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Environmental Impact Assessment of Nuclear Power Plants

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Abstract

Nuclear energy research, initiated in 1939, has advanced significantly with technological progress. In the 21st century, global energy policies have increasingly prioritized sustainable development and climate change mitigation. Conventional energy production, primarily dependent on fossil fuels such as coal, oil, and natural gas, contributes extensively to carbon emissions, exacerbating global warming and environmental degradation. Additionally, the finite nature of fossil fuel reserves underscores the necessity of alternative energy sources. As a low-carbon energy option, nuclear power presents a viable solution to reducing environmental impact. Unlike fossil fuels, it does not produce greenhouse gas emissions during electricity generation, positioning it as a competitive and environmentally sustainable energy source. However, challenges such as radioactive waste management, long-term storage, and leakage risks remain unresolved. Public perception of nuclear energy is further shaped by historical incidents such as Chornobyl (1986) and Fukushima (2011). Nevertheless, advancements in reactor safety, containment technologies, and risk management have significantly mitigated these concerns. Compared to hydroelectric and thermal power plants, nuclear facilities require less land and do not emit pollutants such as NO_x and SO_2. Despite high construction costs, nuclear energy contributes to long-term energy security through economic and environmental benefits. The future role of nuclear power in the global energy landscape will depend on addressing key challenges, including waste disposal, accident prevention, and environmental impact. Integrating advanced safety protocols and efficient waste management practices further strengthens its position as a critical component of sustainable energy policies. This research assesses nuclear energy's viability as a sustainable energy source, critically analyzing its benefits and drawbacks within the broader discourse on environmental responsibility.

Keywords: Environmental Pollution, Climate Change, Nuclear Waste, Nuclear Energy, Sustainability.

1. INTRODUCTION

The growing energy demand is guided by world economic advancements, along with studies indicating that coal reserves may run out in 250 years while oil in 50 years has raised the demand for nuclear energy as an alternate means of energy supply [1-2]. There is no denying that energy is one of the most valuable assets today and even essential for the continuity of life. Energy consumption is steadily increasing to sustain energy demand and maintain an acceptable quality of living. Most of the world's energy comes from fossil fuels. However, in recent years, the expanding energy demand has not been met with sufficient ability [3], as the contribution of renewable energy sources has not reached an adequate magnitude. The environmental impact of fossil fuels is also considerable. Emitting greenhouse gases exactly influences climate change, damaging the environment and endangering the habitats of living organisms. Scientists identify fossil fuels as the primary driver of climate change. The extensive use of these fuels in industry, transportation, residential areas, and vehicles poses the risk of resource depletion. Consequently, countries are compelled to shift toward alternative energy sources and increase the use of domestic energy resources. In the 21st century, "energy diversity" has become a crucial element of global energy policies, with nuclear energy gaining increasing significance within this context. Nuclear energy is widely utilized in electricity generation and sectors such as technological defense industries and medicine. Agriculture, industry, and research are significant application areas of nuclear energy [4]. The rapid advancement of artificial intelligence (AI) and digital technologies has led to a significant increase in global energy demand. Data centers have substantially increased their energy consumption due to the widespread adoption of AI applications. For instance, with the rapid adoption of generative AI tools, the energy consumption of data centers is expected to increase by 160% by 2030.

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Additionally, in 2022, data centers accounted for approximately 1% of global electricity consumption, and their electricity demand is projected to range between 1.5% and 3% by 2026. This trend indicates that the share of AI and digital technologies in energy consumption is continuously increasing. Furthermore, according to the International Energy Agency (IEA), global electricity demand is expected to grow at an average annual rate of 4% until 2027, with 85% of this increase anticipated to come from developing economies. These data suggest that the rapid development of AI and digital technologies will significantly contribute to the rising global energy demand and underscore the increasing importance of sustainable energy policies [5-7]. It is an attractive alternative to mitigate high oil and natural gas prices and reduce energy dependency in countries heavily reliant on external energy supplies. Although establishing nuclear power plants (NPPs) involves high initial costs, the operational costs of energy production are less volatile compared to fluctuations in coal, natural gas, and oil prices. For instance, the average cost of constructing an NPP ranges between \$6 billion and \$9 billion [8]. Additionally, uranium, the raw material for nuclear energy plants, is distributed globally. The primary uranium reserve-holding countries include Canada, Australia, Kazakhstan, Russia, and Namibia. With its capacity to respond to the rapidly growing energy demand, ensure energy security, and reduce air pollution and greenhouse gas emissions, nuclear energy is more appealing than other energy sources [8].

This study evaluates the advantages and disadvantages of nuclear energy as an alternative energy source from a sustainability perspective. It also examines global nuclear energy applications, the environmental impacts of NPPs, and the management of radioactive waste. Additionally, it investigates the long-term ecological consequences of NPP accidents and discusses the role of nuclear energy in energy security.

2. NUCLEAR ENERGY AND NUCLEAR POWER PLANTS WORLDWIDE

Nuclear energy is obtained from the fission reactions occurring within the nuclei of radioactive elements such as uranium and thorium. This energy is released through fission and fusion reactions resulting from splitting atomic nuclei [9]. NPPs have significantly lower emission rates than thermal and hydroelectric power plants. In addition to their safety advantages, NPPs provide long-term economic benefits despite their high establishment costs due to their low fuel and operational expenses. Another notable feature of these plants is their operational lifespan, typically between 30 and 40 years [10].

