



THE IMPORTANCE OF EXERGY ANALYSIS OF NUCLEAR REACTORS FOR THE ENERGY TRANSITION PROCESS

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ABSTRACT

The transition to low-carbon energy systems underscores the critical role of nuclear power as a reliable and dispatchable electricity source. This study presents a comparative exergy assessment of nuclear reactors and hybrid configurations, aiming to identify the main sources of irreversibility and propose strategies for improving exergy efficiency. A systematic literature review (2015–2025) was conducted to compile normalized data on thermal and electrical outputs, exergy destruction rates, and subsystem performance across nuclear technologies, such as Nuclear Power Plants (NPPs) and Small Modular Reactors (SMRs), including cogeneration and desalination hybrid systems. Exergy analyses highlight that the highest irreversibilities typically occur in reactor cores, steam generators, turbines, and condensers. To confirm these facts, a bibliographic research methodology was adopted involving publications on exergy analysis applied to nuclear energy generation and cogeneration systems and other supplies. The aim was to build a study and verify what are the main irreversibilities involved in these systems and mainly what are the components that affect their efficiency. A time window of the last ten years was selected and preference was given to publications in indexed journals with an impact on the scientific community. The results of the analyzes showed that the main irreversibilities are connected to reactor cores, steam generators, turbines, and condensers, due to high thermal gradients, mismatched heat exchange, and non-ideal expansion processes. Based on this result, case studies can be carried out in the future to delve deeper into such irreversibilities and the means to mitigate them and how technology influences the efficiency of systems.

Keywords: Nuclear reactors; Exergy analysis; Hybrid energy systems; Thermodynamic efficiency; Energy optimization.

1 INTRODUCTION

The accelerating global transition toward low-carbon energy systems increasingly emphasizes the importance of nuclear reactors as critical sources of dispatchable, reliable, and low-emission electricity. According to the World Nuclear Association (WNA), nuclear power contributed approximately 9% of global electricity generation in 2023, delivering 2,602 TWh, and its capacity factor averaged around 81.5%, reflecting strong performance across the operational fleet [12], as can be seen in Figures 1 and 2. Simultaneously, projections from the IEA suggest that to align with Net Zero emissions targets, nuclear energy capacity must expand significantly. In many scenarios, expansions are modest but capacity must grow to maintain or increase nuclear's share in electricity mixes, as renewables alone may not always meet grid stability and continuous supply needs [5].



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Figure 1 - Nuclear Electricity Generation (WNA, 2025).

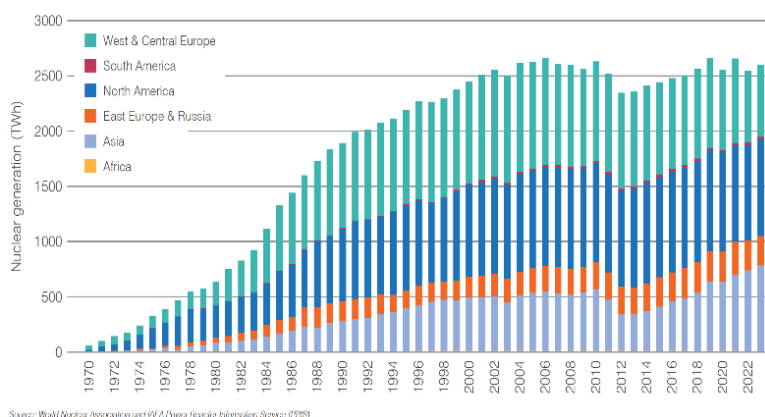


Figure 2 - World electricity sources (WNA, 2025).

