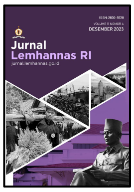

Jurnal Lemhannas RI (JLRI)
E-ISSN : 2830-5728
Vol. 12 No. 2, June 2024: 131-148
DOI: 10.55960/jlri.v12i2.930
https://jurnal.lemhannas.go.id/index.php/jkl

The Role of Nuclear Energy in Achieving Sustainable Energy Solutions

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Article Info:

Keywords:
carbon emissions, energy transition, nuclear advantages, nuclear security, technological advancements

Article History:
Received : 11-11-2023
Revised : 27-03-2024
Accepted : 30-06-2024

Article DOI :
10.55960/jlri.v12i2.930

Abstract

Purpose: The aim is to assess the role of nuclear energy as a stable and environmentally friendly energy source, as well as its advantages over fossil fuels and renewable energy. The research identifies the benefits, challenges, and technological advances in nuclear energy, as well as the potential for its expanded use in global efforts to reduce carbon emissions and transition to more environmentally friendly energy sources.

Study Design/Methodology/Approach: The study used qualitative methodology. Data was collected from secondary sources; scientific papers, government reports, and industry assessments.

Findings: Nuclear energy is a stable, low-carbon energy source that is independent of weather conditions, supporting grid stability, especially during times of peak demand or low renewable energy availability. But there are significant challenges. Modern reactor designs and new cooling systems can overcome these challenges and improve nuclear energy efficiency. International co-operation and oversight by the IAEA are essential to ensure global nuclear security.

Originality/Value: Comprehensively analyses the role of nuclear energy in meeting global energy needs, combating climate change, and driving technological innovation. Evaluates the benefits and challenges of nuclear energy, with an emphasis on safety, waste management, and technological advancement. Policy recommendations, investment guidelines, and strategies to extend the lifetime of nuclear power plants.

How to cite : Rajagukguk, M.H., Siagian, R.B., Gunawan, B. (2024). The Role of Nuclear Energy in Achieving Sustainable Energy Solutions. *Jurnal LemhannasRI, 12*(2), 131-148. https://doi.org/10.55960/jlri.v12i2.930

E-ISSN: 2830-5728

INTRODUCTION

A global shift towards carbon-free energy sources is critical to addressing climate change and reducing environmental impact (Jayabal, 2024). Nuclear energy plays a role in the transition by reducing greenhouse gas emissions and meeting the challenge of providing stable energy supplies (Mathew, 2022). Nuclear energy plays a key role in the global electrical energy supply, with major countries like the United States, France, and China significantly contributing to its production (Sovacool et al., 2020). Nuclear energy offers advantages in stability and reliability over fossil fuels and renewable energy sources. Unlike solar and wind energy, nuclear power provides a continuous and consistent energy output (El-Emam et al., 2024). The adoption of nuclear energy is currently a complex issue involving various factors, from cost to safety, that influence the acceleration of the transition to carbon-free energy (Krūmiņš & Kļaviņš, 2023). Nuclear energy has significant potential to reduce carbon emissions as it generates electricity without producing greenhouse gases. However, its global implementation faces substantial challenges.

A major challenge in nuclear power development is the high cost and long development time required for building and operating nuclear plants, due to complex designs, stringent regulations, and safety standards (Eash-Gates et al., 2020; Stewart & Shirvan, 2022). For many countries, particularly developing ones, nuclear energy is less attractive compared to cheaper, rapidly growing renewables like solar and wind (Strielkowski et al., 2021). Safety concerns, fuelled by past disasters such as Chernobyl and Fukushima, continue to influence public perception (Guo et al., 2020; Nakamura et al., 2021). Although new technologies like small modular reactors offer potential solutions, gaining public trust will take time (Ghimire & Waller, 2023). While Finland and Sweden have made progress in safe underground storage, many countries still face challenges in finding sustainable solutions, with political and social factors complicating waste management (Batista et al., 2021; Lieskoski et al., 2024). Radioactive waste continues to be a primary source of public opposition to nuclear energy (Sengupta, 2023).

