

Review

Nuclear Energy as a Strategic Resource: A Historical and Technological Review

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Abstract

Nuclear energy has undergone a significant transformation over the past decades, driven by technological innovation, shifting safety priorities, and the urgent need to mitigate climate change. This study presents a comprehensive review of the historical evolution, current developments, and future prospects of nuclear energy as a strategic low-carbon resource. A structured literature review was conducted following Kitchenham's methodology, covering peer-reviewed articles and institutional reports from 2000 to 2025. Key advances examined include the deployment of Small Modular Reactors, Generation IV technologies, and fusion systems, along with progress in safety protocols, waste management, and regulatory frameworks. Comparative environmental data confirm nuclear power's low life-cycle CO₂ emissions and high energy density relative to other generation sources. However, major challenges remain, including high capital costs, long construction times, complex waste disposal, and issues of public acceptance. The analysis underscores that nuclear energy, while not a standalone solution, is a critical component of a diversified and sustainable energy mix. Its successful integration will depend on adaptive governance, international cooperation, and enhanced social engagement. Overall, the findings support the role of nuclear energy in achieving global decarbonization targets, provided that safety, equity, and environmental responsibility are upheld.

Keywords: nuclear energy; small modular reactors; nuclear fuel cycle; radioactive waste management; climate change mitigation



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1. Introduction

The global energy sector is undergoing a profound transformation driven by the urgent need to reduce carbon emissions and ensure a stable, secure, and sustainable electricity supply. The sustainable growth of the world's population, along with industrial development and technological advancements, has significantly increased energy demand, prompting a gradual transition from fossil fuels to cleaner and renewable sources.

In 2019, total final energy consumption reached 418 EJ/year [1]. In the same year as shown in Figure 1a, renewable energies such as photovoltaic solar and wind generated 680 TWh/year and 1420 TWh/year, respectively, accounting for 8% (2.5% photovoltaic and 5.5% wind) of global electricity [2,3]. Hydropower was responsible for 4290 TWh/year, representing 16% of global electricity supply, while nuclear energy generated 2970 TWh/year, contributing 10% to global electricity production [3]. Altogether, low- or zero-carbon

technologies accounted for 37% of total electricity generation [4]. However, fossil fuels continued to dominate, producing 25,818 TWh/year, which represents 63% of global production [5].

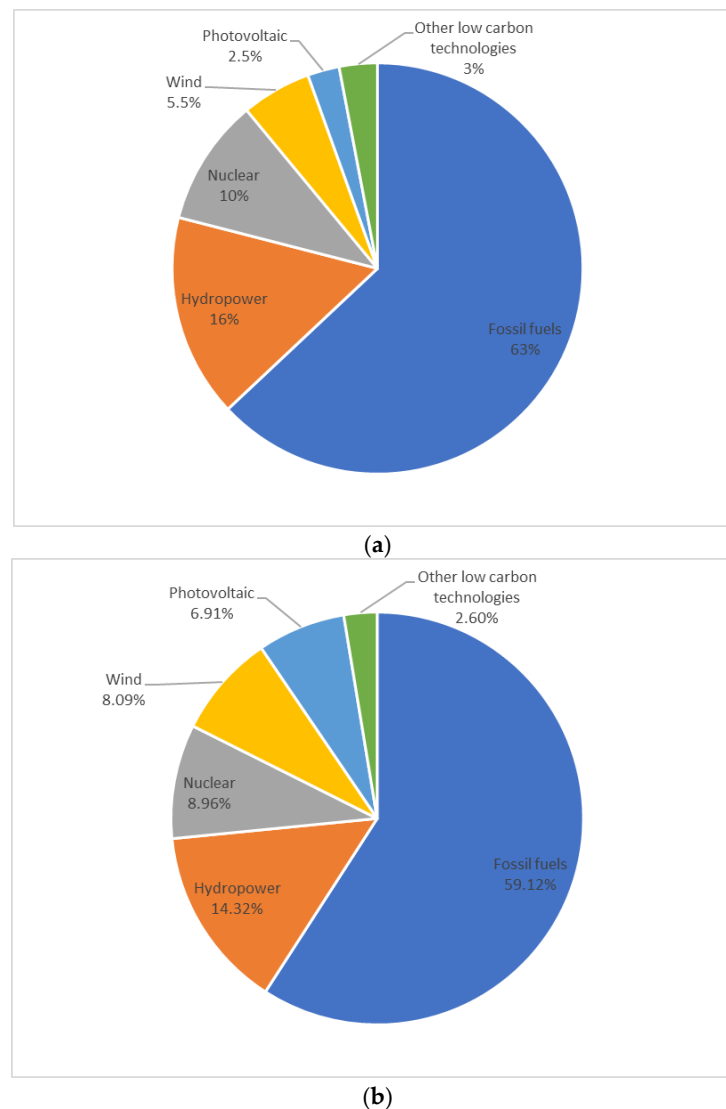


Figure 1. Energy generated in (a) 2019 and (b) 2024.

On the other hand, in 2024, as shown in Figure 1b, there was a continued increase in renewable energy generation compared with 2019. Solar photovoltaic and wind power, for example, generated 2130.64 TWh/year and 2497.64 TWh/year, respectively, together accounting for 15% of global electricity production (6.91% solar and 8.09% wind), representing a significant increase in their share of the energy mix compared to five years earlier. Hydropower was responsible for 4418.96 TWh/year (14.32% of the total), maintaining its role as one of the main renewable sources, although its percentage share varied slightly compared to 2019 due to the growth of other technologies. Nuclear power generated 2746.67 TWh/year, contributing 8.96% of production, a figure that reflects stable output compared to the previous period, although with a slight decline in its share of the global energy mix. Overall, low-carbon energy sources accounted for 40.88% of global electricity production. Despite this progress, fossil fuels continued to dominate with 18,240.90 TWh/year, representing 59.12% of the total. However, this figure marks a slight but noteworthy decrease in their dominant share compared to five years earlier [6].

This dominance of fossil sources in electricity generation is critical, as the energy sector is responsible for 75% of greenhouse gas emissions [7]. This represents a severe problem, given that the Earth has already warmed by more than 1.1 °C [8]. Continuing along this path may lead to a point of no return in global warming. However, this problem also contains its own solution, as the transition of our energy systems to cleaner sources is key [9]. One of the most important strategies for decarbonizing our energy systems is electrification, which involves replacing fossil fuels in industrial or transport sectors. To achieve decarbonization, electricity generation must shift to low-carbon sources. Although this is transforming global energy systems, greater efforts are still required, as fossil fuels still account for more than 60% of global electricity generation [10,11].

In this context, nuclear energy emerges as a strategic alternative to diversify clean energy sources and support the energy transition. Its development dates back to the first half of the 20th century, when the necessary scientific foundations were laid, from the discovery of subatomic particles to the understanding of the atom's structure and nucleus. The discovery of nuclear fission by Hahn and Strassmann in 1939 [12] (theoretically explained by Meitner and Frisch) revealed that heavy nuclei such as uranium could split into lighter elements, releasing large amounts of energy. This reaction, capable of producing a self-sustaining chain, gained strategic relevance with the onset of World War II, driving the Manhattan Project and the development of nuclear weapons, marking the beginning of the atomic age with profound scientific, political, and social implications [13].

The development of nuclear energy for civil purposes in the following decades was heavily conditioned by its military origins. The technological infrastructure, state secrecy logic, and strategic decisions stemming from the Manhattan Project influenced the initial configuration of the sector. The light-water reactor (originally designed for naval applications) became the dominant design, not due to energy efficiency criteria, but because of technical availability and institutional interests. This technological trajectory had complex structures, high costs, and a negative public perception that worsened after the accidents at Three Mile Island and Chernobyl. Despite technical advances, these limitations defined the following decades, with a notable slowdown in new implementations [14].

Over time, nuclear energy has evolved through various generations of reactors, each incorporating improvements in safety, efficiency, and sustainability. Generation I reactors, developed in the 1950s and 1960s, were directly derived from military technologies, such as the British Magnox and early American PWRs [15]. Generation II, adopted since the 1970s, introduced improvements in reliability and active safety, establishing the foundation of today's global nuclear fleet [16]. Generations III and III+, in operation since the early 21st century, feature modular designs, passive safety systems, and extended lifespans, including models such as the Advanced Boiling Water Reactor (ABWR), Advanced Passive 1000 (AP-1000), and European Pressurized Reactor (EPR) [14,15]. Currently, Generation IV reactors (still under development) aim to address challenges of sustainability, efficient resource use, and greater intrinsic fault tolerance, with notable technologies such as Very High Temperature Reactor (VHTR), Molten Salt Reactor (MSR), and Sodium-cooled Fast Reactor (SFR) [15].

Nuclear energy is the second-largest low-carbon source of electricity in the world after hydropower. Figure 2 shows the number of nuclear reactors currently in operation in a selection of countries: the United States, France, China, Russia, Japan, India, South Korea, Canada, the United Kingdom, and Ukraine [17]. Nuclear energy accounts for one-third of all low-carbon electricity production and contributes to energy security [18]. As more intermittent renewable sources such as solar and wind are integrated, nuclear energy offers a continuous and reliable energy supply, as its output can be adjusted in response to changes in supply and demand [18,19].