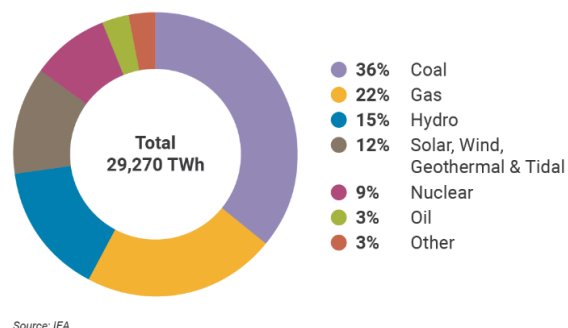
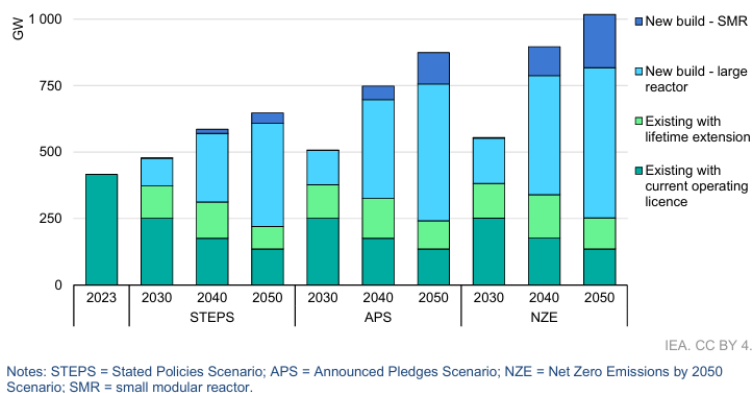


Figure 3 - Projected Global Nuclear Capacity Growth to 2050 under Various Scenarios (IEA, 2025).



Empirical data on exergy efficiency of nuclear plants provides crucial evidence of where losses are concentrated. For example, in a recent study of a PWR coupled with desalination systems, the overall thermodynamic efficiency reached approximately 35.4%, with nearly half of the total exergy destruction concentrated in the reactor core. Other significant irreversibilities were identified in steam generators, turbines, and condensers [11]. These findings highlight how exergy analysis can pinpoint the main bottlenecks of nuclear systems and indicate where design and operational improvements can have the greatest impact. Given these observations, exergy analysis is not merely academic; it becomes essential for nuclear power plants in the energy transition process. By quantifying irreversibilities and locating components or operating regimes with the highest exergy destruction, designers and operators can prioritize interventions, whether in reactor core design, steam generator heat transfer



surfaces, turbine expansions, or condenser improvements, that yield the greatest improvements in exergy efficiency. The main aims of this work are to compile and standardize exergy metrics from recent literature focused on nuclear reactors, identify subsystems with the largest irreversibilities, and propose a reproducible methodological protocol for design, retrofit, and operational decisions to reduce exergy destruction. In doing so, this research provides actionable insights for better aligning nuclear power with global decarbonization, energy security, and reliable electricity supply goals.

For the modeling phase, exergy balance equations can be applied to control volumes representing the reactor core, steam generators, turbines and other auxiliaries, calculating specific physical exergy, exergy flow rates, component-level exergy destruction, and exergetic efficiencies. The Equation 1 defines the specific physical exergy of a flow state relative to the environment and quantifies the maximum useful work extractable as the fluid reaches the chosen reference state.

$$e_{ph} = (h - h_0) - T_0(s - s_0) \quad \text{Eq. (1)}$$

In Eq. 1, h is the specific enthalpy at the state, h_0 is the enthalpy at the reference state, s is the specific entropy, s_0 is the specific entropy at the reference, and T_0 is the reference temperature. Equation 2 converts specific exergy into an exergy flow by multiplying the specific exergy by the mass flow.

$$\dot{E}_{ph} = \dot{m} e_{ph} \quad \text{Eq. (2)}$$

In Eq. 2, $\dot{m}$ denotes the mass flow rate and $\dot{E}_{ph}$ is the physical exergy flow rate. Equation 3 states the steady-state exergy balance for a control volume.

$$\sum \dot{E}_{in} - \sum \dot{E}_{out} = \dot{E}_d + \dot{E}_{loss} \quad \text{Eq. (3)}$$

Where $\dot{E}_{in/out}$ are exergies carried by incoming/outgoing streams, $\dot{E}_d$ is the exergy destruction rate inside the control volume and $\dot{E}_{loss}$ denotes exergy physically lost to the environment or rejected as non-useful heat. Equation 4 links exergy destruction to entropy generation, providing a thermodynamic measure of irreversibility.