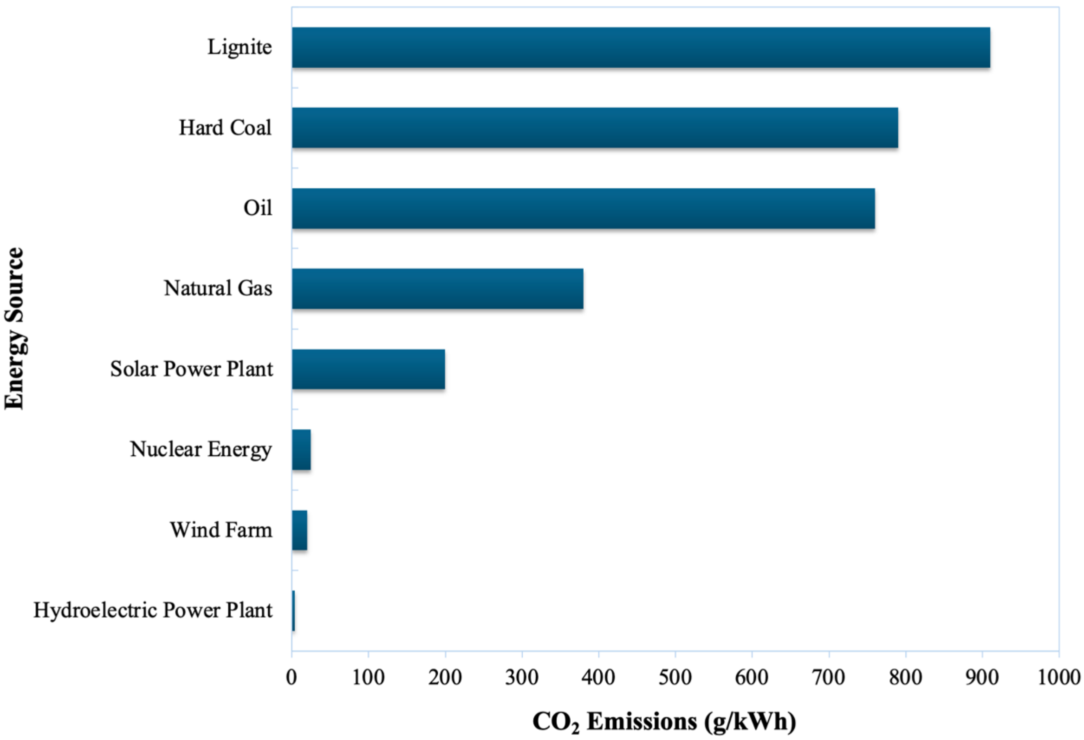

Figure 1. CO_2 Emissions of Different Energy Sources (g/kWh) [10].

Figure 1 compares CO_2 emissions from various energy sources. Hydroelectric power plants (4 g/kWh), wind power plants (20 g/kWh), and nuclear energy (25 g/kWh) are among the energy sources with the lowest carbon emissions. These sources also stand out as environmentally friendly and sustainable for energy production.

In NPPs actively used in commercial production today, uranium is predominantly preferred as the fuel. Uranium, abundantly available in nature, has no significant industrial applications beyond this domain. Another critical raw material for nuclear energy production is thorium. Turkey is among the countries with the largest thorium reserves globally, possessing a total of 9,100 tons of uranium (U_3O_8) and 380,000 tons of thorium (ThO_2) [11]. The potential of thorium in nuclear energy production should be further explored, and Turkey's strategic advantages in this area should be utilized. The energy production processes of NPPs inevitably lead to the generation of nuclear waste. These wastes are primarily generated from cleaning reactor cooling systems and fuel storage pools. Nuclear waste is stored until its activity decreases or is mixed with cement or bitumen to prevent environmental contamination, then buried in land masses or seabeds. Depending on the type of waste and storage methods, it is possible to reprocess certain fuels, particularly those containing uranium and plutonium. These materials can be recovered in reprocessing facilities and reused in energy production. It is common practice to store spent fuels in intermediate storage before transferring them to final disposal facilities. These processes generate approximately 3-5 m^3 of solidified waste annually [11].

Table 1. Global Nuclear Energy Status in 2022 [12].

Country	Operating Reactors (Number)	Operating Reactors (Total MW)	Reactors Under Construction (Number)	Reactors Under Construction (Total MW)	2022 Production Share (TWh)	2022 Production Share (Total %)	Total Operating Experience (Years)	Total Operating Experience (Months)
USA	92	94,718	2	2,234	772.2	18.2	4,825	2
France	56	61,370	1	1,630	282.1	**62.6**	2,449	9
China	54	52,181	20	20,284	395.4	4.9	623	6
Russia	37	27,727	3	2,700	209.5	19.6	1,447	7
Japan	10	9,486	2	2,653	60.3	5.9	2,020	6
South Korea	25	24,489	3	4,020	167.5	30.4	640	9
India	19	6,290	8	6,028	42.7	3.1	594	1
Canada	19	13,624	0	0	92.6	14.6	953	6
Ukraine	15	13,107	2	2,070	81.0	6.0	563	6
United Kingdom	9	5,883	2	3,260	43.6	14,5	163	3
Spain	7	7,123	0	0	55.9	20.9	286	7
Czech Republic	6	3,934	0	0	30.4	36.4	283	3
Sweden	6	6,937	0	0	50.9	29.8	266	0
Pakistan	6	3,262	0	0	22.2	16.2	98	9
Belarus	1	1,110	1	1,110	4.4	11.9	92	3
Finland	5	4,394	0	0	24.2	33.9	175	0
Slovakia	4	1,868	2	880	14.8	**59.2**	184	7
Hungary	4	1,916	0	0	15.0	**46.7**	150	4
Switzerland	4	2,973	0	0	23.2	36.0	191	2
UAE	3	4,011	1	1,310	19.3	6.8	63	1
Germany	3	4,055	0	0	31.9	**5.8**	834	8
Argentina	3	1,641	1	25	7.5	5.4	97	2
Belgium	6	4,936	0	0	41.7	**46.4**	324	7
Bulgaria	2	2,006	0	0	15.9	33.2	96	0
Romania	2	1,300	0	0	10.2	19.3	41	11
South Africa	2	1,854	0	0	10.1	4.9	76	3
Mexico	2	1,552	0	0	10.5	3.5	61	1
Brazil	2	1,884	1	1,340	13.7	2.5	63	3
Bangladesh	0	0	2	2,160	0	0	4	3
Egypt	0	0	2	2,200	0	0	0	0
Slovenia	1	688	0	0	5.3	37.8	41	3
Armenia	1	416	0	0	2.3	24.3	55	0
Netherlands	1	482	0	0	3.9	3.3	48	3
Iran	1	915	1	974	6.7	1.7	11	4
Türkiye	**0**	**0**	**4**	**4,456**	**0**	**0**	**0**	**0**
Worldwide[a,b]	**438[c]**	**393,823[c]**	**58**	**59,334**	**2,486.6**	**100.0**	**19,764**	**11**

[a] The total figures include the following data from Taiwan, China: 3 units, 2 859 MW(e) in operation and 22.9 TW·h of electricity supplied, accounting for 9.1% of the total electricity mix.
[b] The total operating experience also includes shutdown plants in Italy (80 years, 8 months), Kazakhstan (25 years, 10 months), and Lithuania (43 years, 6 months), and shutdown and operational plants in Taiwan, China (239 years, 8 months).
[c] The total figures include data for units where operation remained suspended: India (4 units; 639 MW(e)) and Japan (23 units, 22 193 MW(e)).

Scientific and technological studies on nuclear energy began in 1939, with the first nuclear energy production in the United States. The first NPP generating electricity became operational in 1957. Today, approximately 64.5% of the world's electricity production comes from fossil fuels (38.7% coal, 18.3% gas, 7.5% oil), 16.6% from hydropower, 17.1% from nuclear energy, and 18% from renewable energy sources. These figures demonstrate the significant role of nuclear energy in the global energy supply. Globally, there are 438 nuclear reactors with an electricity generation capacity of 393,823 MW. However, some reactors are not operational; for instance, four reactors in India and 23 in Japan have been decommissioned.