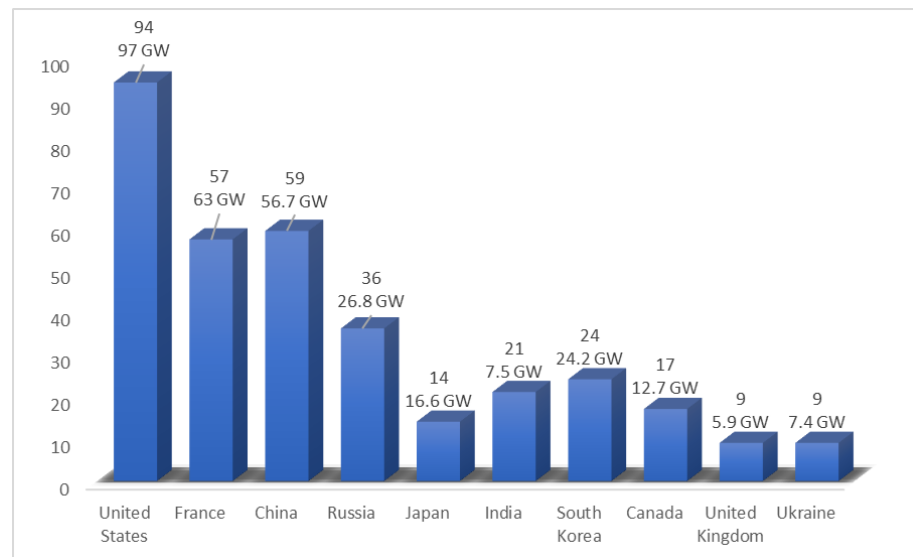


Figure 2. Number of operational nuclear reactors and total installed nuclear capacity (GW) in selected countries as of 2025.

There are three reactions through which nuclear energy can be obtained: fusion, fission, and radioactive decay [20]. Among these, fission is the most commonly used, while fusion is still under development. The production of electricity through nuclear energy occurs via fission, as shown in Figure 3, where energy is released in the form of heat. This heat is used to produce steam that drives turbines, converting mechanical energy into electrical energy [21].

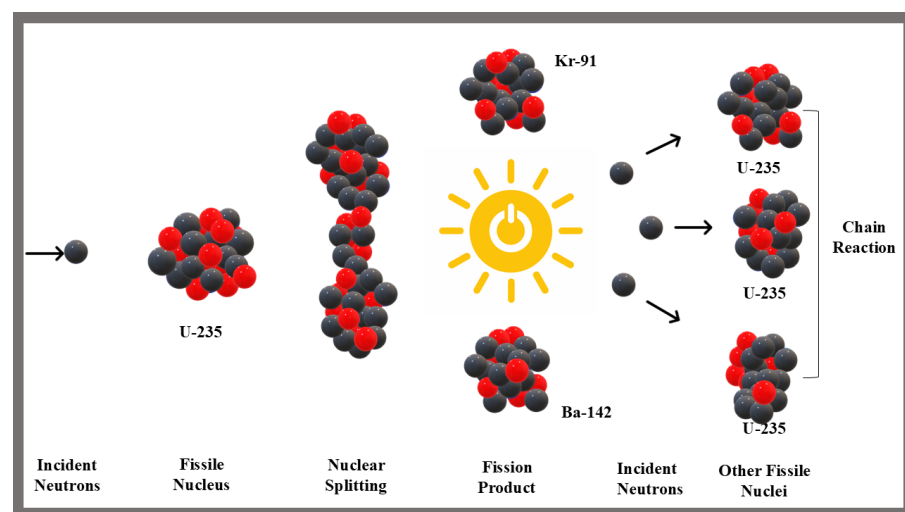


Figure 3. Nuclear fission.

Several recent studies have examined the role that nuclear energy may play in the energy transition and sustainability. Asif et al. [22] explore the role of nuclear energy in the global energy transition, highlighting its benefits as a low-carbon source through a multi-criteria analysis based on expert opinions from various regions. Zubair and Akram [23] address technological advances and current challenges through a comprehensive approach supported by a case study on the Barakah plant. Complementarily, Adamantiades & Kessides [24] emphasize that renewed interest in nuclear energy is driven by fossil fuel price volatility, energy security concerns, and climate change, factors that, along with technological advances in safety and cost, have supported its repositioning in the global energy debate.

The objective of this paper is to critically and thoroughly analyze the work of various authors on the historical development, fundamental principles, and current applications of nuclear energy, highlighting its benefits, challenges, and its impact on the energy, environmental, and social sectors. This analysis seeks to provide a balanced perspective that fosters understanding of this technology and its relevance in the global context.

2. Methodology

In order to collect, synthesize, and critically evaluate the most significant advancements in the field of nuclear energy, a structured bibliographic analysis approach was implemented. The methodological design is based on the guidelines for systematic reviews proposed by Kitchenham [25], which provides a rigorous procedure for identifying, assessing, and interpreting all available evidence on the topic. This framework was complemented and aligned with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure maximum transparency, reproducibility, and scientific rigor. Evidence was gathered from highly reliable sources, including scientific databases such as Google Scholar, Scopus, ScienceDirect, and SpringerLink, as well as technical reports from international organizations such as the International Atomic Energy Agency (IAEA), the International Energy Agency (IEA), the Nuclear Energy Agency (NEA), and the Intergovernmental Panel on Climate Change (IPCC). The temporal scope of the search was limited to the period between 2000 and 2025. The search strategy employed a combination of key terms (“Nuclear Energy”, “Small Modular Reactors”, “Generation IV Reactors”, “Nuclear Fusion”, “Nuclear Waste Management”, “Nuclear Safety”, “Nuclear Regulation”, and “Environmental Impact of Nuclear Energy”) structured with Boolean operators to optimize the retrieval of relevant studies.

The screening and selection of studies were carried out systematically, following the explicit phases recommended by PRISMA. The initial identification phase gathered the raw set of records. The second phase, screening, involved reviewing titles and abstracts to exclude studies without direct relevance. Finally, the eligibility phase consisted of a full-text analysis of the preselected articles, rigorously applying the inclusion and exclusion criteria, with priority given to those with strong methodological foundations and a focus on technology, sustainability, governance, or regulation. This selection protocol, inspired by the application of PRISMA in studies such as Ramírez López et al. [26], will be represented in this study through a flow diagram.

Once the final literature corpus was consolidated, structured data extraction and subsequent qualitative synthesis were performed. Adopting a methodological approach inspired by high-rigor studies such as Hayibo et al. [27], predefined attributes were systematically extracted from each study, including type of technology, thematic area, geographic focus, methodological design, and main contribution. The subsequent qualitative analysis aimed to establish correlations between technological developments, regulatory evolution, and the strategic role of nuclear energy in the global energy transition. In addition, a critical evaluation of the consistency and scope of the literature was conducted to identify patterns, disciplinary strengths, and research gaps. The synergy between Kitchenham’s systematic procedure and PRISMA’s transparency architecture enables the development of a detailed, objective, and representative synthesis of the state of the art, providing a solid foundation for future research and policy formulation in the sector.

3. Advances in Nuclear Energy (2000–2025)

Nuclear energy has undergone constant evolution as a strategic component within the global energy portfolio, driven by technological innovations, emerging safety requirements, and the imperative of environmental sustainability. This section examines major devel-

opments recorded between 2000 and 2025, including the advancement and maturation of Small Modular Reactors (SMRs), progress in Generation IV fission reactor technologies, and breakthroughs in nuclear fusion research. It also explores advancements in safety systems, regulatory changes impacting the deployment of new technologies, and strategies for radioactive waste management and recycling. Finally, the environmental impact of nuclear energy is assessed, including a comparison with other generation sources and its potential contribution to reducing greenhouse gas emissions. The analysis offers a structured overview of the technological, regulatory, and environmental factors shaping the current landscape and future direction of nuclear energy.

3.1. Small Modular Reactors (SMRs)

According to the IAEA [28], SMRs are defined as advanced nuclear reactors with an electrical output of up to 300 MWe. These reactors exhibit the following characteristics: first, modularity refers to the standardization of components manufactured in factories and later assembled at the final site; second, passive safety implies that in the event of an unexpected incident, the reactor will automatically shut down and cool without external intervention [29,30]; and third, SMRs can provide backup power during the intermittency of renewable sources such as solar and wind energy [31].

The safety of SMRs relies heavily on the performance of their passive safety systems, which are designed to mitigate accidents without human intervention or external power supply. However, their absolute reliability under certain extreme conditions remains an area of critical analysis. On one hand, advanced designs such as the i-SMR developed in South Korea demonstrate exceptional performance through a fully passive approach, including emergency core cooling, auxiliary water feed, and containment cooling systems. Rigorous simulations of this system have projected a core damage frequency of 1×10^{-9} , highlighting inherent robustness in loss-of-coolant scenarios and positioning it as a reliable alternative [32].

Nevertheless, the reliability of passive safety can be compromised by the failure of specific components. Studies on the MASLWR design, using the RELAP5 code, have shown that although natural circulation mechanisms are effective, the overall system may depend on critical elements such as vent and recirculation valves. Simulations of failures in these valves revealed a continuous loss of coolant inventory and a significant reduction in the system's cooling capacity [33].

