentioned that the cooling process in nuclear power plants requires large quantities of cooling water, and the withdrawal and consumption of water can pose challenges due to climate change impacts such as increasing sea temperatures and water scarcity. The total water requirements of a power plant depend on various factors, including the generation technology, capacity, environmental conditions, and the cooling system employed.

Rauf Terzi et el. [7] performed study on Energy and exergy analyses of a VVER type nuclear power plant and focused on conducting energy and exergy studies based on the second law of thermodynamics to evaluate the efficiency and losses within the plant's subsystems. The research examined a specific VVER NPP with a thermal reactor capacity of 3900 MW heat generation to produce a nominal power output of 1000 MW. The study identified that the reactor pressure vessel units contribute significantly to energy losses, along with the condenser, turbines, and steam generators. VVER has the finest capacity to enhance the plant performance in such VVER NPP via way of means of thinking about new strain vessel components. While the thermodynamic efficiency of the NPP is found as 30%, the irreversibilities of pressure vessel and steam generator have been calculated as 49% and 13%, respectively. There exist additionally low irreversibilities with inside the additives of turbines, condensers and moisture separator.

Augustine et el. [8] performed an analysis of factors affecting thermodynamic efficiency in Generation III+ PWR nuclear power plants. They explored the parameters affecting the thermodynamic efficiency of Pressurized Water Reactor (PWR) nuclear power plants. The authors focused on the three main factors influencing the Rankine cycle: boiler pressure, steam temperature, and condenser pressure. They analyzed the relationship between these factors and the gross and net electrical efficiency of the power plants. The authors summarized their findings, noting the linear relationship between steam temperature and efficiency, the limiting temperature for net electrical power efficiency, the relationship between steam pressure and efficiency, and the lack of a clear relationship between condenser pressure and efficiency. They recommend further investigation into the optimal scale for thermal reactor output in relation to net electrical efficiency and more research on optimizing condenser pressure in the Rankine cycle. The findings contribute to the understanding of the relationships between key parameters and efficiency, highlighting areas that require further investigation for optimization.

Andhika and Eugene [9] studied thermodynamic performance of Pressurized Water Reactor power conversion cycle combined with fossil-fuel super heater. The paper discussed the thermodynamic performance of a hybrid system that combined a Pressurized Water Reactor (PWR) with a fossil-fuel super heater. The aim of this hybrid system is to improve the flexibility and load-following capabilities of PWRs, which are typically used for base load electricity generation. By incorporating a conventional superheater, the thermal efficiency of the PWR can be increased. The superheater can be powered by the exhaust gas from a gas turbine or a conventional gas burner. The paper investigated the thermodynamic performance of this hybrid system for both large reactors and Small Modular Reactors (SMRs). The results show that the thermal efficiency of the PWR, specifically the AP1000 reactor, can be improved from 30.2% to 45.8% by using a combined cycle gas turbine (CCGT) as the heat source for superheating. Other configurations, such as using a gas burner or a gas burner with reheating, also improved the thermal efficiency but to a lesser extent. Similar improvements in thermal efficiency were observed for SMR applications. The hybrid system allows for load following between 65% and full power load without affecting the operation of the nuclear reactor. The coupling of the PWR with a super-heater enhances the utilization of the nuclear heat source while utilizing low-capital-cost fossil heat for peak power production. The increased steam temperature from the super-heater also improves turbine performance and overall cycle efficiency.

Morteza Gharib et al. [10] described the thermal efficiency challenges faced by pressurized-water reactor (PWR) nuclear power plants, which currently operate at around 33% efficiency. This low efficiency has negative economic implications and contributes to environmental thermal pollution. The paper explored the possibility of increasing the thermal efficiency of PWRs to approximately 40% by superheating live steam with natural gas, making them more competitive with fossil-fueled power plants. It highlights the increasing demand for power and steam generation due to population growth and industrial expansion, placing a burden on the electrical utility industry and process plants. Steam generation and heat recovery boilers are essential in these industries, and engineers are seeking innovative methods to improve energy utilization, recover energy efficiently, and minimize environmental pollution. Superheating live steam is a common practice in fossil-fueled power plants to enhance efficiency and reduce environmental impact. However, nuclear power plants face challenges in achieving high temperatures and thermal efficiencies due to their reliance on solid nuclear fuel. The paper suggested that improving existing reactors, particularly PWRs, by boosting live steam into a superheated state using an external heat source like natural gas can lead to higher thermal efficiency. The Bushehr nuclear electricity plant (BNPP) turned into used as a conventional model, and it turned into proven that the extra power generated using natural gas was cost-effective, particularly in regions with cheap and abundant gas resources. The paper emphasized that higher efficiencies result in lower power generation costs and suggested that employing a natural gas-assisted burner for steam superheating and efficiency increase in nuclear power plants is economically viable.