Nuclear energy can reduce dependence on fossil fuels, but its success hinges on addressing cost, safety, and waste management challenges (Tran, 2024). While renewable energy offers cheaper and safer alternatives, nuclear power remains vital for stable baseload energy (Arefin et al., 2021). Nuclear energy adoption will remain slow without significant investments in technology, safety, and waste management. To transition to carbon-free energy, it is crucial to address the potential and challenges of nuclear power by reducing costs, improving safety, and managing waste effectively in the fight against climate change.

This research explores nuclear energy's potential in reducing greenhouse gas emissions, improving energy stability, and addressing challenges in nuclear technology. It focuses on emission reduction, safety, waste management, and cost, with an emphasis on developing safer, more efficient technologies, without excluding comparing nuclear energy to other renewables or modeling future scenarios. Findings have implications for energy policy and sustainable energy strategies. Previous studies (Mathew, 2022; Zohuri et al., 2023) highlight nuclear energy’s potential and key challenges in safety, waste management, and costs, as well as advances in reactor design and coolant technologies.

DOI: 10.55960/jlri.v12i2.930

E-ISSN: 2830-5728

Literature Review

Integrating Nuclear and Renewable Energy Systems for Sustainable and Resilient Energy Solutions

Combining renewable energy sources with nuclear energy is an innovative solution to meet the increasing global energy demand, which can significantly reduce greenhouse gas emissions (Liu et al., 2024). Renewable energy sources like wind, solar, tidal, wave, and geothermal are recognized for their low emissions, making them crucial for mitigating climate change (Sayed et al., 2021). The main challenge of renewable energy is its intermittent nature - it is not available all the time, depending on weather conditions and geography (Impram et al., 2020). This is where the role of nuclear-renewable energy hybrid systems (N-R-HES) becomes very important.

Source: Arefin et al. (2021)

Figure 1. Optimizing Energy Utilization through Innovative System Integration

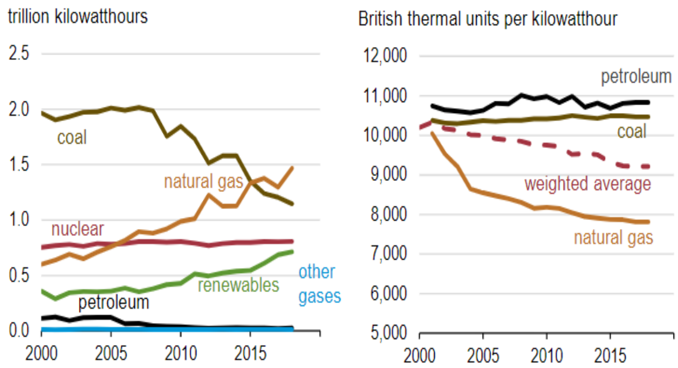
Figure 1 illustrates that Nuclear-Renewable Hybrid Energy Systems (N-R-HES) combine nuclear energy's stability with renewable energy's flexibility and environmental benefits, offering a resilient and cost-efficient solution. N-R-HES balances energy production and costs, particularly when natural gas prices increase, and supports the production of derivative products like fuel (Cantrell, 2022). By enhancing grid flexibility, they ensures a stable energy supply, with nuclear energy filling gaps when renewable sources are unavailable (Basit et al., 2020). Despite technical integration challenges, the shift to hybrid systems like N-R-HES is essential for meeting future energy demands, promoting sustainability and economic viability (A. Gabbar et al., 2020).

Contribution of Non-Combustible Renewable Energy to U.S. Electricity Generation and Energy Consumption

On August 22, 2019, the US Energy Information Administration (EIA) released data on non-combustible renewable energy's contribution to energy consumption and electricity generation in the US (Otto et al., 2022). In 2018, non-combustible renewables

E-ISSN: 2830-5728

like hydropower, solar, and nuclear provided 5.989 trillion Btu, or 15% of utility-scale power generation. As seen in figure 2, it shows that this includes 2.218 trillion Btu converted to electricity and an adjustment of 3.771 trillion Btu based on the heat rate of fossil plants. Without the adjustment, non-combustible renewables would account for about 6% of total energy consumption. The adjustment reflects efficiency differences in energy conversion between renewables and fossil fuels.