In contrast, three new reactors in China have been added, collectively producing 2,859 MW of energy. France, the leading country in nuclear energy production, generates 62.6% of its electricity from NPPs. Furthermore, 58 new NPPs are currently under construction worldwide, and once completed, these plants will add a total installed capacity of 59,334 MW [12].

Nuclear energy is vital for sustainable energy policies and low carbon emission targets. However, nuclear energy research must progress regarding energy production, waste management, and minimizing environmental impacts. With its natural resources and strategic reserves, Turkey has the potential to enhance its energy production capacity and become a significant player in the international arena. Nevertheless, the future of nuclear energy varies by country, depending on their energy policies and environmental concerns. For example, Germany's policy of phasing out nuclear energy has accelerated the adoption of renewable energy sources. In this context, the role of nuclear energy in the global energy balance continues to evolve according to individual countries' strategic goals and technological capacities. This process is a gateway to the embrace of nuclear by states seeking energy security and the private sector, fueled by the skyrocketing need for power. Technology companies have looked to nuclear energy in recent years as they grapple with the increasing energy consumption demands of AI and data center operations. As an example, Google can buy nuclear energy thanks to small modular reactors (SMR) to run its AI data centers, signing such an agreement with the company "Kairos Power" [13]. Likewise, Amazon has also signed three new agreements to fund nuclear energy projects for its cloud computing subsidiary, Amazon Web Services (AWS), among others, to build several new SMRs [14]. Microsoft also announced it would obtain power from the Three Mile Island nuclear plant to power its AI data centers [15]. This trend reflects the growing need of technology giants for sustainable and reliable energy sources.

The data presented in Table 1 comprehensively reflect the status of nuclear reactors worldwide, including their capacities, contributions to energy production, and operational experience. According to the data, nuclear energy holds strategic importance in global energy production due to its low carbon emissions and high energy efficiency. France, where 62.6% of electricity is generated from nuclear power, stands out as one of the most dependent countries on nuclear energy. Similarly, countries like Slovakia, Hungary, and Belgium also meet a significant portion of their electricity needs through nuclear energy. On the other hand, some countries, such as Germany, have adopted gradual nuclear phase-out policies, shifting their focus toward renewable energy sources. However, other nations continue to invest in nuclear energy to ensure long-term energy security and achieve sustainability targets. In this context, developing economies and energy-dependent countries consider nuclear energy a crucial component of their energy strategies. The construction of the Akkuyu NPP in Turkey is ongoing within this framework. This project involves installing four VVER-1200 reactors, each with a capacity of 1,114 MW. The first unit is expected to be commissioned in 2025, while the subsequent units are scheduled to become operational in 2026, 2027, and 2028, respectively [16]. This development underscores Turkey's strategic approach to enhancing energy security and reducing carbon emissions, positioning nuclear energy as a critical element of the country's energy policy.

3. ENVIRONMENTAL IMPACTS OF NUCLEAR ENERGY

Carbon emissions caused by fossil fuels are among the leading global environmental issues. However, the environmental impacts of NPPs emerge on a different scale than those caused by fossil fuels. Issues such as radioactive pollution, loss of thousands of lives, or severe injuries due to nuclear accidents are frequently debated aspects of nuclear energy use in the public sphere [17]. Nuclear energy has benefits and drawbacks like other energy sources [18-19]. These drawbacks are evaluated within the framework of environmental, human, and economic impacts. While the environmental effects of NPPs are more limited than fossil fuels, they are higher when compared to renewable energy sources. Fossil fuels accelerate global warming and air pollution by releasing greenhouse gases such as carbon dioxide (CO_2) and sulfur dioxide (SO_2). In contrast, NPPs do not emit carbon or sulfur dioxide. On an annual basis, nuclear energy prevents approximately 2,300 million tons of CO_2 and 42 million tons of SO_2 emissions, significantly contributing to reducing environmental damage [20]. Additionally, nuclear energy production does not generate fly ash, preventing the production of 210 million tons annually. These data demonstrate that nuclear energy holds significant advantages over fossil fuels regarding environmental impact. However, the most critical impact of nuclear energy on human health is the risk of radiation exposure. Radiation can cause long-term and permanent harm to human health, leading to severe diseases such as cancer. Particularly in the aftermath of nuclear accidents, widespread radioactive contamination directly affects human lives and ecosystems. Such effects increase concerns about the use of nuclear energy and encourage the consideration of renewable energy sources as more environmentally friendly alternatives in energy policies. The environmental impacts of renewable energy sources are generally more limited and less severe.

Table 2 highlights the multidimensional nature of nuclear energy's environmental impacts, emphasizing the need to consider both its positive and negative aspects. While nuclear energy plays a significant role in combating climate change by reducing greenhouse gas emissions, it also brings challenges, such as radioactive waste management and radiation risks. In this context, nuclear energy policies must balance their environmental and human impacts and contribute to sustainable energy goals.

Table 2. Environmental Impacts of Energy Sources [21].

	Climate Change	Acid Rain	Water Pollution	Soil Pollution	Noise	Radiation
Oil	X	X	X	X	X	-
Coal	X	X	X	X	X	X
Natural Gas	X	X	X	X	X	-
Nuclear	X	-	X	X	-	X
Hydropower	X	-	X	X	-	-
Wind	-	-	-	-	X	-
Solar	-	-	-	-	-	-
Geothermal	-	-	-	X	-	-

Table 2 compares the environmental impacts of various energy sources and the issues they cause. The data shows that solar, wind, and geothermal energy are the energy sources with the lowest environmental impacts. These renewable energy sources are significant in future sustainable energy policies due to their environmentally friendly characteristics. While hydropower and nuclear energy also contribute to some environmental challenges, they stand out for their low carbon emissions. In contrast, fossil fuels such as coal and oil are the energy sources with the highest environmental impacts. Reducing their usage is critical in combating climate change and environmental pollution. Under normal operating conditions, NPPs are noted not to have adverse effects on agricultural lands, vegetation, tourism activities, or air quality. NPPs require less land than other energy sources and generate limited amounts of environmentally harmful by-products such as ash and slag. These characteristics make nuclear energy a relatively low-impact option on the ecological environment.