### 3.2 Boiling Water Reactors (BWR)

The BWR makes use of normal water (light water) as each its coolant and its moderator. Its particular function is that steam is generated at once within the reactor core. In the BWR, the water with inside the reactor middle is authorized to boil under a pressure of 75 atm, raising the boiling point to 285°C and the steam generated is taken from the core and used directly to drive a steam turbine. This steam is then condensed and recycled again to the reactor core.

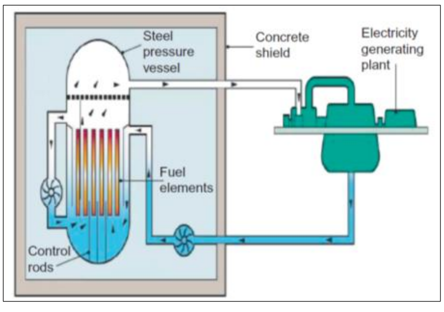


**Figure 5** Boiling water reactor [11].

Since the steam is exposed to the core, there is some radioactive contamination of the turbines but this is short-lived and turbines can normally be accessed soon after shutdown [11]. Figure 5 shows the Boiling water reactor [11]. The BWR (Boiling Water Reactor) configuration is considered one of the simplest types of nuclear reactors as it does not require additional steam generators. However, the internal systems within a BWR are intricate. These reactors utilize enriched uranium as fuel, with an enrichment level of approximately 2.4% uranium-235. The fuel is in the form of uranium oxide pellets enclosed in zirconium alloy tubes. A BWR may contain as much as 140 tons of fuel distributed across 75,000 fuel rods. During refueling, the top of the reactor is removed, while the core remains submerged in water, shielding operators from radioactivity. Control rods made of boron are inserted into the core from beneath the reactor. In modern BWRs, these control rods serve to maintain power generation within the reactor core evenly and compensate for fuel consumption (burn-up). The rate of water flow through the core is adjusted to control power. However, some early BWRs relied on natural water circulation without pumps, making it necessary for the control rods to control power between 0% and 100%. Like all reactors, the fuel rods removed from a BWR reactor core remain highly radioactive and continue to produce energy for several years. These spent fuel rods are carefully stored in controlled storage pools at the plant and are eventually planned for either reprocessing or final storage. Most BWR reactors typically have a generating capacity of 900-1100 MW, with an efficiency of 32%. Early plants, primarily commissioned in the early 1970s, had capacities of around 500-600 MW. Advanced BWR designs have increased capacities of up to 1400 MW with an efficiency of about 33%. Some of these advanced reactors are operational in Asia.

Govind et al. [12] performed a study focused on analyzing the temperature drop across a fuel element in a nuclear reactor. The fuel element consists of fuel pellets, a helium gas gap, and cladding material. The goal of the analysis is to understand the temperature distribution from the center of the fuel element to the gas gap and cladding surface. The fuel element used in the study was uranium dioxide, which is commonly used in Light Water Reactors. The methodology involves the formulation of analytical results and mathematical modeling of a nuclear reactor, specifically a Boiling Water Reactor (BWR). The heat transfer and energy balance equations are used to calculate various parameters such as heat received from the reactor, heat received from the superheater, work output from the steam turbine, energy balance across the condenser, work done by condenser and feed water pumps, and energy balance across the open feed water heater. The results of the study include temperature distributions in the fuel pellets, gas gap, and cladding, as well as variations in efficiency, heat input, mass flow rate in the open feed water heater, work output, and dryness fraction at the condenser inlet with respect to the superheater temperature.