Source: U.S. Energy Information Administration, (2024)

Figure 2. Development Trend of Emergy Per Kilowatt-hour over Time

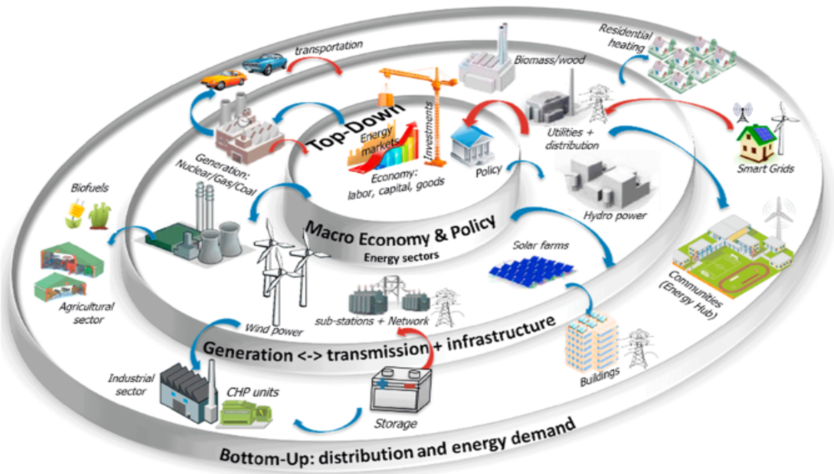
As shown in Figure 2, non-combustible renewables contributed 650,008 thousand MWh, or 16% of total utility-scale net generation in 2018, emphasizing their role in providing green electricity and promoting sustainable energy growth. The report also highlights a decline in the average heat rate of fossil fuel power plants from 10,333 Btu/kWh in 2001 to 9,213 Btu/kWh in 2017, reflecting an 11 per cent increase in efficiency, mainly due to the adoption of more efficient gas combined cycle units. This efficiency improvement reduces energy use, emissions, and operating costs.

Model of the Nexus-e Energy Transition

The Nexus-E energy transition theory model, developed by ETH Zurich, focuses on analyzing and planning future energy systems in Switzerland (Federer, 2022). The Nexus-E platform aims to model the future evolution of Switzerland's energy system, considering technological, economic, and regulatory changes (Gjorgiev et al., 2022). Developed with support from the Swiss Federal Office of Energy (SFOE) and ETH Zurich, it helps Switzerland reduce reliance on nuclear energy and achieve zero carbon emissions by 2050 (Hug et al., 2023). The energy transition includes increased use of renewable energy sources such as solar power and the need for efficient energy storage and conversion technologies.

DOI: 10.55960/jlri.v12i2.930

E-ISSN: 2830-5728



Source: (Keller et al., 2021)

Figure 3. Swiss Energy Transition Model for a Future Sustainable Energy System

Nexus-E is a modular model with five key components: the Swiss economy, electricity market, investment, grid security, and grid expansion (Garrison et al., 2020). The model integrates electrical engineering and macroeconomics to analyze energy scenarios, such as the nuclear energy phase-out and investments in photovoltaics. It combines top-down and bottom-up approaches: top-down focuses on government policies and energy supply stability, while bottom-up addresses local energy distribution and demand, promoting sustainability and affordability for a reliable energy system.

Table 1. Comparison of top-down and bottom-up Approaches in Energy Systems

Approach	**Top-Down**	**Bottom-Up**
Main Focus	Macroeconomic policy and energy infrastructure	Energy distribution and energy demand
Units Involved	Governments, regulatory agencies, large energy providers	Consumer, local energy distribution unit
Managed Aspects	Generation, transmission, energy storage	Energy demand management, energy distribution to end consumers
Policy	Energy resource management policies, national infrastructure development	Adaptation of distribution infrastructure to local needs and energy demand
Infrastructure	Large energy plants, transmission networks, storage facilities	Distribution infrastructure, energy supply for households and small industries
Objective	Guaranteeing the stability of the overall energy supply for national needs	Ensure energy accessibility at the local level and efficient management of energy demand
Relatedness	Macro policies determine the direction and development of infrastructure that influences energy distribution	Energy distribution that is efficient and meets society's needs depends on decisions taken at the top level