Additionally, NPPs help avoid environmental problems caused by fossil fuels, such as acid rain, air pollution, and biodiversity loss from mining activities. From the perspective of greenhouse gas emissions, nuclear energy significantly reduces carbon emissions compared to coal. NPPs are essential in combating climate change by preventing the release of millions of tons of carbon dioxide annually. However, it must be acknowledged that every energy production method entails environmental risks and adverse effects. While no energy production method is entirely risk-free, nuclear energy is advantageous due to its low carbon emissions and sustainability [22-27]. Nuclear energy is a significant opportunity for countries dependent on external energy sources because it provides clean, reliable, and low-cost electricity. Global electricity demand is increasing significantly due to the widespread adoption of energy-intensive technologies such as AI, big data analytics, and cloud computing, as well as the growing use of electric vehicles and the accelerating pace of digitalization. Technology companies consume vast amounts of energy to ensure the uninterrupted operation of data centers and to support high-performance AI models. Additionally, expanding innovative city applications, the Internet of Things (IoT), and 5G infrastructure further increases the burden on electricity grids. Therefore, ensuring an affordable and uninterrupted electricity supply has become more critical. The electricity generated by NPPs is lower than that generated by many other energy production methods, creating a strategic advantage for countries aiming to reduce energy costs. Furthermore, reprocessing nuclear fuel enables more efficient use of resources. Valuable materials such as uranium and plutonium can be recovered from spent fuel and reused in energy production. This enhances the sustainability of nuclear energy from an environmental perspective and makes it a viable option in terms of economics and resource management. Unlike fossil fuels, nuclear energy does not emit carbon dioxide into the atmosphere, giving it the potential to mitigate the effects of global warming. Nuclear energy plays a vital role in the energy transition process due to its low carbon emissions, high energy density, and economic advantages [28].

4. NUCLEAR ENERGY: WASTE MANAGEMENT, ENVIRONMENTAL IMPACTS, AND ADVANTAGES

NPPs hold a significant advantage over other energy production methods regarding fuel consumption. A thermal power plant operating at the same power level consumes more fuel than an NPP. In contrast, NPPs can generate the same amount of energy using only one-thousandth of the fuel thermal plants require. This highlights the resource efficiency of nuclear energy production. However, despite these advantages, nuclear energy generation results in three levels of radioactive waste: low, intermediate, and high [29].

Low- and intermediate-level wastes can generally be treated similarly to conventional industrial waste and, after a certain period, can be reassessed as radioactive industrial waste. HLW, on the other hand, primarily consists of used fuel and materials that have become radioactive. The uranium content in spent fuel is approximately 3-4%, while the remaining comprises recyclable materials. However, deciding to recycle these materials depends on countries' energy policies and strategies. For example, while some countries choose to reprocess these materials, others do not adopt this approach. This results in variations in international approaches to nuclear waste management.

NPPs do not rely on combustion reactions, unlike conventional power plants. During the energy production process, reactor buildings are maintained under low pressure to prevent the uncontrolled release of radioactive elements. Air release from the plant is carefully controlled and passes through several layers of filters before being released into the environment via controlled ventilation systems. This process is essential for reducing environmental risks and advancing safety. Latest data (2024) show that around 17% of global electricity sites rely on nuclear energy, a resource of great potential to replace rapidly depleted fossil energy. Currently, there are 438 NPPs in operation worldwide, three decades after the first commercial nuclear plant was established. As far as environmental issues are concerned, the core of an NPP produces about 200 m^3 over about 40-50 years. High-end containment technologies are utilized for radioactive waste storage, making it not sociologically harmful to nature. In this sense, nuclear energy provides sustainability and security for waste treatment. Nuclear energy is also beneficial in minimizing harmful emissions, e.g., CO_2, SO_2, and nitrogen oxides (NO_2). SO_2 and NO_2 are carcinogenic substances that pose significant health risks, and their reduction benefits public health. Moreover, the production of nuclear energy assists in reducing greenhouse gas emissions that cause global warming, making it less harmful to the environment.

Table 3. Sudden Death Risk Rates of Energy Systems [30].

Energy Systems	Fatal Accidents (Per Year)	Total Sudden Deaths	Total Energy Produced (GW-Year)	Death Rate (Per GW/Year)
Coal (Including Mining Accidents)	62	3,600	10,000	0.36
Oil (Including Prod. & Transp.)	63	2,070	21,000	0.10
Natural Gas (Explosion)	24	1,440	8,600	0.17
Hydropower (Dam Failure)	8	3,839	2,700	1.42
Nuclear Power Plant (Chernobyl)	1	31	1,000	0.031

Table 3 presents a comparative analysis of the sudden death risks associated with various energy systems, highlighting their respective safety profiles. The selection of an energy source for production should consider its economic and environmental implications and potential risks to human life. As global energy policies increasingly emphasize safety and sustainability, understanding the risk levels and fatality rates of different energy sources is critical [30].

Coal remains one of the most hazardous energy sources due to frequent mining accidents, which often result in significant loss of life. According to Table 3, coal-related fatal accidents occur at a rate of 62 per year, leading to a total of 3,600 sudden deaths. Despite its high-risk profile, coal remains widely utilized due to its substantial energy production of 10,000 GW-year. However, given its detrimental effects on environmental quality and occupational safety, coal-based energy generation necessitates stringent regulatory oversight and a strategic shift toward safer and more sustainable alternatives.

Oil extraction and transportation also pose considerable risks. As indicated in Table 3, oil-related fatal accidents occur 63 times annually, resulting in 2,070 sudden deaths. Notably, oil contributes to a higher total energy output than coal, reaching 21,000 GW-year. Although the fatality rate per unit of energy is comparatively lower, oil-related accidents, particularly those associated with transportation, have severe ecological consequences. Therefore, robust safety protocols and risk mitigation strategies should be implemented to minimize human and environmental hazards associated with oil-based energy production.

Natural gas is often considered a relatively safer energy source than coal and oil. However, gas-related explosions can still lead to substantial casualties. As reported in Table 3, 24 fatal accidents linked to natural gas occur annually, resulting in 1,440 sudden deaths. The total energy produced from natural gas is 8,600 years, demonstrating a moderate balance between energy efficiency and safety risks. Although the overall fatality rate remains lower than coal and oil, proactive safety measures must be continuously enhanced to mitigate explosion-related hazards.

Hydropower is generally recognized as an environmentally sustainable energy source. However, catastrophic infrastructure failures, such as dam collapses, can cause extensive fatalities. According to Table 3, hydropower-related accidents, though relatively infrequent at eight occurrences per year, have resulted in 3,839 sudden deaths, highlighting the potential for large-scale disasters. The total energy output from hydropower is 2,700 GW-year, considerably lower than that of fossil fuel-based systems. These findings underscore the necessity of sustained investments in infrastructure resilience and the implementation of stringent safety regulations to prevent large-scale human casualties resulting from hydropower failures.