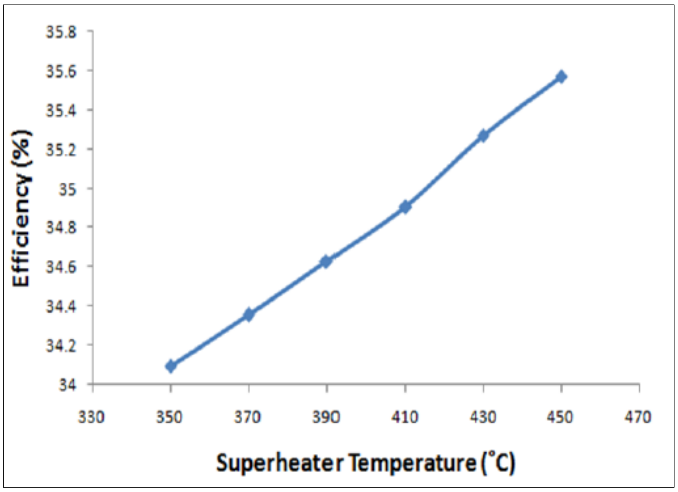


**Figure 6** Variation of Efficiency of plant with Super heater Temperature [12].

Figure 6 shows the variation of Efficiency of plant with Super heater Temperature [12]. In the Figure 6, it is shown that with increase of super heater temperature the efficiency increased.

## 4. Small Modular Reactor (SMR)

Small modular reactors (SMRs) are advanced nuclear reactors that have a power capacity of up to 300 MW(e) per unit, which is about one-third of the generating capacity of traditional nuclear power reactors. SMRs, which can produce a large amount of low-carbon electricity [13].

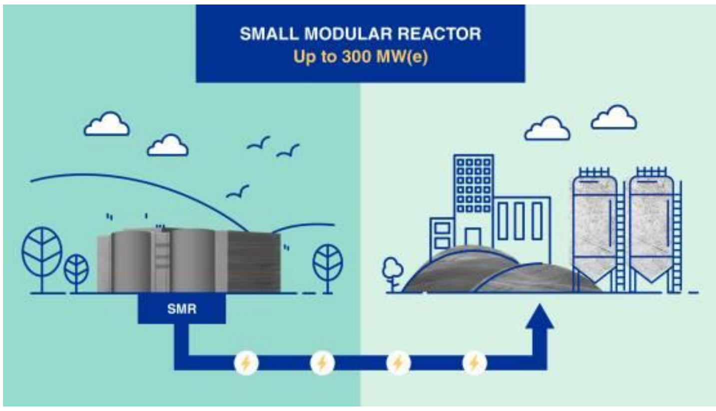


**Figure 7** Small Modular Reactor [14].

Figure 7 demonstrates the Small Modular Reactor [14]. Small modular reactors (SMRs) are becoming an attractive option for new nuclear reactor construction due to their simple, standardized, and safe modular designs. These reactors are manufactured in factories, resulting in lower initial capital investment and shorter construction times compared to traditional large reactors. While the construction costs of many SMR projects in their design stages are not publicly available, variable costs can be estimated based on fuel enrichment, average burn-up, and plant thermal efficiency, which are publicly accessible for several near-term SMR projects. To assess the economic viability of SMRs, the fuel costs of electricity generation for selected SMRs and large reactors were simulated, incorporating calculations for optimal tails assay in the uranium enrichment process. A rough comparison of the long-term economics of new nuclear reactor projects was conducted, revealing that SMRs are predicted to have higher fuel costs than large reactors. In particular, integral pressurized water reactors (iPWRs) exhibit fuel costs 15% to 70% higher than large light water reactors, as per the 2014 nuclear fuels market data [15].

Advanced SMRs provide many advantages, which include noticeably small bodily footprints, decreased capital investment, capacity to be sited in places now no longer feasible for large nuclear plants, and provisions for incremental electricity additions. SMRs additionally provide wonderful safeguards, protection and non-proliferation advantages [16].