$$\dot{E}_d = T_0 \dot{S}_{gen} \quad \text{Eq. (4)}$$

In Eq. 4, $\dot{S}_{gen}$ is the entropy generation rate and T_0 is the reference temperature. Finally, Equation 5 defines exergetic efficiency as the ratio between useful exergy outputs and exergy supplied.

$$\eta_{ex} = \dot{E}_{usefull} / \dot{E}_{supplied} \quad \text{Eq. (5)}$$

Here $\dot{E}_{usefull}$ is the exergy associated with useful outputs and $\dot{E}_{supplied}$ is the total exergy supplied to the system.

2 METHODOLOGY

The methodology of this study comprises a systematic literature review and a technical-computational protocol for future analysis, exclusively focused on nuclear reactor systems. The literature review targets peer-reviewed studies from 2015 to 2025 that feature exergy analysis of nuclear reactors (PWR, LWR, SMRs) or reactor systems with hybrid configurations (e.g., cogeneration or desalination). Key data to be extracted include nominal thermal and electric power, global and component-level exergy efficiency, rates of exergy destruction in megawatts and/or percentage, operating temperatures and pressures, and ambient reference conditions. All extracted data will be normalized: converting powers to MW where necessary, unifying the



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environmental reference temperature at $T_0 = 298.15$ K unless otherwise specified, and harmonizing definitions of “useful exergy” (i.e., whether it includes electricity only or includes thermal output) to ensure internal consistency across cases.

3 RESULTS AND DISCUSSION

After critically reviewing the selected literature, the pertinent data extracted for comparative analysis are compiled and presented in Table 1.

Table 1 – Comparative exergy parameters

Reference	Type*	Context / Focus	Methodological approach	Main results	Major exergy destruction	Suggested strategies
Boldon et al. (2016) [1]	SMR (hybrid)	Exergy/ exergoeconomics of SMR hybrid with storage, electrolysis & renewables	Steady-state integrated cycle modeling; exergy & exergoeconomic assessment	Identifies exergy losses and exergetic costs; hotspots in high-T heat transfer	Reactor core / high-T heat exchangers	Integrate storage; optimize operating points; exergoeconomic trade-offs
Cenușă et al. (2019) [20]	PWR	Maximize exergetic performance in steam generators of PWR secondary side	Pinch-point method & LMTD-equivalent exergy analysis	Method allows simultaneous optimization of p_0 and feedwater T to reduce exergy degradation	Steam generator & downstream cycle (if poorly matched)	Optimize secondary-side pressures/temperatures; minimize local ΔT
Durmayaz et al. (2000) [2]	PWR	Locate where most useful work is lost in a plant	Exergy analysis (2nd law) per subsystem	Identifies RPV as most inefficient equipment; turbines second	Reactor pressure vessel (RPV) and turbines	Improve RPV design and turbine performance; optimize heat exchangers
Elwardany et al. (2023) [16]	Combined cycle	Real plant thermodynamic assessment; identify main exergy destruction sources	1st & 2nd law balances using operational data per subsystem	$\eta_{\text{energy}} \approx 34.6\%$; $\eta_{\text{ex}} \approx 33.5\%$; major exergy destruction in combustion (53%) & HRSG (32%)	Combustion chambers and HRSGs	Prioritize combustion and HRSG optimisation (reduce irreversibilities)
Eshun (2019) [14]	PWR (AP1000)	Component-wise energy/exergy diagnosis of AP1000	1st/2nd law balances, Gouy–Stodola; project data	$\eta_{\text{global}} \approx 35.3\%$; core exergy consumption ≈ 1814.8 MW (core $\eta_{\text{ex}} \approx 46.6\%$); steam-generation sections ≈ 1868.4 MW destroyed	Reactor core / steam generation assembly	Focus on core and steam generators; improve fuel/clad & heat transfer interfaces
Ferroni et al. (2016) [15]	PWR	Apply exergy method to core heat transfer processes	Thermodynamic modeling of core: mass/energy balances; heat transfers	Core exergy efficiency $\approx 50\text{--}60\%$ (order of magnitude)	Heat transfer within fuel $\rightarrow$ cladding $\rightarrow$ coolant	Optimize fuel assembly/cladding design; reduce local thermal gradients
Forghani et al. (2023) [21]	CCHP + desalination	Optimal design & energy storage performance in solar hybrid multi-gen for a city	MATLAB modelling; GA optimization (36 & 61 variables); objective: annual cost	Storage reduced annual cost objective by 11.3%; exergetic metrics qualitative	Solar field / evaporators (desalination)	Use thermal storage; optimize collector area, number of effects
Huang et al. (2023) [3]	Geothermal + trans-critical CO_2	Exergy assessment and optimization of combined geothermal + CO_2 cycle	EES modeling; optimization by GA and Nelder–Mead simplex	Initial $\eta_{\text{ex}} 32.46\%$; GA $\rightarrow 39.21\%$; NMS $\rightarrow 36.16\%$	Vapor generator (36%); CO_2 turbine (23%); CO_2 condenser (17%)	Optimize separator pressure, turbine inlet pressures; focus on vapor generator