Integral pressurized water reactor (PWR) SMR designs, such as the MASLWR, i-SMR, and NuScale Power Module, exhibit notable differences in their thermohydraulic design philosophy, reactivity control, and safety strategies. The MASLWR, with a net output of 35 MWe, relies exclusively on natural circulation for core cooling under all operating conditions, employing a vertical helical-coil steam generator to produce superheated steam [34]. In contrast, the i-SMR, rated at 170 MWe, while also an integral design, incorporates four internal reactor coolant pumps (RCPs) and is distinguished by the elimination of boron as a neutron absorber, which simplifies coolant chemistry and core reactivity control [35]. The NuScale Power Module (77 MWe) also relies on natural circulation for primary circuit heat transfer and, like the i-SMR, uses a standard 17×17 fuel assembly format. However, its key technical and regulatory differentiator is the first design to obtain certification from the U.S. Nuclear Regulatory Commission, validating its passive safety system that ensures autonomous shutdown and cooling without human intervention or external power, and demonstrating its resilience to severe external events such as electromagnetic pulses or aircraft impacts [36]. While the i-SMR mitigates the risk of a large-break loss-of-coolant accident (LOCA) by eliminating primary piping entirely, the MASLWR addresses safety

through an Automatic Depressurization System (ADS) and a water-submerged containment that acts as the ultimate heat sink.

These contrasting findings suggest that, while the passive safety paradigm in SMRs is fundamentally sound, its successful implementation for large-scale commercial deployment requires meticulous attention to the redundancy of key components, particularly those prone to mechanical failure that could compromise the integrity of the entire safety chain.

In recent years, SMRs have gained international attention as a strategic alternative for diversifying the energy mix and decentralizing electricity generation, leading to their development in various countries. In the United States, the NuScale design became the first SMR to receive design certification from the Nuclear Regulatory Commission (NRC). Each power module has a capacity of 77 MWe, with the possibility of operating multiple modules simultaneously [36]. In South Korea, the Korea Atomic Energy Research Institute (KAERI) developed the SMART reactor (System-integrated Modular Advanced Reactor) for the cogeneration of electricity and water desalination [36,37]. This integral reactor has a capacity of 100 MWe and was approved in 2012 by the Nuclear Safety and Security Commission (NSSC) [37].

The economic analysis of SMRs reveals a complex landscape, where theoretical advantages and projected competitiveness confront significant uncertainties and discrepancies in cost estimates. From an optimistic perspective, SMRs are proposed as a cost-effective alternative due to their simplified design and reduced component count, which positively influences their economic feasibility [38]. This potential is reflected in early estimates suggesting that investment costs could remain below USD 2000/kWe, making them viable in regions with limited capital or grid infrastructure [39]. More recent analyses in the European context place the levelized cost of electricity (LCOE) at approximately EUR 85/MWh, a competitive figure. However, it is acknowledged that the average capital cost, estimated at EUR 7031/kW, is about 41% higher than that of large-scale reactors, although the lower absolute investment reduces the project's financial risk [40].

The economic viability of SMRs is inherently multifaceted and critically depends on the application, context, and implementation strategy. For example, in hybrid systems for island economies such as the Canary Islands, SMRs have proven to be a viable solution, achieving competitive levelized costs of electricity (LCOE) ranging from EUR 46 to EUR 84/MWh when integrated with renewables and hydrogen production [41,42]. However, this viability is not universal; an analysis of the Helsinki metropolitan area revealed that, for district heating, only reactors designed exclusively for thermal output were economically feasible, whereas cogeneration models faced significant challenges [43]. At the European market level, although their average LCOE of EUR 85/MWh is competitive, SMRs exhibit a capital cost 41% higher than that of large reactors, making intervention through subsidies and adaptive regulatory frameworks necessary [40]. To mitigate these high costs, modularization emerges as a key strategy, as prefabrication can reduce construction costs by up to 45%, thereby enhancing their economic competitiveness [44].

Nevertheless, this perspective is challenged by studies revealing a marked gap between manufacturer-reported costs and those estimated through theoretical models. For instance, Steigerwald et al. [45] indicate that while the advertised construction cost for a design such as CAREM reaches USD 23,187/kWe, simulations project a median LCOE exceeding USD 700/MWh. Critically, the same study concludes that, under realistic parameters and even assuming 10% learning rates, none of the SMR designs analyzed achieved positive profitability, thus calling into question their actual competitiveness compared to other low-carbon technologies.

Numerous studies have highlighted the potential of SMRs to revolutionize the combined production of electricity and potable water. Ingersoll et al. [46] explain that the

NuScale reactor can simultaneously supply electrical energy and residual heat for powering various desalination technologies, such as reverse osmosis and thermal processes like multi-effect distillation and flash distillation. Yoo et al. [47] report that combining SMRs with desalination technologies, particularly reverse osmosis, proves to be more economical and efficient than multi-effect or flash distillation. Their findings also suggest that hybrid systems combining SMRs and renewable energy sources with reverse osmosis may reduce both electricity and water costs.

Recent research expands on these findings by evaluating hybrid systems that integrate SMRs with other processes, such as low-carbon hydrogen production. Chalkiadakis et al. [42] assess the feasibility of a hybrid system that combines SMRs and hydrogen generation. Their analysis highlights the role of SMRs in decarbonizing the power grid and integrating hydrogen production through electrolysis. The study demonstrates that such a hybrid system can supply electricity at competitive costs while profitably producing pink hydrogen and significantly reducing CO₂ emissions. Additionally, a study conducted in the Czech Republic by Sklenka and Losa [48] confirms the potential of SMRs to transform the energy mix. Due to their modular design and cogeneration capacity, they can supply electricity and heat for industrial and urban applications, reduce initial investment, and modernize existing nuclear facilities such as Dukovany.

The versatility of SMRs extends beyond electricity generation, positioning them as key platforms for cogeneration and polygeneration systems aimed at decarbonizing multiple sectors. Theoretical proposals explore a wide range of integrated applications, such as the combined production of electricity and clean hydrogen through thermochemical cycles with estimated exergy efficiencies of 21.42% [49], or polygeneration systems that utilize waste heat to simultaneously produce electricity, cooling, hydrogen, and potable water, achieving efficiencies of 46.44% [50]. Other studies examine the feasibility of coupling SMRs with direct air carbon capture (DACC) technologies and high-temperature electrolysis [51]. Although many of these advanced configurations remain at the stage of techno-economic analysis and simulation [52,53], the application of SMRs in cogeneration has progressed toward practical implementation in specific domains. A notable example is the SMART system developed in South Korea, a pilot project specifically evaluated for nuclear desalination applications, demonstrating the technical and economic viability of dual electricity and freshwater production at a modular scale [54].

3.2. Generation IV Reactors

Generation IV reactors represent a set of advanced nuclear technologies designed to enhance safety, sustainability, economics, and resistance to proliferation. Their development aims to overcome the limitations of current reactor designs by introducing new concepts, closed fuel cycles, and alternative coolants that enable operation at high temperatures with improved efficiency [18]. These reactors are being promoted through the Generation IV International Forum (GIF), a global initiative involving 13 countries and Euratom, which represents the 27 European Union member states. The forum coordinates research and development efforts on Generation IV nuclear reactors with the objective of making them viable for industrial deployment by 2030 [55].

GIF has identified six priority technology systems based on their ability to meet the forum's strategic goals:

Gas-cooled Fast Reactor (GFR): This system uses fast neutrons for fission and helium as a coolant, allowing for high operating temperatures without significant pressure. This enhances thermal efficiency and fuel conversion. GFRs are designed for closed fuel cycles, optimizing fissile material use and minimizing radioactive waste [56].

Molten Salt Reactor (MSR): MSRs utilize molten salts as both fuel and coolant, operating at high temperatures and low pressure. These features improve thermal efficiency and safety. The design allows for fuel recycling, reducing waste and improving sustainability [57].

Sodium-cooled Fast Reactor (SFR): SFRs use fast neutrons and liquid sodium as a coolant. They support closed fuel cycles, reduce waste generation, and enhance material utilization. Operating at a low pressure, they offer improved safety and thermal efficiency [58].

Lead-cooled Fast Reactor (LFR): LFRs use fast neutrons and lead or lead–bismuth as a coolant, allowing for their operation at high temperatures and low pressure. Their design supports closed fuel cycles and enhanced safety due to the chemical inertness of the coolant [59].

Supercritical Water-cooled Reactor (SCWR): SCWRs employ water at supercritical conditions (above 374 °C and 22.1 MPa) as a coolant, enhancing thermal efficiency and simplifying plant design by removing the need for additional components [60].

Very-High-Temperature Reactor (VHTR): VHTRs operate at over 950 °C, using helium as a coolant and graphite as a moderator. They are suitable for cogeneration and hydrogen production, offering high thermal efficiency and improved safety. Their development involves innovations in materials, fuel types, and clean energy systems [61].

The main characteristics of these six technologies are summarized in Table 1.

Table 1. Summary of the main characteristics of Generation IV reactors (Malogulko et al. [56]).