Table 1 compares two energy system approaches: top-down, which focuses on macroeconomic policies and infrastructure for national supply stability, and bottom-up, which emphasizes local distribution and demand management. Nexus-e, a research tool

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used in projects like CH2040 at ETH Zurich, supports energy transition solutions by simplifying access, reducing simulation time, and promoting collaboration (Raycheva, 2023).

METHODS

The study examines the role of nuclear energy in reducing greenhouse gas emissions, focusing on stability, reliability, and advancements in nuclear technology. It aims to assess nuclear energy's contribution to the global transition to carbon-free energy.

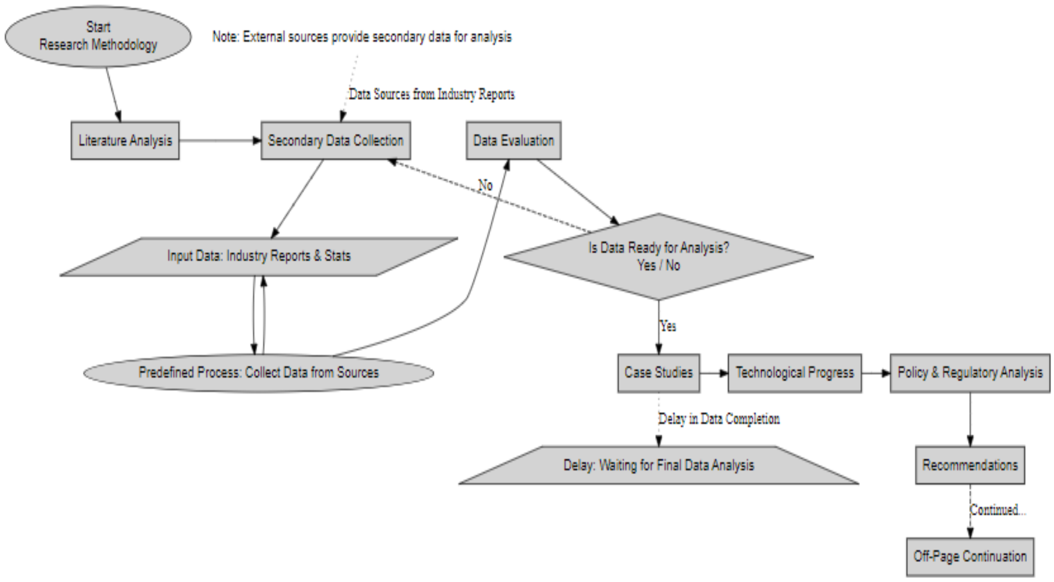


Figure 4. Research flow

As shown in Figure 4, the research flow began with a literature analysis on the contribution of nuclear energy in reducing greenhouse gas emissions, stability, reliability, and challenges as well as advances in nuclear technology. Secondary data was collected from industry reports, global energy statistics, and nuclear power plant operations, then evaluated for its contribution to electricity production and comparison with other energy sources. The research continued with case studies of nuclear power plants related to safety, waste management, and construction and operational costs. Evaluation of technological progress includes reactor design, cooling systems, and automation. Policy and regulatory analyses were conducted to review the role of the IAEA in nuclear safety oversight. Based on the analysis, the research provides recommendations to improve waste management, reduce costs, and increase the safety and efficiency of nuclear technology.