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Marques et al. (2019) [7]	PWR	Energy & exergy analysis of Angra-2, identify component losses	EES mathematical model; energy & exergy balances	$\eta_{\text{energy}} \approx 36\%$; $\eta_{\text{ex}} \approx 49\%$; core $\eta_{\text{ex}} \approx 67\%$; core responsible for $\sim 64\%$ of exergy destruction	Reactor core	Optimize core; improve thermal interfaces and secondary cycle integration
Mrzljak et al. (2021) [8]	Feedwater heating subsystem	Optimize exergy performance of high-pressure feedwater heaters	Exergy analysis of 4 scenarios; optimization with GA/IGSA; study ambient T effect	All algorithms increased exergy efficiency; max $\eta \approx 96.12\%$ (IGSA, $T_{\text{amb}} = 5^\circ\text{C}$)	Feedwater heaters	Optimize extraction steam arrangement, heater configuration; consider ambient T effects
Norouzi, Talebi & Najafi (2020) [17]	SMR	Evaluate energy, exergy and exergoeconomic performance of SMR	Steady-state energy/exergy balances; exergoeconomic analysis	$\eta_{\text{energy}} + \eta_{\text{ex}}$ total $\approx 35.3\%$; core concentrates largest irreversibilities	Reactor core	Focus on core optimization; use exergoeconomic for investment decisions
Rad et al. (2023) [9]	Kalina CCHP + solar collectors	Compare different solar collectors for Kalina CCHP; exergoeconomic assessment	Energy/exergy/exergoeconomic modeling; parametric study	PTC best: $\eta_{\text{energy}} 36.71\%$; $\eta_{\text{ex}} 5.506\%$; VT had highest exergy destruction 11.07 MW (annual \$159,100)	Vacuum tube collectors / solar field	Choose PTC; optimize separator pressure & condenser/evaporator temps
Serbanescu (2024) [18]	SMRs (water / gas / molten-salt)	Layered exergy framework for SMRs + safety/risk integration	Conceptual layered exergy balances (kernel $\rightarrow$ core $\rightarrow$ plant $\rightarrow$ user); exergo-risk matrix	Qualitative: core concentrates largest exergy losses; integrated concepts (MSR+others) can improve exergy	Reactor core / RPV (qualitative)	Apply layered framework; integrate technologies (e.g., molten-salt combinations); weigh exergetic gains vs safety
Talebi et al. (2020) [10]	LWR (VVER-1000)	Exergy diagnosis and optimization of VVER-1000; identify irreversibilities	Energy/exergy balances; Firefly optimization	η_{ex} improved 28.99% $\rightarrow$ 29.3% ($\Delta \approx 0.3$ pp); exergy destruction reduced $\approx 1.18\%$	Reactor, turbines, steam generators (order)	Parameter adjustment via metaheuristics; focus on core & turbines
Triki et al. (2023) [11]	PWR + desalination	Cogeneration (electricity + desalination); identify losses	MATLAB model validated; energy/exergy balances	$\eta_{\text{thermodynamic}}$ global $\approx 35.38\%$; core $\approx 50\%$ of exergy destruction; ME-TVC-MED exergy low (6.43%)	Reactor core + desalination evaporators	Improve integration of electric & thermal production; optimize evaporators & thermocompressor
Norouzi et al. (2023) [19]	SOFC + Kalina + HDH/RO (pentageneration)	Integrated pentageneration (power, cooling, water, H_2)	Steady-state modeling; single & multi-objective optimization	$\eta \approx 74.4\%$; $\eta_{\text{ex}} \approx 50.2\%$; multi-objective optimization reduced total exergy destruction by $\approx 0.74\%$	Reactor (core/heat transfer)	Improve SOFC exhaust integration; adjust T, pressure ratios, current density