Reactor Type	Coolant	Temperature	Thermal Efficiency	Technological and Functional Potential
GFR	Helium	850 °C	48%	High productivity; high-temperature operation without pressure; improved safety
VHTR	Helium	1000 °C	>50%	High-temperature electrolysis; emissions reduction; thermal efficiency; advanced safety
SFR	Liquid sodium	500–550 °C	40–42%	Fuel recycling; waste management; reaction control; safe electricity production
LFR	Liquid lead	500–600 °C	43%	High thermal resilience; military applications; no specific R&D focus mentioned
MSR	Molten salts (fluorides or chlorides)	600–700 °C	44–50%	Fuel flexibility (including spent fuel); waste reduction; use of advanced materials
SCWR	Supercritical water	374 °C	>45%	Stable electricity production; efficiency; low accident risk; evolution of PWR/BWR designs

Several countries have made progress in constructing Generation IV prototypes. China is developing the CFR-600, an SFR. Russia has built the BREST lead-cooled reactor and leads in SFR operation. The United States, Japan, and France have invested heavily in related research, contributing nearly USD 6 billion over 15 years. India is pursuing advanced thorium-based technologies through a three-stage program [62].

The economic assessment of Generation IV reactors presents a dual reality, where the potential for significant advancements is counterbalanced by notable financial uncertainties. This complexity is particularly evident in the case of lead-cooled fast reactors (LFRs), for which the specialized literature suffers from scarcity and limited quality, resulting in

extremely wide cost projections. Specifically, estimates for the capital cost of LFRs range from USD 1500 to 25,000/kWe, while LCOE estimates vary between USD 30 and 350/MWh, reflecting the absence of robust financial models [63]. Similarly, the analysis of molten salt reactors (MSRs) projects initial investment costs between USD 2.8 and 3.7 million/MWe and LCOE values ranging from USD 40 to 90/MWh. However, Mignacca and Locatelli [64] warn that these figures are derived from sources with limited methodological transparency, compromising their reliability for strategic decision-making. In contrast to these uncertainties in cost estimation, the economic appeal of Generation IV technologies is grounded in their intrinsic potential. Abram and Ion [65] emphasize that the expected improvements are directly linked to higher thermal efficiency, exemplified by very-high-temperature reactor (VHTR) designs, which can operate at temperatures above 1000 °C, enabling their integration into high-value industrial processes such as hydrogen production. Additionally, their long-term economic viability is reinforced by the potential implementation of closed fuel cycles and actinide recycling, which would reduce both the demand for fresh uranium and the costs associated with the management of long-lived radioactive waste [65].

Despite their potential, Generation IV reactors face technical, regulatory, and economic challenges. These include the development of new materials, design validation under extreme conditions, and the adaptation of current regulatory frameworks to enable commercial deployment. Nevertheless, their implementation is considered essential for long-term decarbonization and technological diversification.

3.3. *Advances in Nuclear Fusion*

Nuclear fusion has long been considered the energy of the future due to its enormous potential to provide clean, safe, and virtually inexhaustible electricity. Unlike fission, fusion involves the merging of two light atomic nuclei (such as deuterium and tritium) to form a heavier nucleus, releasing large amounts of energy [66]. Achieving stable fusion conditions on Earth requires replicating the Sun's extreme environment, with temperatures reaching 100 million degrees Celsius and intense pressure, representing one of the greatest scientific and technological challenges of our time [67].

Two main experimental approaches are currently under study: magnetic confinement and inertial confinement. Magnetic confinement is a key technique in fusion research used to maintain plasma under extreme conditions without losing temperature or stability. This approach employs powerful magnetic fields, generated by superconducting magnets, to contain plasma within devices such as the tokamak (the most representative design) developed extensively in facilities like JET, KSTAR, and ITER [68]. Inertial confinement, on the other hand, uses intense energy pulses, such as lasers or particle beams, to compress and heat a deuterium–tritium capsule, achieving fusion conditions. Recent advances have increased energy gain and brought this technology closer to commercial viability. Facilities such as the National Ignition Facility (NIF) have set records in energy output, demonstrating its potential to deliver clean and sustainable energy [69].

One of the most significant milestones is the continued development of ITER, a joint international project involving China, the European Union, India, Japan, South Korea, Russia, and the United States. ITER is expected to begin experimental operations by the end of this decade. It will use a large-scale tokamak design with deuterium–tritium plasma and aims to produce 500 MW of fusion power from 50 MW of input power [70,71].

The industrial viability of nuclear fusion, despite its significant potential as a carbon-free energy source with an almost inexhaustible fuel supply, is constrained by a series of major scientific and technological challenges, many of which are concentrated in the ITER project. Conceived as the cornerstone of fusion development, ITER must demonstrate the operation of a plasma with a significant net energy gain (a factor of 10), an objective

that depends on resolving multidimensional issues [72]. Among the most critical are maintaining plasma stability through the control of internal turbulence and developing systems capable of sustaining confinement over extended periods [73].

Equally essential is the management of extreme heat loads in edge components and the development of structural materials capable of withstanding the intense neutron fluxes anticipated in future reactors such as DEMO. Fuel cycle self-sufficiency, through internal tritium breeding systems, also constitutes a key technological pillar for long-term sustainability [72]. From an economic perspective, although the fusion reaction offers unprecedented energy density, the infrastructure required for both construction and operation remains extremely costly due to the complexity of the reactors and the advanced safety systems involved [73]. Achieving a competitive levelized cost of electricity is therefore crucial for the eventual commercial deployment of fusion, highlighting the importance of international collaboration, sustained funding, and knowledge transfer as essential conditions for overcoming these barriers [72,73].

4. Nuclear Safety

Safety is essential to ensure the responsible use of nuclear energy, minimizing risks and protecting both the population and the environment. Over the years, international regulations, advanced technologies, and management strategies have been developed to strengthen safety at nuclear facilities. Among the most relevant advances are the design of safer reactors, the evolution of regulatory frameworks, and the implementation of emergency response measures. These developments have been critical in improving the reliability and global acceptance of nuclear energy [74].

Nuclear accidents have been key events in the evolution of nuclear safety, revealing vulnerabilities and areas for improvement. Incidents such as Three Mile Island, Chernobyl, and Fukushima have demonstrated the importance of robust safety protocols and efficient response strategies. These events have driven the development of stricter regulations, improvements in reactor design, and greater integration between safety and nuclear security, enhancing both risk prevention and mitigation [75].

The modern approach to nuclear safety focuses on the continuous improvement of protection and regulatory systems, with an emphasis on accident prevention and mitigation of radiological risks [76]. Systems thinking has transformed nuclear safety by effectively integrating technological, human, and organizational aspects, enabling a holistic risk analysis. Optimization has driven the development of advanced modeling and predictive analysis tools, facilitating the early identification of vulnerabilities and the implementation of adaptive solutions in the design and operation of nuclear plants. As a result, significant technological progress has been made in raising safety standards and enhancing the ability to respond to potential incidents [77].

Recent advances in nuclear safety focus on the development of passive technologies that enhance reactors' ability to autonomously respond to emergency conditions. The Integrated Passive Safety System (IPSS) proposed by Chang et al. [78] combines multiple passive mechanisms, such as natural convection cooling and pressure relief devices that require no external power, to ensure residual heat removal and reactor containment during severe events. Lim et al. [32] analyze how SMRs incorporate a compact design of the nuclear steam supply system (NSSS), integrating all critical components within a single pressure vessel, significantly reducing the risks of leakage or mechanical failure. Collectively, these technologies aim toward the development of a new generation of reactors with greater intrinsic safety, lower operational dependency, and enhanced passive response, aligned with post-Fukushima standards for more reliable and sustainable nuclear energy.

In parallel, within the field of fusion energy, safety-related technological advances have been consolidated through a defense-in-depth approach. This includes the integration of advanced predictive analysis and simulation methods, such as Failure Modes and Effects Analysis (FMEA) and master logic diagrams, to proactively identify and mitigate potential accident scenarios. Safety has also been strengthened through the implementation of real-time monitoring systems and specific mitigation mechanisms, such as fast-discharge systems for superconducting magnets and improvements in cooling systems. These developments, in both fission and fusion technologies, reflect progress toward a new generation of safer, more resilient nuclear systems aligned with the contemporary challenges of energy sustainability [79].

5. Regulations and Their Impact on the Nuclear Industry

The development and operation of nuclear energy are subject to a complex regulatory framework that addresses the potential environmental and safety risks inherent to this technology. This framework seeks to ensure an equitable allocation of benefits and responsibilities, in line with the principles of energy justice, which promote the internalization and proper management of social and environmental costs. As noted by Heffron and McCauley [80], incorporating justice-based criteria into regulatory policymaking enables a more balanced distribution of risks and benefits, as well as greater legitimacy in decision-making processes.

Nuclear law, as an autonomous discipline, has been consolidated around core principles such as safety, authorization, liability, compensation, sustainable development, and international cooperation. These principles are enshrined in international conventions and supported by organizations such as the IAEA, which provide clarity and predictability regarding the assignment of responsibilities, licensing procedures, and the protection of public health and the environment [81].

In the context of nuclear energy expansion into countries with no prior experience, especially through emerging technologies such as SMRs, the existence of a robust regulatory framework becomes even more relevant. Budnitz et al. [82] emphasize that although SMRs offer advantages such as lower investment costs and better integration into limited electrical grids, their effective deployment depends on the presence of independent and competent regulatory bodies, along with a strong safety culture. International experience demonstrates that these elements are essential for mitigating technical and financial risks, as well as addressing challenges related to construction delays, investment, and public acceptance.

The implementation of legal frameworks for nuclear energy in developing countries or those with weak state institutions presents structural challenges that undermine governance and sectoral safety. In many cases, the push toward nuclear energy in these nations is driven by political and symbolic motivations (such as the pursuit of international prestige) rather than by an energy need justified through technical criteria. This can lead to the premature adoption of nuclear technology without the support of a robust regulatory infrastructure [83]. Such institutional fragility is reflected in the promotion of nuclear projects lacking solid mechanisms to ensure operational safety, waste management, or transparency, resulting in excessive reliance on international standards that may be insufficient in contexts with low regulatory compliance [84].