Nima Norouzi performed the analysis of a Small Modular Reactor (SMR) power plant in terms of energy, exergy, and exergoeconomics [17]. The analysis aimed to investigate the energy quality and cost of energy in SMR plants. The results showed that SMR plants maintain high efficiency despite having smaller reactor temperature, fuel quantity, and mass flow. The main contributor to energy loss was identified as the condenser, while the reactor core was the main contributor to exergy loss. The study highlights the potential for improving the performance of the reactor core. Additionally, the exergoeconomic analysis provided insights into the economic competitiveness of the SMR system. Overall, the analysis provided valuable information for researchers and offers a better understanding of SMR technology.

Fakhrarei et al. [18] performed a theoretical investigation conducted on the NuScale SMR (Small Modular Reactor) regarding its primary circulation and Decay Heat Removal System (DHRS). The study aimed to evaluate the plant's safety and the effectiveness of its passive safety features. The NuScale SMR was designed to be a pump-less Pressurized Water Reactor (PWR), which eliminates the need for major facilities and reduces costs while enhancing safety against accidents such as Loss-of-Coolant Accident (LOCA) and primary pump failures. A comparison between the NuScale SMR and the AP-1000 reactor is also mentioned, highlighting the comparable Core Damage Frequency (CDF) of the two designs. Previous studies have examined the behavior of the NuScale SMR during Station Blackout (SBO) accidents, focusing on decay heat removal. Significant improvements were observed compared to typical PWRs, although flow oscillations were observed during some stages of the accidents. The study proposed ways to mitigate these flow oscillations. The current research involves theoretical investigations into the NuScale SMR, specifically its primary natural circulation and the DHRS. The obtained flow rates are compared with the NuScale Design Certificate Analysis and previous RELAP5 results. The results indicate that the primary circulation and the DHRS of the NuScale SMR can effectively remove decay heat passively after severe accidents without operator intervention. The theoretical investigation aligns with the previous RELAP5 data, demonstrating the plant's safety and its ability to cope with severe accidents. In conclusion, the study confirms that the NuScale SMR's passive safety features, including the DHRS, provide inherent safety and unlimited coping-time without the need for operator action. The plant's natural circulation system is capable of transferring heat effectively.

Farrukh Khalid and Yusuf Bicer [19] proposed a hybrid nuclear small modular reactor (SMR) system assisted by wind energy for a net zero emissions tri-generation system. The advantages of SMRs include improved thermal efficiency, building efficiency, and lower operation and maintenance costs compared to standard nuclear power generation. By combining SMRs with wind turbines, the system aimed to produce electricity, hydrogen, and hot water. A two-step high-temperature thermochemical cycle was used for hydrogen production, and the system's energy and exergy efficiencies are evaluated. A parametric study was conducted to examine the effects of various parameters on the system's performance. The results showed that the overall system can achieve an energy efficiency of 57.5% and an exergy efficiency of 38.1%. The study emphasized the importance of hybridizing SMRs with renewable energy systems and highlights the potential of such systems for efficient and sustainable energy production.

Giorgio et al. [20] discussed the challenges faced by engineers and scientists in meeting global energy demand while reducing greenhouse gas emissions. It explores Small Modular Reactors (SMRs) as a potential solution, with a focus on Light Water Reactors (LWRs), the most common type of SMR. The paper highlights safety concerns post-Fukushima and economic hurdles as major impediments to SMR deployment. Despite these challenges, SMRs are considered suitable for power installations in the 1,000 GWe range, particularly when job creation is a goal. Non-OECD countries' increasing energy consumption drives the need for new power plants, and some countries continue pursuing nuclear energy. The advantages of SMRs include simplicity, enhanced safety features, and lower financial requirements. However, SMR deployment has been limited due to the belief in economies of scale, preference for proven designs, and lack of enabling factors. SMRs are designed to be transportable, factory-manufactured, and suitable for various applications. The paper concluded by emphasizing the importance of SMRs as a promising technology for meeting future energy needs, acknowledging ongoing global development and potential benefits. It provided insights for governments, stakeholders, and investors on the economic and social boundaries for viable SMR deployment in emerging nuclear markets.