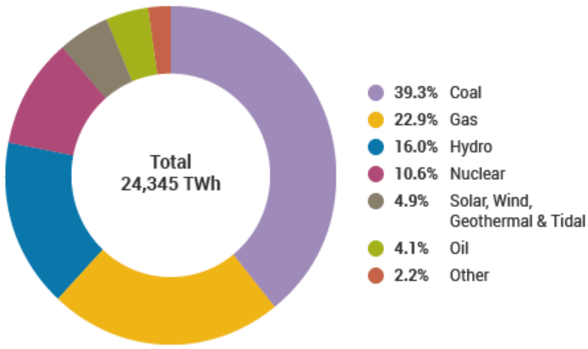
DOI: 10.55960/jlri.v12i2.930

E-ISSN: 2830-5728

RESULT AND DISCUSSION

The Role of Nuclear Power in Global Energy Supply and its Contribution to Carbon-Free Electricity

Nuclear power supplies about 10% of total electricity generation worldwide, as shown in Figure 5 (Poneman, 2023). In 2017, global energy consumption totaled 24,345 TWh, with coal as the largest source, contributing 39.3%. Gas followed at 22.9%, and renewable energy, mainly hydroelectricity, accounted for 16.0%. Nuclear power contributed 10.6%, while non-hydro renewables like solar, wind, and geothermal made up 4.9%. Oil contributed 4.1%, and other sources added 2.2%. Despite its smaller share compared to fossil fuels, nuclear power is crucial for carbon-free energy, supplying nearly a third of total carbon-free electricity and playing a key role in reducing greenhouse gas emissions (Krūmiņš & Kļaviņš, 2023).



Source: Ruby, (2017)

Figure 5. World elecricity production

Historically, nuclear power has been a stable and reliable option for meeting large electricity needs (Mathew, 2022). Nuclear power plants (NPPs) can generate continuous electricity regardless of weather conditions, unlike renewable sources like solar and wind, which depend on sunlight and wind speed (Fadillah, 2024; Susiati et al., 2023). With the capacity to operate stably 24 hours a day, 7 days a week, nuclear power plants contribute to maintaining a stable electricity supply (Rauf, 2023). Although nuclear power supplies most of our carbon-free energy needs, many countries still rely on fossil fuels to meet their electricity needs (Krūmiņš & Kļaviņš, 2023). The potential for expanding nuclear power is critical to global efforts to reduce dependence on fossil fuels (Michaelides & Michaelides, 2020). As awareness of climate change and the need to reduce carbon emissions grows, more countries are exploring or planning to incorporate nuclear energy into their energy mix.

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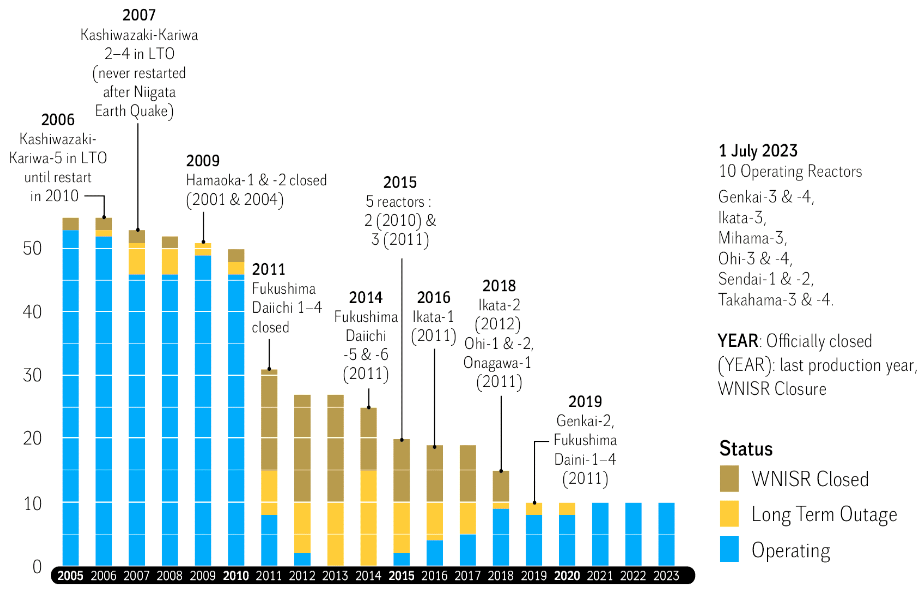

Source: Schneider et al. (2023)