In this scenario, the International Atomic Energy Agency (IAEA) plays a strategic role by providing regulatory guidance and technical training, enabling states with nascent regulatory structures to progressively align with global standards. However, the success of equitable and resilient nuclear governance in these vulnerable contexts depends not only on the adoption of regulations but also on strengthening institutional capacities and evolving

nuclear law to allow the flexibility necessary to accommodate the specific circumstances of each state [85].

International nuclear law is structured through a combination of binding treaties, non-binding instruments, and technical standards that establish the principles and requirements for ensuring operational safety, the physical protection of nuclear material, safeguards, and civil liability related to the peaceful use of nuclear technology. This framework, led by the IAEA, includes mechanisms for international cooperation, inspections, peer reviews, and the implementation of key conventions such as the Convention on Nuclear Safety and the Joint Convention on the Safety of Spent Fuel Management, along with codes of conduct endorsed by member states [85].

Following events such as the Fukushima accident, it has become clear that regulatory systems should not be conceived as closed, hierarchical structures, but rather as open and interactive systems. Gunawan et al. [86] argue that effective nuclear regulation in high-uncertainty contexts requires institutional flexibility, continuous feedback capacity, and dynamic adaptation to technological, social, and environmental change. This approach enhances the resilience of the regulatory system and improves its capacity to mitigate complex systemic impacts.

The combination of a solid legal framework, principles of energy justice, and adaptive governance mechanisms is essential to ensure the safe, efficient, and socially responsible development of nuclear technology, both in countries with established programs and in those currently adopting it.

5.1. Nuclear Waste Management

Nuclear waste management is one of the main technical, environmental, and social challenges for the sustainable development of nuclear energy. To ensure its safe disposal, nuclear waste must undergo a comprehensive treatment process. This includes several stages, beginning with collection and classification, followed by volume reduction and chemical and physical conditioning, including the concentration of liquid waste. Finally, the waste is immobilized and packaged for storage and final disposal [87].

Radioactive waste is classified based on two main criteria: activity level and radioactive decay duration. Five categories are commonly identified according to their hazard level. For example, Very Short-Lived Waste (VSLW) decays rapidly and can be managed temporarily with relatively basic safety measures. Very Low-Level Waste (VLLW) contains such low concentrations of radioactivity that it poses minimal hazard and requires only minimal protective measures. Low-Level Waste (LLW) and Intermediate-Level Waste (ILW) may contain higher concentrations or longer-lived radionuclides, requiring stricter control protocols [88]. High-Level Waste (HLW) contains extremely high radioactivity levels, often generating heat, and thus requires rigorous containment and long-term storage strategies. HLW is the most complex to manage due to its high toxicity and longevity [88].

According to the IAEA, radioactive waste management is divided into three stages: pretreatment, treatment, and conditioning [87]. Pretreatment involves extracting and segregating materials from their original location using cutting, dismantling, or demolition techniques, and placing them into provisional containers to facilitate handling. The treatment phase reduces waste volume using methods such as drying for spent fuel residues and central components, or crushing for pipes, equipment, and structures, enabling safe packaging. During conditioning, waste is transformed into a stable and durable state suitable for long-term storage, using vitrification for high-level waste or cementation for other types [89].

The predominant global approach for managing high-level waste, such as spent nuclear fuel, is geological disposal. This method provides a definitive solution for permanently

isolating such waste by depositing it in underground repositories located hundreds of meters below the surface in stable rock formations [87–90]. The geological disposal concept is based on a multiple barrier system, which integrates several layers of protection: first, the waste is enclosed in highly resistant metal containers; second, it is surrounded by backfill materials such as clay or cement that minimize interaction with groundwater; and third, the host rock acts as a natural barrier to delay the migration of radionuclides into the biosphere. This multi-layered strategy ensures both environmental protection and the safety of future generations [90].

The final disposal of radioactive waste, although technically centered on the concept of Deep Geological Repositories (DGRs), faces a dual set of critical challenges encompassing both geomechanical engineering and socio-political legitimacy. On the technical side, significant risks persist even at geologically stable sites such as those in Sweden and Finland. Modeling studies indicate a high potential for thermo-mechanical damage in deposition boreholes, a risk that increases if the low permeability of the host rock delays the saturation of the barrier system beyond the thermal peak, which may occur 50 to 100 years after waste emplacement [91]. These technical factors, including the complex coupled interactions of thermal, hydraulic, mechanical, and chemical processes, increase uncertainties in long-term safety predictions [92].

Parallel to these technical challenges, site selection is hindered by complex social dynamics. Public perception, shaped by concerns about the toxicity of the waste and the aging of infrastructure, is a decisive factor [92]. The case of contaminated soil in Fukushima illustrates how the absence of clear guidelines and public distrust (rooted in values such as interregional equity and distributive justice) can stall the final disposal process [93]. The experience of South Korea further supports this reality: nine failed attempts to establish a repository between 1986 and 2004 demonstrated that success cannot be achieved through technical criteria alone. It was only on the tenth attempt (through a process that included special legislation and a public vote to confirm citizen acceptance) that a site was selected, highlighting that building trust and fostering social participation are essential for the viability of such projects [94].

In addition to geological storage, other methods are employed to safely contain spent fuel during an intermediate management phase. Initially, spent fuel elements are stored underwater in specially designed pools at nuclear power plants. These pools enable the cooling of recently discharged fuel and provide shielding from radiation. Once residual heat decreases, the fuel can be transferred to dry storage systems composed of sealed metal cylinders, shielded with high-density concrete. Among the technologies used to enhance the efficiency of these systems is Ducrete, a composite material developed by the Idaho National Engineering and Environmental Laboratory (INEEL), which combines depleted uranium with conventional concrete, allowing for more effective radiation attenuation and more compact designs [95].

5.2. Nuclear Fuel Recycling

Recycling spent nuclear fuel is a key strategy to improve resource efficiency and reduce the volume of high-level waste. This process recovers fissile and fertile materials, primarily by converting U-238 into fissile plutonium, allowing part of the used material to be reintegrated into the nuclear fuel cycle [96]. Advanced reprocessing technologies are also being developed in conjunction with fast neutron reactors to convert not only plutonium and uranium but also long-lived actinides into less hazardous products. This comprehensive approach extends the useful life of original uranium and reduces both the quantity and radiotoxicity of waste, supporting a more sustainable and safer nuclear sector [62].

The nuclear fuel cycle is addressed through two main strategies, as shown in Figure 4. In the open cycle, fuel is used once in the reactor and, after a cooling period, is sent directly to final disposal. This results in the loss of potentially reusable fissile material in the form of high-level waste. In contrast, the closed cycle includes a reprocessing phase in which spent fuel is chemically treated to separate and recover valuable components such as uranium and plutonium. These materials are then recycled for the fabrication of new fuel. This approach not only maximizes resource utilization but also reduces waste volume and radiotoxicity [90].

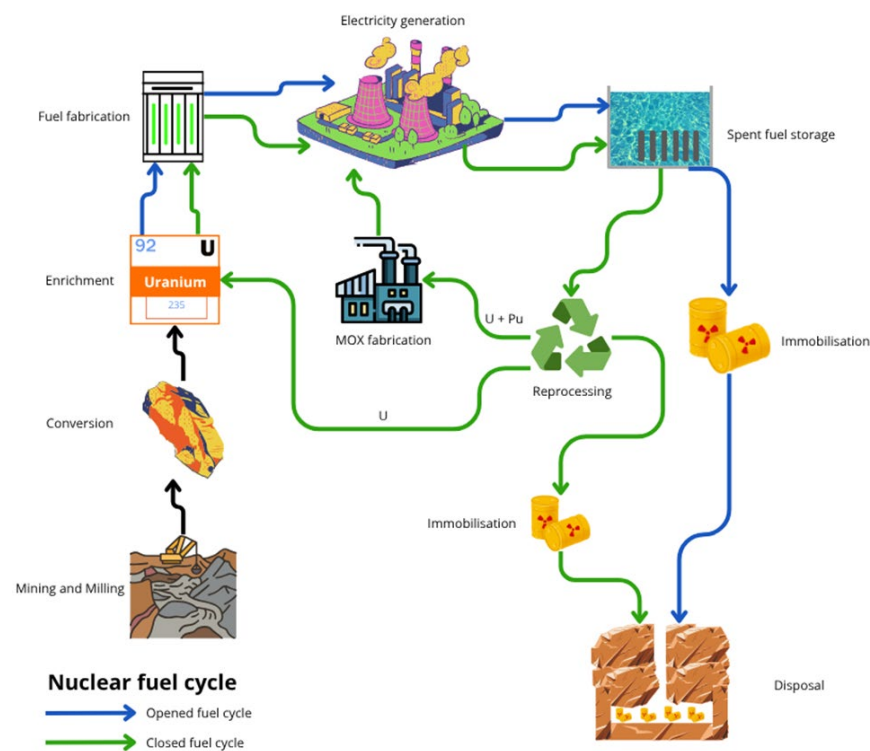


Figure 4. Nuclear fuel cycle.