Lauren Bolden et al. [21] discussed the application of thermoeconomics and exergy analysis in the context of Small Modular Reactors (SMRs) coupled with storage technologies and renewable energy sources. SMRs offer a promising opportunity for nuclear development with reduced financial risks and a focus on safe, reliable, and clean electricity generation. The paper emphasized the importance of understanding both the quantity and quality of energy available, with exergy analysis providing a more comprehensive assessment than traditional energy analysis. The paper aimed to discover exergy evaluation strategies to estimate and optimize sources and expenses for subsystems within an SMR plant, taking into account thermodynamic principles and the coupling of physical and economic environments. It highlights the need to balance technological efficiencies and economics to create financially competitive SMR systems. Overall, the study focused on the use of exergy analysis to assess the efficiency and cost allocation among subsystems, ultimately aiming to improve the profitability and competitiveness of SMRs in comparison to other generation technologies.

Hidayatullah et al. [22] studied about the design and technology development for small modular reactor with Safety expectations, prospects and impediments of their deployment. The International Atomic Energy Agency (IAEA) has observed a significant increase in member states' participation and expertise in the development of Small and Medium-sized Reactors (SMRs). There is a high level of interest in SMR development and deployment in both technology holder and user countries. These reactors are designed to be built in factories and transported to utilities for installation based on demand. Advanced SMRs offer advantages over traditional large nuclear power plant designs, such as greater simplicity, economy of mass production, smaller footprint, enhanced safety, security, and proliferation resistance features. Modularization is a key aspect of advanced SMR systems, allowing for shop fabrication and on-site assembly, reducing construction time and initial capital investment. Advanced SMRs offer promising benefits in terms of safety, reliability, affordability, and flexibility. However, several challenges need to be addressed for their successful deployment, including technical, regulatory, economic, and legal considerations. International collaboration and knowledge sharing are key to advancing SMR technology and realizing its potential for the future of nuclear power generation.

## 5. Summary

The efficiency of the nuclear power plant depend on various factors. There are many types of nuclear power plant. The key factors affecting the thermodynamic performance of various nuclear power plants is discussed in the following Table 1.

**Table 1** Key Factors affecting the thermodynamic performance of various nuclear power plants.

| Type of Nuclear Power Plant | Methodology | Observation | Reference |
|---|---|---|---|
| Pressurized Water Reactor (PWR) | Cooling Temperature | Power output and the thermal efficiency decrease by approximately 0.45% and 0.12%, respectively, for 18°C increase in temperature of the coolant extracted from environment. | [4] |
| | Irreversibility | As a comparison, it is estimated by this study that approximately 53.7 % of the total exergy rate produced as fission power is destroyed in the primary system, i.e. the PWR, steam generators, reactor coolant pumps and via frictional pressure drops and heat losses in the primary-circuit pipes, of PWR 1500 MW NPP. | [5] |
| | Cooling Water Temperature | Output power and the thermal efficiency of the plant decrease by approximately 0.44% and 0.15%, respectively, for 1°C increase in temperature of the condenser cooling water extracted from the environment. | [6] |
| | Irreversibility | While the thermodynamic efficiency of the NPP is found as 30%, the irreversibilities of pressure vessel and steam generator have been calculated as 49% and 13%, respectively. There exist also low irreversibilities in the components of turbines, condensers and moisture separator. | [7] |
| | Steam Temperature and Pressure | A direct linear relationship can be seen between the steam temperature at the turbine and the power plant efficiency. A limiting temperature is observed around 290°C for net electrical power efficiency. A weaker but still observable linear relationship is seen between steam pressure and efficiency. | [8] |
| | PWR with Superheater | The thermodynamic performance of the hybrid system (PWR with superheater) is investigated for large reactor and Small Modular Reactor (SMR) application. The thermal efficiency of the AP1000 can be improved from 30.2% to 45.8% (with CCGT), 35.6% (with gas burner) and 36.6% (gas burner with reheating). | [9] |
| | Superheating Live Steam | The possibility of increasing the thermal efficiency of PWRs is approximately 40% by superheating live steam with natural gas, making them more competitive with fossil-fueled power plants. | [10] |
| Boiling Water Reactor (BWR) | Advanced BWR | Most BWR reactors are typically 900-1100MW in generating capacity, with an efficiency of 32%. Early plants, mostly entering service in the early 1970s, were around 500-600MW in capacity. Advanced BWR designs have capacities of up to 1400MW and an efficiency of around 33%. A small number of these are in operation in Asia. | [11] |
| | Super-Heater Temperature | As stream of water through the center is expanded, steam bubbles are immediately eliminated from the center, the measure of fluid water in the center builds, neutron control expands, more neutrons are eased back to be consumed by the fuel, and reactor power increments. As stream of water through the center is diminished, steam voids stay longer in the center, the measure of fluid water in the center reductions, neutron control diminishes, less neutrons are eased back to be consumed by the fuel, and reactor power diminishes. The efficiency of power plant increases linearly as the superheating temperature increases. As the superheating temperature increases heat input also increases linearly. | [12] |