Nuclear energy emerges as the safest energy source in terms of immediate fatality rates. Table 3 reveals that NPPs have recorded only one fatal accident, leading to 31 sudden deaths. Nuclear energy production has generated 1,000 GW of energy despite its relatively low fatality rate. While nuclear power is associated with rigorous safety protocols that enhance its operational reliability, major nuclear disasters, such as the Chornobyl accident, demonstrate the potential for long-term health and environmental repercussions. Consequently, effective radioactive waste management, comprehensive emergency preparedness, and stringent regulatory frameworks are imperative to ensuring nuclear energy systems' long-term viability and security [30].

4.1. Radioactive Waste

Radioactive waste is materials containing radionuclides (radioactive nuclei) or contaminated by these particles, with radioactivity levels exceeding acceptable limits. These wastes originate from various fields, including nuclear energy production, medicine, industry, and agriculture, where radioactive materials are utilized. Radioactive waste can exist in solid, liquid, or gaseous forms and is classified into low (LLW), intermediate (ILW), and high-level waste (HLW) based on its radioactivity levels and potential hazard levels. The process involving the extraction, processing, and disposal of nuclear fuel after its operational lifespan is called the "Nuclear Fuel Cycle." This cycle consists of two fundamental stages:

a) Front-End Fuel Cycle,

b) Back-End Fuel Cycle.

The front-end fuel cycle includes the extraction, conversion, enrichment, and fabrication of uranium ore for use in reactors. These steps form the preparatory phase required for the NPP to commence energy production. On the other hand, the back-end fuel cycle involves the removal, storage, reprocessing, and final disposal of spent fuel used in nuclear reactors. Approximately three years after a nuclear plant begins operation, the spent fuel is removed from the reactor and becomes part of this process.

Radioactive waste is generated at every stage of the nuclear fuel cycle, even during uranium mining and processing. However, the highest-level nuclear waste is produced when fuel is burned in the reactor. The radioactivity of spent nuclear fuel takes more than 100,000 years to decay to the level of natural uranium ore. This highlights the critical importance of radioactive waste management and long-term storage strategies. The classification, management, and disposal of radioactive waste are paramount for environmental protection and human health. The sustainability of nuclear energy production relies on the safe storage and management of nuclear waste. In this context, developing nuclear waste management and secure storage systems remains crucial to national and international energy policies.

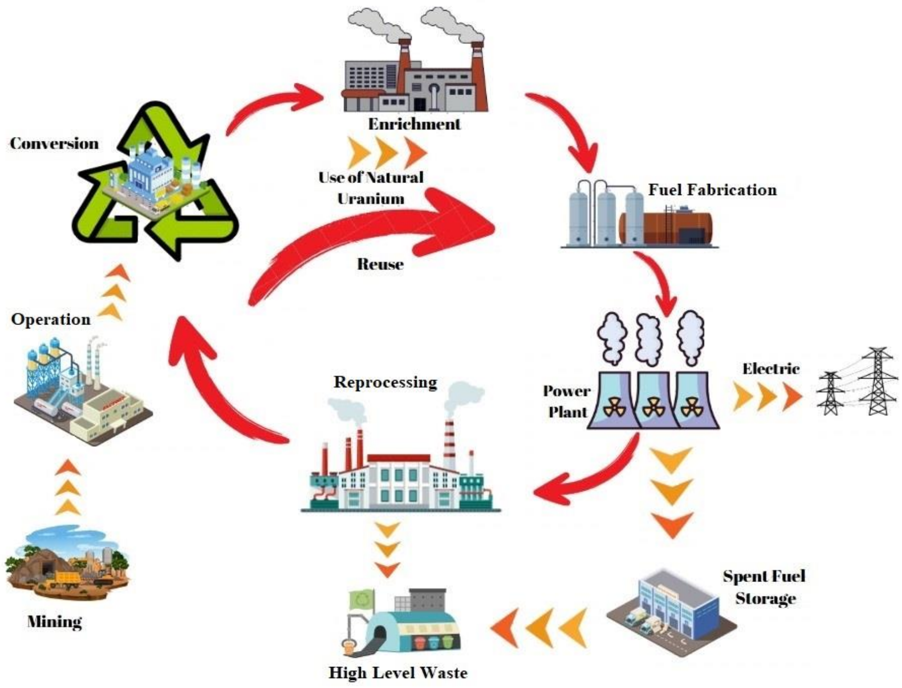

Figure 2. Nuclear Fuel Cycle.

Figure 2 illustrates the nuclear fuel cycle in detail. This cycle encompasses the entire process, from uranium mining to energy production in NPPs and the subsequent management of radioactive waste. Additionally, the cycle includes the reuse and recycling of nuclear fuel. The nuclear fuel cycle aims to enhance resource efficiency in energy production while minimizing environmental risks.

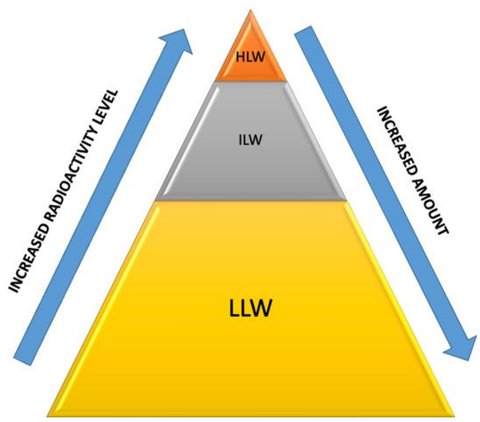

Figure 3. Quantities and Radioactivity Levels of Low, Intermediate, and High-Level Waste.

A pyramid structure such as that shown in Figure 3 depicts the volumes and radioactivity of LLW, ILW, and HLW. NPPs produce radioactive waste as a byproduct of uranium atom fission. The fission process releases several radioactive substances that can harm the environment and require proper storage and handling. Proper treatment is required for these wastes as they are a potential source of environmental pollution and cannot be stored.

Radioactive waste, which can harm human health, undergoes various treatment processes to be rendered safer and is subsequently stored appropriately. During the nuclear fuel cycle, 95% of the waste generated in NPPs is liquid. However, 99% of this waste is later converted into solid waste, making it suitable for storage [27]. Safely managing radioactive waste is critical for controlling the environmental impacts of NPPs. These processes are designed to prevent the release of radioactive substances into the environment, thereby protecting public health and ecosystems.

Table 4. Types of Waste Generated in NPPs [31].