Figure 6. Japanese reactor operations and WNISE Assessment

Statistically, as shown in Figure 6, nuclear energy faces significant challenges in the global transition to a carbon-free system, as highlighted by incidents at Kashiwazaki-Kariwa and Fukushima Daiichi (Kumar, 2022). Despite its potential as a low-carbon energy source, these incidents highlight the need for strict safety management and risk mitigation in reactor operations. Following the 2006 Niigata earthquake and the 2011 Fukushima disaster, many reactors were decommissioned or shut down indefinitely (Ibrion et al., 2020; Schreurs, 2021). Advances in nuclear technology, such as small modular reactors, or SMRs, aim to improve safety and sustainability (Kamran et al., 2024). Effective policies, public acceptance, and waste management are key for nuclear energy's role in reducing carbon emissions.

As of 2024, there are about 440 nuclear reactors worldwide, with a total capacity surpassing 400 gigawatts (Rector & Yu, 2024). The U.S., France, and China are the leading countries in nuclear capacity (Pata & Samour, 2022). The U.S. operates over 90 reactors, generating 20% of its electricity, while France relies on nearly 60 reactors for over 70% of its electricity (Bragg-Sitton et al., 2020; Lebrouhi et al., 2022). Nuclear power plays a crucial role in stabilizing the grid, particularly during peak demand or when renewable energy production drops (A. Gabbar et al., 2020). Despite challenges such as safety, waste management, and high costs, many countries are considering expanding nuclear energy as part of their clean energy strategies to combat climate change (Muellner et al., 2021; Yue et al., 2022). Nuclear power is especially important for ensuring reliable, carbon-neutral energy, complementing the limitations of renewable sources like wind and solar (Thellufsen et al., 2024; Usman & Radulescu, 2022).

Renewable energy sources like wind and solar offer significant environmental benefits by reducing carbon emissions (Algarni et al., 2023). However, they face challenges in consistency and reliability, as wind energy is dependent on wind speed, and solar power requires daylight and good weather (Hassan et al., 2023). These limitations can impact grid stability and necessitate backup solutions. In contrast, nuclear power

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plants provide a continuous, reliable energy supply unaffected by weather or time of day (Ramirez-Meyers et al., 2021). Nuclear power is efficient, producing large amounts of energy with minimal fuel and low carbon emissions, making it an effective complement to renewable sources (Imran et al., 2024; Usman & Radulescu, 2022).

Ensuring Nuclear Safety in the Expansion of Nuclear Power

Nuclear safety is crucial for the growth of nuclear power, as mismanagement can lead to severe consequences. The IAEA sets key safety principles, focusing on strict standards for the safe and sustainable development of nuclear energy (Ibodullaev, 2023). These principles address various aspects, including the design and operation of nuclear facilities, aiming to minimize radiation risks and protect both people and the environment.

National operators ensure nuclear safety through safety measures and continuous monitoring, while regulators oversee compliance and safety management. Their collaboration is essential for safe operations, public and environmental protection, and public confidence in nuclear energy. The 2011 Fukushima disaster exposed vulnerabilities in reactor design and crisis management, underscoring the impact of technical failures and human error (Bansal & Selvik, 2021).

The case studies emphasize the need for transparency, preparedness, and strengthening global nuclear safety. After Fukushima, international safety measures were improved with stricter reactor standards, enhanced oversight, and better emergency response. The IAEA plays a key role in ensuring safety standards and managing risks (Rockwood, 2022). As nuclear technology evolves, new risks arise, making it crucial to continuously adapt safety practices. Fukushima's lessons remind us that safety must always be prioritized, and global efforts to improve nuclear safety should persist.

Strengthening the Global Nuclear Safety Regime

The Global Nuclear Safety Regime ensures safety standards in the nuclear sector, with key organizations like the IAEA and NEA shaping international regulatory frameworks (Pilat, 2021). The IAEA coordinates international efforts to ensure nuclear safety, providing guidance and conducting inspections to ensure compliance with safety standards (Cha, 2024). The NEA, part of the OECD, supports research and policy development for the safe use of nuclear energy (Zhang et al., 2024). A network of national regulators and nuclear operators collaborates to share best practices, manage risks, and enhance safety across countries (Orikpete & Ewim, 2024; Schöbel et al., 2022).