The most widely used method for spent fuel recycling is the PUREX (Plutonium and Uranium Recovery by Extraction) process. In this method, spent fuel is dissolved in nitric acid, allowing for the efficient separation of fissile materials from fission products [97]. An organic solution composed of tributyl phosphate (TBP) mixed with a hydrocarbon diluent is then used to selectively extract uranium and plutonium. These materials can be recycled and reused to manufacture new fuel, such as Mixed Oxide Fuel (MOX) [97].

Recycling becomes even more relevant in the context of Generation IV reactors, particularly fast neutron reactors. Lindley et al. [98] used the ORION fuel cycle model to simulate scenarios in which transuranics recovered from light water reactors (LWRs) are recycled in sodium-cooled fast reactors (SFRs). Their results showed that through a closed fuel cycle with minimal reprocessing losses, the inventory of transuranics can be halved with each generation of SFRs. This progressive reduction lowers the radiotoxicity of spent fuel to levels comparable to that of natural uranium in approximately 500 years [97,98]. This approach highlights the potential of SFRs to transform waste management and move toward a more sustainable and secure long-term solution.

Nuclear fuel recycling represents a technically viable option to improve fuel cycle sustainability, reduce pressure on geological repositories, and optimize resource utilization. However, its widespread adoption will depend on the ability to balance its technological benefits against the economic, regulatory, and geopolitical challenges associated with large-scale implementation.

6. Environmental Impact

Nuclear energy entails environmental risks that require rigorous and specialized management, particularly with regard to protecting the natural and human environment from radiation exposure. As noted by Salter et al. [99], the potential damage associated with nuclear facilities can be significant if proper controls are not implemented, especially in the event of accidental discharges of radioactive materials that alter the chemical and biological composition of ecosystems. Furthermore, incidents such as Three Mile Island, Chernobyl, and Fukushima have demonstrated that the environmental and social consequences of nuclear accidents can extend beyond national borders, affecting public perception and generating sustained opposition to the development of new nuclear projects [100]. These precedents have placed environmental concerns at the forefront of contemporary nuclear energy planning and evaluation, requiring increasingly rigorous and transparent environmental impact assessments.

Nuclear accidents trigger deep and long-lasting ecological consequences that go beyond the immediate effects on human health, compromising biodiversity and the integrity of ecosystems. The release of radionuclides such as cesium-137 and strontium-90 following disasters like Chernobyl and Fukushima results in persistent soil and water contamination, affecting multiple levels of the trophic chain [101,102]. Scientific evidence has documented a wide range of biological impacts on exposed wildlife, including genetic, physiological, and morphological alterations in species as diverse as butterflies, birds, monkeys, and plants [102,103]. These effects manifest in reduced genetic diversity, decreased reproductive capacity, and behavioral changes, ultimately compromising the resilience and adaptive capacity of populations [101–104]. Beyond the harm to individual species, such events affect key ecosystem services and generate heightened public perception of eco-environmental risk. This underscores the need to move beyond the compartmentalization of nuclear and environmental risks and to integrate a holistic ecological perspective into energy governance and planning [104,105].

On the other hand, according to the IPCC and IEA, nuclear energy is characterized by near-zero operational CO₂ emissions during electricity generation [106]. When assessing its full life cycle (including uranium extraction and processing, plant construction, decommissioning, and waste management), indirect emissions are identified, although these remain considerably lower than those associated with fossil fuel-based technologies. The IEA also highlights that, over the past 50 years, nuclear energy has contributed to avoiding nearly 70 gigatons of CO₂, underscoring its crucial role in climate change mitigation [5–107]. In this context, McCombie and Jefferson [108] emphasize that nuclear energy exhibits favorable environmental performance compared to other low-carbon technologies, with low land use requirements per unit of electricity generated, lower CO₂ emissions, and high efficiency in the use of materials such as steel and concrete, in contrast to the high land, rare metals, and critical material demands of photovoltaic and wind technologies.

One of the main ongoing concerns is the management of nuclear waste, which remains a critical challenge for the sustainable development of atomic energy. According to Hejazi [109], the magnitude of this waste is often overestimated in public opinion, since, in quantitative terms, it represents a minimal fraction compared to waste from fossil fuels. Globally, approximately 12,000 tons of spent fuel are generated annually, versus more than 25 billion tons of carbon emissions from fossil sources [109]. Additionally, through reprocessing, up to 96% of the spent fuel (mainly uranium and plutonium) can be recovered, significantly reducing the volume of waste requiring final disposal. Nevertheless, it is also acknowledged that the success of waste management policies depends not only on the safe implementation of geological repositories but also on strengthening public trust in the technological and financial frameworks that support them.

Despite the perceived risks associated with accidents and waste, nuclear power presents a relatively low environmental footprint compared to other energy sources, especially when considering the full life cycle. Its inclusion in a low-carbon energy mix should be based on objective, comparative analysis that considers not only climate potential but also technical, economic, territorial, and social viability.

6.1. Comparison with Other Energy Sources

Nuclear power plants contribute significantly to the reliability of the electricity supply, not only because of their low carbon footprint but also due to their ability to maintain grid stability, particularly in systems with a high share of variable renewable energy. According to the IEA, nuclear plants can partially adjust their output to follow demand fluctuations and complement intermittent supply from sources such as solar photovoltaics and wind power [107]. As the share of these technologies increases, so too will the need for firm backup services, in which nuclear energy can play a key role. In this context, comparisons of energy sources must take into account not only emissions but also operational reliability, energy density, material use, and associated environmental and social risks, as shown in Table 2.

Table 2. Comparison of electricity generation sources (data partially adapted from Markandya and Wilkinson [110], Brook and Bradshaw [111], United Nations [112], and IEA [113]).

Energy Source	CO ₂ -eq. Emissions (g/kWh) (Direct + Indirect) [110]	Land Use (km ² /TWh) [111]	Fatalities (Accidents Per TWh) [111]	Solid Waste (Tons Per TWh) [111]	Remarks [110]	Estimated Deployment Time [112]	Demand Flexibility [113]
Coal	1290	2.1	161	58,600	High impacts on health, emissions, and waste.	Up to 5 years or more	Moderate to Low (dispatchable, slow ramps, baseload)
Gas	689	1.1	4	–	Lower than coal, but still with significant emissions.	Up to 5 years or more	Very High (fast start/stop, agile, balances renewables)
Nuclear	30	0.1	0.04	–	Low mortality, radioactive waste, and high decarbonization potential.	10–15 years	Low (baseload only, constant output, inflexible)
Hydro	37	50	1.4	–	Low emissions, high local ecological impact (river fragmentation).	Up to 5 years or more	Very High (near-instant response, grid stability, reserves)
Wind	9	46	0.15	–	Low mortality, intensive land and material use.	1–3 years	Very Low (non-dispatchable, variable, weather-dependent)
Solar	116	5.7	0.44	–	Very low emissions, but extensive land use.	1–3 years	Very Low (non-dispatchable, variable, weather-dependent)
Biomass	460	95	12	9170	Potentially high emissions and use of agricultural land.	3–6 years	Moderate (dispatchable, slow ramps, baseload)

A life cycle analysis of electricity generation technologies shows that nuclear energy has one of the lowest carbon footprints per kilowatt-hour, comparable to wind power and lower than solar photovoltaics, especially when considering material demands, component manufacturing, and construction and decommissioning phases [110]. Likewise, studies such as that by Brook and Bradshaw [111] demonstrate that when integrated impacts are assessed (including emissions, land use, metals, water, and biodi-

versity) nuclear and wind energy offer the best cost–benefit ratio in terms of emissions, land use, and safety, positioning them as strategic options for mitigating climate change without compromising biodiversity.

In contrast, renewable energy sources, while characterized by low emissions and minimal environmental risks, exhibit low energy density. This implies that large territorial areas are needed for their implementation. Technologies such as solar, wind, and hydropower involve relatively low and localized risks (such as dam failures or equipment fires), but require costly infrastructure and greater land intervention. By contrast, nuclear energy, primarily based on fission, is distinguished by a high energy density of processed fuel, which translates into lower input volume requirements, limited waste generation, and a reduced land footprint for equivalent levels of electricity generation [114].

A comparison between nuclear energy and other sources, such as renewables and fossil fuels, reveals that both categories can make substantial contributions to climate change mitigation. On the one hand, renewables benefit from significant political incentives and generate negligible waste, although they face challenges such as high production costs and low efficiency in certain applications. On the other hand, nuclear technologies are notable for their near-zero greenhouse gas emissions, operational stability, and potential for cost and waste reduction, yet still face issues of proliferation, waste management, and public acceptance, especially following events like Fukushima. Therefore, none of these technologies should be considered mutually exclusive but rather complementary components of a diversified and sustainable energy strategy [115].

6.2. Limitations and Critical Perspectives

Despite its potential for decarbonization and energy security, nuclear energy faces structural, epistemological, and social limitations that compromise its viability as a sustainable solution and its public acceptance. These barriers are not limited to technical challenges but also involve the way public narratives are constructed and inherent risks are managed.

One of the central critiques concerns the public perception of risk, which is often not based on informed evaluation but on strategically constructed narratives. A longitudinal analysis of media coverage in France shows that the press tends to consolidate a positive image of nuclear energy, downplaying systemic issues such as radioactive waste management and the possibility of catastrophic failures. This favorable perception is reinforced through comparisons that depict wind energy as conflictive and unstable, creating a bias that excludes a critical assessment of the risks associated with the nuclear model and prioritizes technological feasibility over democratic deliberation [116]. This citizen ambivalence also reflects a deep mistrust of the institutions responsible for nuclear regulation and operation, which amplifies the perception of risk and limits the social consensus necessary for its expansion [117].