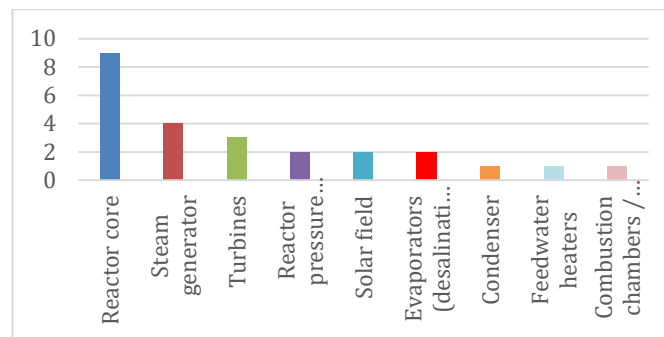
* acronyms: PWR – Pressurized Water Reactor; SMR – Small Modular Reactor; LWR – Light Water Reactor; CCHP - Combined Cooling, Heat and Power; SOFC - Solid Oxide Fuel Cell; VVER - Vodo-Vodyanoi Energetichesky Reaktor; HDH - humidification-dehumidif.; RO – Reverse Osmosis

The literature synthesis shows that the reactor core is the most frequent locus of exergy destruction, followed by steam-generation components, as shown in Figure 4. This predominance is explained by very high local power density and steep temperature gradients within the fuel assembly, which increase entropy production during heat transfer from fuel to cladding and coolant [7;14;15]. Steam generators produce significant exergy loss when primary/secondary temperature profiles are



poorly matched (large local ΔT or pinch), raising irreversibility in heat exchange [11;20]. Turbine losses are mainly associated with non-isentropic expansion, flow inefficiencies and leakage, while RPV-related destruction typically stems from structural heat leakage and complex heat exchanges that detailed T_{fiss} modeling can reveal [10;15]. Hybrid and multi-generation studies show that when present, solar fields and desalination evaporators can dominate exergy losses in the auxiliary chain, so mitigation priorities must be context-dependent [9;21].

Figure 4 - Frequency of components identified as the main source of exergy destruction.



As future work, detailed thermodynamic models coupled with Python-based data processing and optimization routines will be implemented. Simulation scenarios can include a literature-based base case, optimized cases varying key parameters, such as core outlet temperature, steam pressure and turbine isentropic efficiency, and sensitivity runs. Deliverables can comprise a normalized exergy database, documented simulation and optimization scripts, comparative reports of base versus optimized scenarios, sensitivity analyses, a prioritization matrix of technical measures by expected exergy gain, and validation criteria for reproducing benchmark studies.

4 CONCLUSIONS

This comparative review consolidates recent exergy evidence and shows that reactor cores and steam-generation components are the primary sources of irreversibility in nuclear and hybrid plants. Standardizing exergy reporting and integrating exergoeconomic metrics are necessary to prioritize interventions that are both technically effective and economically justified. Short-term mitigation should focus on core heat-transfer improvements and steam-generator pinch matching, followed by targeted turbine and RPV interventions; hybrid plants additionally require optimized collector and evaporator integration. The next stage is to quantify these potential gains with detailed modeling and optimization, producing actionable system improvements and design recommendations.

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