| | | | |
|---|---|---|---|
| Small Modular Reactor (SMR) | Hybrid SMR | The thermal efficiency of the SMR can be improved from 33.4% to nearly 45% (with CCGT), 35.5% (with gas burner) and 37.4% (gas burner with reheating). | [9] |
| | Exergy Analysis | The analysis aims to investigate the energy quality and cost of energy in SMR plants. The results show that SMR plants maintain high efficiency despite having smaller reactor temperature, fuel quantity, and mass flow. The main contributor to energy loss is identified as the condenser, while the reactor core is the main contributor to exergy loss. | [17] |
| | Decay Heat Removal System | The study confirms that the NuScale SMR's passive safety features, including the DHRS, provide inherent safety and unlimited coping-time without the need for operator action. The plant's natural circulation system is capable of transferring heat effectively. | [18] |
| | Hybrid SMR | The results show that the overall system can achieve an energy efficiency of 57.5% and an exergy efficiency of 38.1%. The study emphasizes the importance of hybridizing SMRs with renewable energy systems and highlights the potential of such systems for efficient and sustainable energy production. | [19] |

The summary tables highlights the various factors affecting the performance and efficiency of different types of nuclear power plants. These factors include cooling temperature, irreversibility, steam temperature and pressure, the addition of a super heater, and the implementation of passive safety features in SMRs. The following section deals with the specific types of Nuclear Power Plant in terms of their efficiencies for various conditions.

### *5.1 Pressurized Water Reactor (PWR)*

It is seen from the Table 1 that due to irreversibility, about 57.5% of the total exergy rate produced as fission power is destroyed in the primary system of a PWR. Also, increasing about 18°C coolant temperature decreases about 0.12% thermal efficiency. In addition, the addition of a super heater improves the thermal efficiency of the PWR, resulting in higher efficiency percentages. The thermal efficiency of the AP1000 can be improved from 30.2% to 45.8% (with CCGT), 35.6% (with gas burner) and 36.6% (gas burner with reheating). On the other hand, thermal efficiency of PWRs is approximately 40% by superheating live steam with natural gas, making them more competitive with fossil-fueled power plants.

### *5.2 Boiling Water Reactor (BWR)*

It is seen from the Table 1 that, most BWR reactors are typically 900-1100MW in generating capacity, with an efficiency of 32%. Early plants, mostly entering service in the early 1970s, were around 500-600MW in capacity. Advanced BWR designs have capacities of up to 1400MW and an efficiency of around 33%.

### *5.3 Small Modular Reactor (SMR)*

It is seen from the Table 1 that the thermal efficiency of the hybrid SMR can be improved from 33.4% to nearly 45% (with CCGT), 35.5% (with gas burner) and 37.4% (gas burner with reheating). In addition, the overall system can achieve an energy efficiency of 57.5% and an exergy efficiency of 38.1%.

The approximate efficiencies of the various types of Nuclear Power Plant can be illustrated in the Table 2. The variation of the thermodynamic efficiencies are demonstrated for different types of Nuclear Power Plant (NPP) in Figure 8.

| Types of Nuclear Power Plant | BWR | Advanced BWR | PWR | SMR | SMR with Gas Burner | PWR with Gas Burner and Reheating | SMR with Reheating | SMR with CCGT |
|---|---|---|---|---|---|---|---|---|
| Efficiency (%) | 32 | 33 | 33 | 33.4 | 35.5 | 36.5 | 37.4 | 45 |