Waste Type	Cause of Generation	Quantity (for a 1000 MW Reactor)	Disposal Method
Low-Level Waste (LLW)	Generated during reactor maintenance operations.	50 m^3/year (including packaging)	Sealing in barrels and burial underground
Interm.-Level Waste (ILW)	Produced during reactor operation.	50 m^3/year (including packaging)	Sealing in barrels and burial underground
High-Level Waste (HLW)	Radioactive materials originating from spent nuclear fuel.	3 m^3/year (including packaging)	Vitrification and storage in metal canisters and deep geological repositories

Table 4 summarizes the annual waste production of a 1000 MW nuclear reactor and the disposal methods for these wastes. LLW is generated during reactor maintenance operations. The annual volume of such waste is approximately 50 m^3 (in packaged form). These wastes are sealed in barrels and buried underground for storage. Due to their low radioactivity levels, they do not require long-term isolation. Typical LLW comprises protective clothing, filters, and reactor maintenance materials. The management of this waste is relatively straightforward. ILW is produced during reactor operation and maintenance. The annual volume is also approximately 50 m^3 (in packaged form). Like LLW, ILW is sealed in barrels and buried underground. However, it requires thicker barriers and deeper storage due to its higher radioactivity levels compared to LLW, yet lower than HLW. These wastes primarily originate from reactor structural materials and filtration systems. HLW results from radioactive substances within spent nuclear fuel. The annual volume is approximately 3 m^3 (in packaged form). This waste is vitrified (converted into glass) and stored in metal canisters. For long-term isolation, it is placed in deep underground repositories. HLW contains the most hazardous and long-lived radioactive materials, making its isolation crucial for environmental and human health protection.

4.2. Low- and Intermediate-Level Radioactive Waste

This definition of LLW and ILW is based on different levels of radioactivity and requirements related to the transportation and treatment of this waste. These two types of waste should be handled appropriately to minimize environmental and human health repercussions. So, LLW stands for low-level radioactive waste, which is not very high in radioactivity and does not need further shielding during transportation. It makes up 10% of the overall volume of radioactive waste but only 1% of the total radioactivity. These wastes include contaminated protective clothing, filters, and cleaning materials produced during the operation of hospitals, laboratories, and nuclear power plants. Low-level radioactive waste is low risk when properly managed because it is not too physically damaging to the environment. Intermediate-level radioactive waste (ILW): This is more radioactive than LLW and needs additional shielding during transport and treatment. Its management requires shielding, remote handling systems, and other advanced safety precautions. The volume of ILW is 7% of total radioactive waste, whereas the total radioactivity contributed by ILW is 4%. ILW examples are from the industrial and NPP applications (gloves, plastics, resins, filters), radioactive materials from medical applications, ore processing, oils, radioactive substances, and sludge from industrial by-products.

The processing and storage of low- and intermediate-level radioactive waste involve five key stages, ensuring their safe management without harming the environment or human health:

1. Solidification
2. Storage Period
3. Volume Reduction
4. Solidification of Liquid Waste
5. Conditioning

These steps are implemented to enhance safety and ensure long-term radioactive waste containment.

4.3. High-Level Radioactive Waste

High-level radioactive waste (HLW) consists of the residual radioactive materials remaining after nuclear fuel is used for energy production in NPPs. Due to their high radioactivity levels, these wastes pose significant risks to human health and the environment. The safe management of HLW is crucial for the sustainability and safety of nuclear energy production.

While amounting to just 3% of the total volume of radioactive waste, HLW holds about 95% of the total radioactivity. This places HLW in the most dangerous and challenging class of nuclear waste. HLW typically includes a number of isotopes with short half-lives, resulting in the waste generating considerable heat. HLW is particularly hazardous to both humans and ecosystems as it has a high level of radioactivity and elevated temperatures. Thus, HLW requires particular safety precautions for its storage and transport.
Overall, the management of high-level radioactive waste incorporates three primary processes.

a) Pool Storage:
Spent nuclear fuel is stored in specialized pools within the reactor for 10 to 40 years after it has been used for energy production. During this period, the radioactivity reaches ~1% of its initial amount. During this phase, the waste can be cooled in stages, and the radioactivity level can gradually decrease until reaching a safe level.

b) Cooling:
In this case, the storage pool uses water as a cooling medium to absorb the waste's high heat. Even the building containing the reactor is filled with water that serves as a barrier, keeping radiation from escaping into the environment. Cooling is the first step in this process and is essential to ensure the waste's safe disposal and subsequent treatment.

c) Reprocessing:
After this pool storage period is achieved and the radioactivity has dropped sufficiently, the waste is moved to reprocessing facilities. Reprocessing recovers and reuses valuable materials (like unshaped uranium and plutonium) for nuclear fuel production. This initial stage maximizes the utilization of resources in the nuclear energy cycle.

4.4. Solid Waste

Depending on the type and contents of solid waste produced in nuclear facilities, it can typically be classified into two types: wet solid waste and dry solid waste based on the solid waste content and physical properties. Safe storage and handling of these wastes are essential for reducing nuclear energy production's environmental and human health risks. Wet solid waste relates to by-products containing radioactive matter generated in the treatment process of liquid waste. Ion exchange resins, filtration residues, and radioactive sludge generated during evaporation, among others, fall into this waste category. Wet solid wastes contain radioactivity at high levels, and their processing and storage require specialized infrastructure. Solid dry waste comprises solid materials inside radioactivity. This type of waste includes ventilation filters, contaminated protective clothing, and flooring materials exposed to radioactive materials. While dry solid waste has a lower radioactivity level than wet solid waste, it must also be stored and managed correctly, as it can cause potential hazards.

4.5. Liquid. Waste

NPPs produce liquid radioactive waste, including various contaminants and long-lived isotopes with potential risks to the environment and human health. Liquid waste is mainly contaminated with cesium-134 (half-life: 2 years) and cesium-137 (30 years). These isotopes are fission products in nuclear fuel rods. Although other fission products are housed inside the fuel rods, structural damage or fuel rod failures can allow these radioactive materials to leak out of the fuel rods and into the cooling water. Filtration and separation techniques remove radioactive substances from water and then manage their safe disposal. Low- and intermediate-level liquid waste in nuclear facilities is treated using different treatment methods that are used to reduce the levels of radioactivity and minimize their risk to the environment. These methods include:

- **Chemical Precipitation:** Separation of radioactive substances from water through chemical reactions.
- **Centrifugation:** High-speed rotation to separate liquid and solid phases.
- **Filtration:** Removal of radioactive particles using specialized filters.
- **Hydro Cyclone Separation:** Mechanical process for separating liquid waste based on density.
- **Ion Exchange:** Remove of radioactive ions from water using suitable ion exchange materials.

Processing of High-Level Liquid Waste

High-level liquid waste requires specialized treatment and storage due to its high radioactivity levels. The processing of such waste consists of four key stages:

1. **Evaporation:**
    - Remove excess water to increase the concentration of radioactive materials.
    - This process reduces waste volume, making storage more efficient.
2. **Solidification:**
    - Radioactive substances are converted into solid form by immobilizing them in lime-based sludge or embedding them into ceramic materials.