From an epistemological perspective, nuclear energy is hindered by the inability to accurately estimate the probability of severe accidents, which undermines the legitimacy of deterministic models and fuels public apprehension [118]. This uncertainty is evident in the paradox that, although the number of deaths associated with nuclear energy is low compared to other conventional sources, high-severity events such as Chernobyl reveal a systemic vulnerability with long-lasting impacts, thereby affecting its environmental legitimacy [119]. The gap between the technical discourse of experts and the subjective perception of risk among the public is further exacerbated when metrics are used for political purposes, distorting public debate [118]. Even in routine operations, there remains critical ambiguity about the long-term effects of low-dose radiation exposure, as current

epidemiological studies have limited capacity to detect conclusive causal links with diseases such as cancer [120].

Finally, there are structural and economic limitations that challenge the sustainability of nuclear energy. The inherent risk of nuclear safety is so high that coverage in free markets is unfeasible without state subsidies, which undermines the principles of just sustainability and intergenerational responsibility. Moreover, the full life cycle of the technology (from uranium mining to plant decommissioning and waste management) entails an emissions footprint and environmental impacts that contradict its claimed climate benefits. In the face of increasingly competitive and safer renewable technologies, the continued relevance of the nuclear sector demands radical transformations in its governance and a structural reduction in risk in order for it to be considered a truly sustainable option [121].

7. Potential of Nuclear Energy for Carbon Emissions Reduction

Climate change has reinforced the need to transform the global energy system toward low-carbon technologies. In this context, nuclear energy is an already established source of low-carbon electricity with significant potential in deep mitigation scenarios. In addition to its continuous 24/7 operation and flexible dispatch capability, it can support the decarbonization of power systems and complement intermittent renewable sources [5,122].

Numerous studies have shown that energy systems incorporating a substantial share of nuclear energy achieve significant emissions reductions without compromising supply reliability. For example, the study by Majeed et al. [123] asymmetrically evaluates the impact of nuclear energy on carbon emissions in Pakistan, incorporating a life cycle analysis covering plant construction through operation. The authors demonstrate that nuclear energy yields lower emissions over its entire life cycle compared to fossil fuels and emphasize that its deployment alongside renewable sources is essential to achieve comprehensive decarbonization. Similarly, Chen et al. [124] argue that nuclear power is a critical component of the transition to a low-carbon energy system, particularly if it replaces coal in electricity generation. Due to its continuous operation and low life cycle emissions, it is positioned as a reliable source for large-scale emissions reduction. The authors also highlight its cogeneration potential, enabling the simultaneous use of electricity and heat for residential and industrial applications, thereby improving overall system efficiency. In addition, they point to the potential use of advanced reactors to produce hydrogen and desalinate seawater, thereby reducing indirect emissions associated with fossil fuel consumption in these sectors.

According to the IAEA, nuclear energy has historically avoided the emission of nearly 70 gigatons of CO₂, a figure equivalent to the global electricity sector's emissions over five years [115–122]. At present, it continues to contribute to climate change mitigation by preventing the release of more than 1 gigaton of CO₂ annually [123]. Furthermore, IEA reports that nuclear energy currently accounts for 10% of global electricity generation and that this share must be maintained or even increased in order to meet net-zero emission targets by 2050 [122]. This projection entails the sustained expansion of nuclear capacity, including life extension of existing reactors and accelerated deployment of new technologies such as SMRs, to reduce dependence on fossil fuels alongside the growth of renewable sources [107].

Nuclear energy represents a strategic tool in the fight against climate change, particularly as a complement to renewable sources. Its low emissions profile, firm generation capacity, and high land use efficiency position it as a key component of future electricity systems aimed at achieving climate neutrality, provided that institutional, economic, and public acceptance challenges are effectively addressed.

8. Challenges and Opportunities

The deployment of nuclear energy as a strategic component of the global energy transition presents a complex landscape of challenges and opportunities. While nuclear technologies offer considerable benefits in terms of low-carbon electricity generation, energy security, and operational reliability, their widespread adoption remains conditioned by technical, economic, social, and institutional factors. A comprehensive assessment of these dimensions is essential to understand the constraints that hinder nuclear energy's expansion and to identify the strategic pathways that could enhance its role in achieving climate and sustainability goals. The following subsections examine key technological, regulatory, and societal barriers, as well as opportunities for innovation, public engagement, and international collaboration.

8.1. Technological and Economic Barriers

Nuclear energy faces significant barriers that limit its integration as a low-emission source within the energy transition context. One of the main constraints relates to the structural complexity of its infrastructure and the geopolitical risks associated with its implementation. In politically unstable environments, these conditions can even lead to increased emissions, undermining climate mitigation objectives. It is therefore essential to strengthen institutional governance and establish robust risk management mechanisms to ensure the effective and sustainable deployment of this technology [125].

In the case of Japan, the development of advanced nuclear technologies is hindered by financial and regulatory barriers. High upfront investment requirements, combined with extended project approval timelines, create uncertainty that delays implementation. This is compounded by persistent social opposition, fueled by concerns over operational safety and radioactive waste management. Additionally, there are significant technical and infrastructural limitations, such as the need to modernize electrical grids and the country's limited experience with emerging technologies like SMRs. Environmental challenges also remain, particularly those associated with the fuel cycle and facility decommissioning [126].

Globally, key obstacles hinder the consolidation of nuclear energy as an effective tool against climate change. These include the risk of accidents, the complexity of managing long-term radioactive waste, and, in particular, the potential for the civil development of this technology to facilitate nuclear weapons' proliferation. This last issue constitutes a major ethical dilemma, as it can undermine the perceived legitimacy of peaceful uses of nuclear energy, even when its energy and climate benefits are acknowledged [127].

In the United States, the deployment of advanced nuclear technologies encounters several obstacles arising from the economic and regulatory environment. Despite advantages such as operational reliability and low variable costs, the sector is constrained by high capital costs, long and often uncertain construction timelines, and ongoing concerns regarding safety and waste [128]. Moreover, a market context characterized by low natural gas prices, high penetration of renewables, and stalled climate policy further reduces the competitiveness of nuclear energy in the short and medium term. This situation creates structural uncertainty that affects the commercial viability of new projects, particularly in the absence of regulatory or financial mechanisms that supplement revenues from electricity sales [128].

To illustrate these competitive dynamics, Table 3 presents a comparative analysis of the economic profiles of nuclear energy against other key electricity generation sources.

Table 3. Comparison of energy economic profiles (Keppler and Cometto [129], and Ram et al. [130]).

Economic Parameter	Nuclear Energy (LWRs)	Renewable Energies (Wind and Solar pv)	Fossil Fuels (Coal and Gas)
Levelized costs (LCOE) (G20, 2015)	~100 EUR/MWh	Wind: ~73 EUR/MWh Solar PV: ~111 EUR/MWh	Coal: ~67 EUR/MWh Gas: ~80 EUR/MWh
External costs (health and environment)	Very Low (~4 EUR/MWh)	Very low (~2–4 EUR/MWh)	Extremely high (coal exceeds 100 EUR/MWh)
System costs (from variability)	Nil (Firm power source, provides stability).	High and growing (adds up to +50 USD/MWh to cost at high penetration).	Nil (firm and dispatchable source).
Investment profile and risk	Very high capital and long construction times; high market risk.	Decreasing capital; market risk from price cannibalization.	Low capital (especially gas); high regulatory risk from carbon pricing.

8.2. Social Acceptance

The social acceptance of nuclear energy is deeply influenced by ideological, cultural, and territorial factors, rather than a simple assessment of technical risks or economic costs. In many contexts, public skepticism is driven by the memory of past accidents, concerns about waste management, and associations with military uses. As a result, acceptance becomes a process of negotiating values, perceived risks, and benefits [131].

Public perception of nuclear energy is deeply shaped by its historical origins, which are intrinsically linked to military development. This enduring legacy continues to generate distrust and skepticism toward its civilian applications. From the outset, nuclear technology was harnessed for military purposes, and the imagery associated with its destructive power, such as the mushroom cloud and the devastation of Hiroshima and Nagasaki, has left a strong and lasting emotional imprint on the collective memory [132]. This initial association with weaponry contributes to the general public perceiving nuclear energy with “fear” and as an “unknown” risk, a perception that persists even when it is used for peaceful purposes [132,133]. This legacy fosters a cognitive bias that conflates civilian technology with its military counterpart, hindering an objective evaluation of its risks and benefits [134]. As a result, historical mistrust and the public’s tendency to overestimate technological risks become significant barriers to the social acceptance of nuclear energy as a viable solution, particularly in democratic contexts where public opinion plays a crucial role [133,134].

Social acceptance of nuclear energy constitutes a critical and often contentious dimension, historically marked by the emergence of organized opposition movements and persistent public resistance across various national contexts. In Germany, concerns over radioactive waste management (particularly plans for a repository in Gorleben during the 1970s) catalyzed intense opposition, giving rise to a powerful anti-nuclear movement and the founding of the Green Party [135]. Similarly, in Italy, the Three Mile Island accident in 1979 served as a turning point that “rekindled anti-nuclear protests,” shifting the debate from a technical matter to a political choice concerning the country’s development model [136]. Social mobilization in Italy was so significant that it led to a 1987 referendum establishing a moratorium on nuclear energy, an oppositional stance that has remained largely unchanged since then [137].