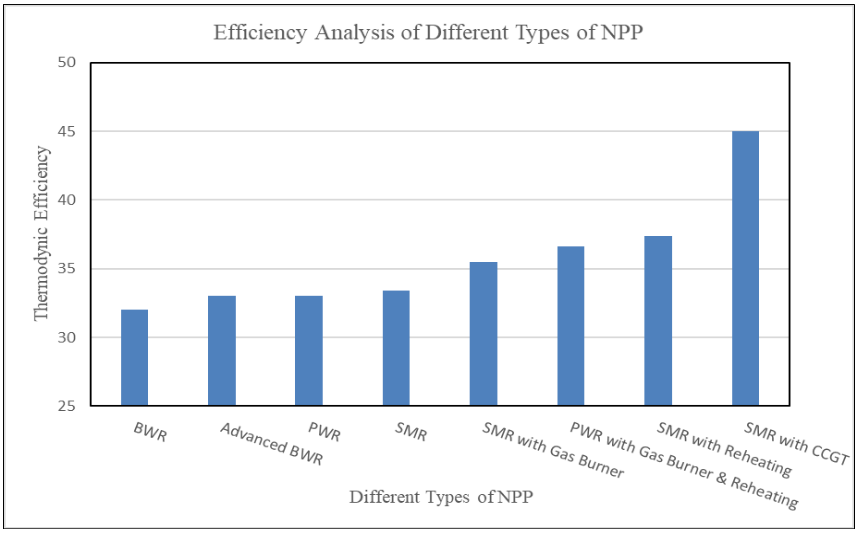


**Figure 8** Thermodynamic efficiency analysis of different types of NPP.

From the Figure 8, it is seen that the efficiency of BWR Nuclear Power Plant is 32%. The PWR Power Plant have higher efficiency when it operates with super heating live steam with natural gas. Now a days SMR is becoming the new hope in the field of nuclear industry. The efficiency of SMR nuclear power plant is 33.4% which can be increased with gas burner. Using the combined cycle gas turbine (CCGT), SMR can perform more thermodynamic performance and give higher efficiency as much as 45% than other type of nuclear power plant.

## 6. Conclusion

The discussed papers investigate various aspects of thermodynamic efficiency and performance in nuclear power plants. The authors presented highlights several key factors that influence the performance and efficiency of different types of nuclear power plants. The cooling temperature of a pressurized water reactor (PWR) and the condenser cooling water temperature affect the power output and thermal efficiency, emphasizing the importance of maintaining optimal cooling conditions. Irreversibility, particularly in the primary system of a PWR and components like the pressure vessel and steam generator in VVER, contributes to energy loss and decreased efficiency. Increasing steam temperature and pressure in both PWRs and boiling water reactors (BWRs) enhances power plant efficiency. Furthermore, the addition of a super heater in PWRs improves thermal efficiency. In the case of small modular reactors (SMRs), exergy analysis reveals their ability to maintain high efficiency despite smaller reactor temperature and fuel quantity. Additionally, the implementation of passive safety features, such as the Decay Heat Removal System (DHRS), ensures inherent safety and effective heat transfer in SMRs. The concept of hybridizing SMRs with renewable energy systems shows promise for achieving high energy and exergy efficiency, leading to sustainable energy production. Overall, these findings underscore the importance of optimizing various parameters and employing innovative approaches to enhance the efficiency and sustainability of nuclear power plants. The major findings of the present analysis can be illustrated in the following way.

- The efficiency of the Boiling Water Reactor (BWR) of the Nuclear Power Plant is 32% and which can be increased to 33% by using advanced BWR.
- The efficiency of the Pressurized Water Reactor (PWR) of the Nuclear Power Plant is 33% and which can be increased to 36.5% by using the PWR with Gas Burner and Reheating.
- The efficiency of the Small Modular Reactor (SMR) of the Nuclear Power Plant is 33.4% and which can be increased to 35.5%, 37.4% and 45% by using SMR with Gas Burner, SMR with Reheating and SMR with CCGT, respectively.

Therefore, it is predicted that the Small Modular Reactor (SMR) is the most economic Nuclear Power Plant as it has higher thermal efficiency when it is incorporated with Combined Cycle Gas Turbine (CCGT).

## Compliance with ethical standards

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*Disclosure of conflict of interest*

No conflict of interest to disclosed.

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