    - Solidification enhances safety during transportation and storage.
3. **Storage:**
    - Solidified waste is stored in double-walled specialized tanks designed to meet high-security standards and prevent radioactive leakage.
4. **Vitrification:**
    - Radioactive waste is incorporated into glass materials, creating a stable and durable waste form.
    - Vitrification prevents the release of radioactive materials into the environment while ensuring long-term safe storage [32].

4.6. Gaseous Waste

Gaseous waste generated in NPPs originates from fission reactions within nuclear fuel rods, forming fission products. Due to their radioactive nature, these gases require careful management to ensure environmental protection and public health safety. The most common gaseous waste components encountered in NPPs include:

- Xenon (Xe)
- Krypton (Kr)
- Iodine (I)

Properly managing these gases minimizes environmental impacts and ensures public health safety. The treatment of gaseous waste in NPPs involves several key stages aimed at reducing radioactivity levels and minimizing environmental risks:

- Collection
- Filtration
- Storage

After the processing treatments, the gases are released through ventilation to the atmosphere when their radioactivity drops within the values listed in the safety limits defined by international regulatory agencies. Moreover, this releasing process is done with great rules and monitoring to reduce possible environmental hazards. Modern nuclear plants follow strict gaseous waste safety standards. These stringent measures exclude entirely the release of dangerous radioactive gases, drastically minimizing their environmental repercussions. At nuclear plants that are well-regulated and well-run, the annual population radiation dose to those nearby is less than 0.01 mSv, orders of magnitude below natural background radiation. It does not present a public health hazard. The gaseous waste of NPPs is appropriately managed to minimize the increase of air-polluting gases in the atmosphere, thus further increasing environmentally amicable energy production [33-34].

5. DISPOSAL OF RADIOACTIVE WASTE

5.1. Vitrification Process

Vitrification is an advanced disposal method for safe and long-term radioactive waste storage. The process involves melting radioactive waste at very high temperatures, which is then hardened in a glass-like structure. Vitrification aims to chemically capture radio materials into a stable covering or binding matrix to limit their potential migration into the environment. This method has also been selected for NPP fuel management because it is effective and has the best technology for high-level radioactive waste.
The vitrification process consists of the following steps:

1. Preparation of Waste
2. Vitrification Process:
    - Mixing
    - Melting
    - Homogenization
    - Solidification
3. Storage

<u>Advantages of the Vitrification Process:</u>

- **Chemical Stability:** Vitrified waste has a chemically stable structure and is highly resistant to water, significantly reducing the risk of leakage.
- **Long-Term Durability:** The glass matrix prevents the release of radioactive materials into the environment for thousands of years, ensuring long-term containment.

- **Environmentally Friendly:** This method minimizes the environmental hazards associated with radioactive waste, contributing to environmental sustainability.

Challenges of the Vitrification Process:

- **High Energy Requirement:** The process requires extremely high temperatures, leading to significant energy costs.
- **Mechanical Durability:** The brittle nature of glass necessitates careful handling during transportation and storage to prevent breakage.

5.2. Underground Disposal of Waste

One of the most critical challenges in nuclear energy production is the safe disposal of long-lived and high-level radioactive waste without harming the environment or human health. In this context, deep geological disposal is recognized as one of the most widely used and reliable disposal methods. This method integrates natural geological barriers with engineered containment solutions to ensure long-term safety by preventing the release of radioactive materials into the environment [35].

Underground disposal facilities are constructed at depths ranging from 300 to 1000 meters below the surface to prevent the emission of radiation to the surface. Geologically stable formations, such as granite, salt beds, or clay layers, are typically chosen for storage. These areas are located in regions with limited groundwater movement and minimal geological activity. These natural geological formations serve as barriers, preventing radioactive waste from interacting with the environment and ensuring the necessary conditions for safe disposal.
The secure underground storage of radioactive waste is carried out in four key stages:

- **Preparation of Waste:** The radioactive waste undergoes a series of pre-disposal treatments, including conditioning, encapsulation, and stabilization, to ensure its long-term containment and minimize environmental and human health risks.
- **Construction of the Underground Repository:** A geologically stable underground facility is designed and constructed with engineered barriers to prevent the migration of radioactive materials and to withstand long-term geological and hydrological changes.
- **Placement of Waste:** The processed and contained radioactive waste is systematically transported and emplaced within designated repository sections, following strict regulatory guidelines to ensure structural integrity and radiation shielding.
- **Sealing:** Once waste placement is complete, engineered and natural barriers, such as backfill materials and sealing systems, are applied to isolate the repository, prevent radionuclide leakage, and ensure the long-term safety and stability of the storage site.

6. NUCLEAR POWER PLANT ACCIDENTS AND THEIR ENVIRONMENTAL CONSEQUENCES

Globally, 438 operational NPPs exist across 31 countries. These plants vary in design depending on the technologies used for energy production. Some countries with a significant number of NPPs include 92 in the United States, 56 in France, 54 in China, 34 in Russia, 9 in the United Kingdom, and 3 in Germany. Additionally, 58 new NPPs are currently under construction worldwide, and once completed, they are expected to increase global nuclear energy production capacity. Despite extensive efforts to ensure the safe operation of NPPs, three major NPP accidents have occurred throughout history:

1. 1979 Three Mile Island Accident (United States)

The Three Mile Island accident, which occurred on March 28, 1979, remains one of the most significant nuclear incidents in the United States. Mechanical failures, human error, and inadequate operator training primarily caused it. A cooling system malfunction led to a partial meltdown of Reactor Unit 2, releasing a small number of radioactive gases. Although no direct casualties were reported, the accident had far-reaching social, political, and economic consequences.

Long-Term Impacts:

- Public Perception and Policy Changes: The accident significantly eroded public trust in nuclear energy, leading to widespread protests and opposition to new nuclear projects in the United States and Europe.
- Regulatory Reforms: In response, the Nuclear Regulatory Commission (NRC) implemented stricter safety standards and enhanced reactor operator training programs to prevent future incidents.

- Economic Consequences: The accident resulted in billions of dollars in cleanup costs and a sharp decline in nuclear energy investments in the U.S.

Lessons Learned and Modern Safety Measures:

- Enhanced Training Programs: Improved reactor operator training and simulator-based emergency preparedness programs were introduced.
- Strengthened Reactor Safety Features: Modern reactors now include automated safety systems and real-time radiation monitoring to prevent human errors.
- Improved Crisis Communication: Transparent public communication strategies were developed to avoid misinformation and panic in case of future nuclear incidents.