This dynamic of resistance is neither merely historical nor exclusive to Europe. In contemporary India, social opposition (driven by concerns over safety, waste management, and lack of transparency) continues to be a critical barrier to nuclear expansion, often manifesting through regional protests [138]. Nevertheless, social acceptance is not monolithic; even in ideologically resistant contexts such as Germany, the local economic

benefits associated with nuclear power plants can mitigate negative perceptions and reduce electoral resistance to environmentalist parties [139].

In Sweden, acceptance of nuclear energy reveals strong ideological polarization. Positions for or against nuclear power do not primarily reflect objective evaluations but are shaped by cultural frameworks and personal values [131]. A significant factor is the “proximity effect,” in which support for new facilities decreases significantly when planned near a person’s residence, particularly among individuals with traditional, authoritarian, or nationalist values. Institutional trust also plays an ambivalent role: those who distrust the government are more likely to accept nearby installations, whereas those with high institutional trust tend to be more critical or cautious about expansion. This landscape underscores the need to incorporate principles of procedural and distributive justice in the design of nuclear public policy [131].

In Southeast Asia, the case of Thailand demonstrates how social media can serve as a diagnostic tool for understanding public perception. An analysis of over 12,000 Facebook comments posted between 2009 and 2022 revealed that approximately 80% of opinions were neutral, suggesting the presence of an undecided social base that could be influenced through effective informational strategies [83]. In contrast, 14% of comments expressed negative views, mostly driven by concerns about nuclear accidents, while only 6% expressed support, generally linked to enthusiasm for innovative technologies such as SMRs and nuclear fusion [140].

At the international level, public acceptance of nuclear energy varies significantly between countries depending on perceptual, institutional, and contextual factors. Kim et al. [141] emphasize that public knowledge of nuclear inspections (especially the role of the IAEA) is the most influential factor in promoting strong acceptance, particularly in contexts where reluctant acceptance prevails. They also note that trust in regulatory authorities is crucial for transforming opposition into conditional acceptance, though not necessarily enthusiastic support. Furthermore, risk perception, particularly related to terrorist threats, and the recognition of specific benefits such as electricity generation, significantly influence public attitudes. These findings highlight the need to improve public communication, strengthen technical education, and institutionalize transparency mechanisms to expand societal support for nuclear energy.

In China, public acceptance is strongly influenced by territorial proximity. A comparative study by He et al. [142] revealed that in regions with operational nuclear plants, such as Haiyan, knowledge levels, benefit perception, and institutional trust are significantly higher, leading to greater acceptance. However, despite widespread support, some reluctance to expand the technology remains. This suggests that communication strategies should be context-specific: in regions without prior nuclear experience, the presence of experts and educational campaigns is essential; in exposed areas, emphasis should be placed on the visibility of tangible benefits already achieved.

A successful example of proactive acceptance management is the Experimental Power Reactor (RDE) program in Indonesia [143]. This initiative was conceived not only as a technological project but also as an educational and participatory platform aimed at mitigating public resistance. Located within the Serpong nuclear center, the RDE has facilitated social dialogue, minimizing territorial conflicts and regulatory tensions. Through public communication campaigns, social engineering strategies, and educational tools such as reactor simulators, the program has contributed to strengthening public understanding and rebuilding trust in nuclear energy. This experience demonstrates that, in emerging contexts, the legitimacy of nuclear developments depends as much on sociopolitical anchoring as on technical feasibility [143].

8.3. Research and Development

The Fukushima accident marked a turning point in the trajectory of nuclear energy, prompting a shift in research and development (R&D) priorities. Focus has moved toward technologies with enhanced passive safety, accident-tolerant fuels, and modular designs. China, for instance, adopted third-generation AP1000 and EPR reactors, supported by regulatory reforms and standardized tariff schemes [144]. Globally, this evolution has fostered more active international cooperation aimed at improving safety, optimizing reactor designs, and exploring closed fuel cycles and fast reactors [144].

A central component of current development efforts is SMRs, which offer safer, scalable solutions with more controlled costs. Countries such as the United States, Canada, and the United Kingdom lead in the design and licensing of prototypes, while China and Argentina are advancing pilot projects. This diversity reflects a broad consensus on the need to adapt nuclear technology to decentralized and low-carbon energy systems [144].

This innovation extends to hybrid energy systems, where the reliability of nuclear power complements intermittent renewables to ensure grid stability. To demonstrate this approach, Denysov et al. [145] modeled nuclear-centered scenarios for Ukraine's energy transition toward a low-carbon model. In their analysis, the authors applied advanced diffusion and regression models to forecast the adoption of new technologies, treating economic and technological factors as stochastic variables. This study exemplifies how quantitative modeling can support strategic planning for an energy transition that is both environmentally sustainable and economically viable.

The expansion of nuclear energy is also influenced by political and economic factors. Institutional stability facilitates predictable regulatory environments and safe investment conditions, whereas dependence on hydrocarbons may limit interest in diversifying the energy mix [146]. Despite its advantages in emission reduction, challenges remain, such as the management of high-level waste. In the absence of permanent repositories, strategies such as reprocessing and closed fuel cycles have been promoted to improve uranium utilization and reduce waste toxicity [147].

Innovation has also extended to advanced technologies such as fast reactors, molten salt reactors, and hybrid systems, as well as non-electrical applications like desalination and hydrogen production. These developments are accompanied by regulatory progress and international cooperation, positioning nuclear energy as a key option in decarbonization strategies [148].

From a scientific perspective, the field has evolved from its military origins to civilian applications and, more recently, toward improving operational reliability and safety. Current research incorporates advanced theoretical models to better understand controlled fission, laying the groundwork for a new generation of more efficient and sustainable technologies [149].

9. Conclusions

Nuclear energy is emerging as a strategic component in the global energy transition toward more sustainable, resilient, and low-carbon systems. Over the past decades, it has undergone significant transformation driven by technological advancements, evolving safety priorities, and the urgent need to mitigate climate change. Recent developments in SMRs, Generation IV reactors and fusion technologies have expanded their potential applications in electricity generation, industrial processes, and desalination, reinforcing their role in a diversified energy matrix.

Despite these advances, the deployment of nuclear energy continues to face substantial challenges. Technological, economic, and regulatory barriers, along with social perception, still limit its adoption in certain contexts. Issues such as infrastructure complexity, high

upfront costs, radioactive waste management, and the risk of nuclear proliferation require comprehensive approaches and robust governance frameworks. Furthermore, public acceptance is shaped by cultural frameworks, institutional trust, and geographic proximity to nuclear facilities, highlighting the need for participatory, transparent, and culturally sensitive policies.

The analysis presented here indicates that nuclear energy should not be regarded as a standalone solution, but rather as a complementary technology within a broader low-carbon energy portfolio. Its effective integration will depend on the ability of states to create favorable political, economic, and social conditions, as well as on the strengthening of international cooperation in research, safety, and regulation. In this context, nuclear energy holds the potential to contribute decisively to decarbonization and energy security goals, provided that its development aligns with sustainability criteria, equity, and intergenerational responsibility.

Finally, based on the analysis conducted, several recommendations are proposed for public policy and energy sector stakeholders. First, there is a need to develop more transparent and early-stage communication and public participation strategies, particularly regarding nuclear waste management and the siting of nuclear facilities. Second, it is recommended to promote the integration of flexible nuclear systems such as SMRs into hybrid power grids with high shares of renewables, leveraging their capacity for complementary operation. Lastly, advancing toward greater international regulatory harmonization is advised to facilitate the assessment, certification, and safe deployment of emerging technologies such as Generation IV reactors.

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Abbreviations

The following abbreviations are used in this manuscript:

AP1000	Advanced Passive 1000 Reactor
CFR	China Fast Reactor
CO ₂	Carbon Dioxide
EPR	European Pressurized Reactor
FMEA	Failure Modes and Effects Analysis
GFR	Gas-cooled Fast Reactor
GIF	Generation IV International Forum
HLW	High-Level Waste

IAEA	International Atomic Energy Agency
IEA	International Energy Agency
ILW	Intermediate-Level Waste
INEEL	Idaho National Engineering and Environmental Laboratory
IPCC	Intergovernmental Panel on Climate Change
IPSS	Integrated Passive Safety System
ITER	International Thermonuclear Experimental Reactor
KAERI	Korea Atomic Energy Research Institute
LLW	Low-Level Waste
LFR	Lead-cooled Fast Reactor
LWR	Light Water Reactor
MOX	Mixed Oxide Fuel
MSR	Molten Salt Reactor
NEA	Nuclear Energy Agency
NRC	Nuclear Regulatory Commission
NSSC	Nuclear Safety and Security Commission
NSSS	Nuclear Steam Supply System
PUREX	Plutonium and Uranium Recovery by Extraction
RDE	Experimental Power Reactor (Reaktor Daya Eksperimental)
SMR	Small Modular Reactor
SCWR	Supercritical Water-cooled Reactor
SFR	Sodium-cooled Fast Reactor
TBP	Tributyl Phosphate
VHTR	Very-High-Temperature Reactor
VLLW	Very Low-Level Waste
VSLW	Very Short-Lived Waste

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