2. 1986 Chornobyl Disaster (Soviet Union)

The Chornobyl disaster, which took place on April 26, 1986, was the worst nuclear accident in history. It resulted from reactor design flaws and operator errors during a late-night safety test at Reactor No. 4 of the Chornobyl NPP. The accident caused an explosion and fire, releasing massive amounts of radioactive materials into the atmosphere, which spread across Europe.

Long-Term Impacts:

- Health Consequences: The World Health Organization (WHO) estimates that thousands of cases of thyroid cancer and other radiation-related illnesses occurred due to the accident. Radiation exposure also led to increased rates of leukemia and congenital disabilities in affected populations.
- Environmental Contamination: Large areas, particularly in Ukraine, Belarus, and Russia, remain radioactive exclusion zones. The Pripyat region was abandoned and has become an uninhabitable ghost town.
- Social and Economic Consequences: The disaster displaced over 300,000 people, and billions of dollars were spent on decontamination and health care costs.

Lessons Learned and Modern Safety Measures:

- RBMK Reactor Design Modifications: The flawed RBMK reactor design used in Chornobyl has since been phased out or modified to prevent similar accidents.
- International Safety Collaboration: The International Atomic Energy Agency (IAEA) introduced more stringent global safety standards and enhanced cross-border cooperation in nuclear safety.
- Construction of the Chornobyl Sarcophagus: In 2016, a New Safe Confinement structure was built over Reactor 4 to contain radiation and prevent further leaks.

3. 2011 Fukushima Disaster (Japan)

The Fukushima Daiichi nuclear disaster, which occurred on March 11, 2011, was triggered by a 9.0-magnitude earthquake and an ensuing 15-meter tsunami. These natural disasters turned off the plant's cooling systems, leading to reactor meltdowns in three units and releasing radioactive materials into the environment.

Long-Term Impacts:

- Environmental and Oceanic Contamination: Large quantities of radioactive water leaked into the Pacific Ocean, raising concerns about long-term marine ecosystem damage and seafood contamination.
- Health Effects: Although no immediate radiation-related deaths occurred, studies suggest prolonged low-dose radiation exposure may have long-term effects on public health. The psychological impact of forced evacuations also contributed to increased rates of depression and PTSD among affected individuals.
- Economic Consequences: The disaster resulted in massive cleanup costs exceeding $200 billion, with ongoing decontamination efforts. It also led to the shutdown of all NPPs in Japan, forcing the country to increase its reliance on fossil fuels.

Lessons Learned and Modern Safety Measures:

- Tsunami-Resistant Nuclear Plants: After Fukushima, New and existing NPPs were required to implement stronger flood protection measures and seismic reinforcements.
- Passive Cooling Systems: Advanced reactors now incorporate passive cooling technologies that do not rely on electricity, ensuring core cooling even in extreme conditions.

- Emergency Preparedness Enhancements: Japan and other countries have significantly improved nuclear disaster response strategies, including faster evacuation procedures and better radiation monitoring systems.

These incidents have led to stricter regulations and safety standards to ensure NPP security and minimize risks. NPPs use the most advanced technologies available to generate energy with a negligible chance of an accident occurring. No radioactive materials would directly be released into the environment due to advanced containment systems. Ensure that modern safety systems will help protect workers, nearby communities, and ecosystems from potential radiation exposure. The exposure at NPP sites is usually less than 0.01 mSv annually, which makes it even lower than the maximum permissible annual dose rate of 0.05 mSv for the surrounding population according to international safety standards. NPPs are designed with special protections to limit risks caused by nature or other people. For instance:

- They create buffer zones around reactors so no residences will be near enough to suffer from leaks.
- Containment structures prevent the spread of radioactive material in the event of an accident.

Such regulations must be enforced within the international safety frameworks to protect human health and the natural environment [36-37].

The IAEA, based in Vienna, performs rigorous inspections and imposes regulations during the construction and operation of NPP projects. The IAEA also monitors nuclear projects rigorously to confirm compliance with safety standards and mitigate potential risks. The IAEA performs thorough on-site evaluations of hazards before granting operating licenses. If any risk factors are identified, construction is not approved. Such rigorous regulatory frameworks are expected to ensure NPPs run securely and contribute to environmental sustainability.

7. CONCLUSION

Sustainable energy sources are important because of fossil fuels' rising energy consumption and adverse environmental consequences. The surge in global electricity demand can be attributed, in part, to the rapid acceleration of digitalization and the adoption of energy-intensive technologies, including artificial intelligence (AI) and big data analytics. Significantly, the energy needs of data centers have been rapidly increasing, stressing the need for trusted and low-carbon energy sources. Nuclear energy has proved to be an essential alternative in this context due to its low carbon emissions, high energy density, and long-term energy security features. This study assesses the contribution of nuclear energy to world electricity generation and analyses its environmental implications, benefits, and drawbacks regarding sustainability. The study shows that nuclear energy is the best technical approach to decarbonize our economies and secure our energy supply. Despite this, issues like radioactive waste disposal, risks of nuclear accidents, and public perception are still significant barriers to widespread adoption.

Turkey's deteriorating dependency on energy imports underlines the strategic importance of investments in nuclear energy. The total operation of the Akkuyu NPP is predicted to cover 10% of Turkey's electricity demand, bolstering energy security and minimizing external dependence. Likewise, a proposed nuclear project in Sinop would generate most of its energy in the 2030s, and a planned plant in Thrace has significant potential for bolstering Turkey's energy independence. Apart from securing the energy supply, nuclear energy investments help lower the current account deficit, stabilize energy prices, and accelerate economic growth. The NPPs are further capable of producing a massive amount of energy. However, they require minimal land space, thus making them an efficient and eco-friendly alternative.

The study also states that net-zero carbon goals under the European Green Deal would require nuclear energy alongside renewables. Nuclear energy emits much less carbon and heavy metal pollution than thermal power plants, confirming its role as a sustainable energy alternative. Revolutionizing the energy generation process to be cleaner and greener, AI-based intelligent energy management systems and big data analytics also facilitate the efficiency of NPPs, thus making energy generation processes more efficient, secure, and sustainable. Under such conditions, Turkey's future energy strategies should focus on environmentally friendly, cheaper , sustainable energy plants.

To achieve long-term energy security, Turkey must accelerate investments in Akkuyu and Sinop NPPs and adopt the latest generation reactor technologies and waste management mechanisms. Moreover, public education concerning the environmental advantages of nuclear energy will improve social acceptance of this energy type. Nuclear power is vital for Turkey's energy independence and sustainable development. Therefore, investing in nuclear energy, integrating it with renewable sources, and effectively addressing environmental risks are essential to long-term energy policies.

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1- Study design 2- Data collection 3- Data analysis and interpretation 4- Manuscript writing 5- Critical revision			

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