The international nuclear industry, including manufacturers and service providers, is vital in maintaining high safety standards through collaboration and innovation. Strengthening global nuclear safety requires increased inspections by the IAEA, which help identify risks and ensure adherence to international standards for safe and sustainable nuclear operations.

Transparency in inspection results is vital for boosting public and international trust in nuclear safety. Sharing outcomes ensures compliance, promotes safety improvements, and supports harmonized global standards. This strengthens the global nuclear safety framework, reduces risks, and enhances safety worldwide.

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Integrating safety and security at a Nuclear Power Plant (NPP) is essential for effective operation (Hyvärinen et al., 2022). Achieving synergy between safety and security requires a holistic approach to risk management, balancing safety's focus on protecting people and the environment from nuclear hazards with security's goal of preventing unauthorized access and sabotage (Shubayr, 2024). These distinctions can cause conflicts, especially when policies must be applied together. Limited resources, including trained personnel and technology, pose barriers to optimal integration. A coordinated framework and clear policies can enhance safety and security integration at NPP sites, requiring structured collaboration and commitment from all stakeholders to overcome these challenges (Xu et al., 2021).

Ensuring Safety in Advanced Nuclear Reactors

Advanced nuclear reactors are designed to improve energy efficiency, reduce radioactive waste, and extend operational life. They feature innovations like better fuel use, advanced cooling systems, and increased automation. However, safety remains a critical challenge, particularly ensuring safe operation under normal and extreme conditions, such as loss of cooling, radiation leakage, or control system failure (Cavaliere, 2023). New technologies necessitate reassessment of safety standards, raising regulatory and public acceptance concerns. Addressing these safety challenges requires stricter protocols, thorough testing, and effective public communication to maximize the benefits of advanced reactors.

Countries face significant challenges in meeting international nuclear safety standards, including a lack of experienced personnel, insufficient infrastructure, and limited understanding of nuclear regulations. To build capacity, countries must invest in workforce training, develop appropriate policies, and implement safety technologies. Meeting these standards within tight deadlines, alongside public expectations for safe nuclear programs, adds pressure. International collaboration, support from global nuclear agencies, and bilateral partnerships with experienced nations are crucial to overcoming these barriers. Failure to act promptly could lead to nuclear accidents. A comprehensive and sustainable approach is essential for ensuring long-term safety in emerging nuclear countries.

Ensuring Safety and Reliability in Nuclear Power Plants Beyond 40 Years of Operation

The continued operation of Nuclear Power Plants (NPPs) that have surpassed their 40-year lifespan raises concerns about aging mechanisms in critical components, impacting long-term safety (Bansal & Selvik, 2021). As NPPs age, key parts like reactors and cooling systems experience material degradation, increasing the risk of failure and compromising performance (Jacques et al., 2021). Aging-related challenges such as cracks, corrosion, and structural degradations threaten safety. Effective maintenance strategies and technologies for early detection and management of aging are crucial, alongside a review of safety policies to ensure high safety standards.

Aging mechanisms are technically challenging, requiring a multidisciplinary approach integrating materials science, structural engineering as well as safety management. It is important to develop and apply the latest technologies and risk-based

 DOI: 10.55960/jlri.v12i2.930

approaches to mitigate potential safety threats caused by the aging of components in aging NPPs (Adumene et al., 2022). Continued operation of nuclear power plants can be carried out while still ensuring the safety and reliability of operations, even though their lifespan has reached or exceeded 40 years.

Strengthening Global Nuclear Safety through Enhanced IAEA Inspections, Compliance, and International Collaboration

To strengthen global nuclear safety, enhancing the IAEA's role in inspections and compliance is crucial. By providing the IAEA with greater inspection powers and stricter enforcement mechanisms, the organization can more effectively monitor nuclear activities, conduct thorough inspections, and address violations swiftly. This will ensure compliance, reduce proliferation risks, and foster global security. Harmonizing nuclear standards will create a unified global framework, promoting transparency and trust among nations.

Improving transparency and communication between operators and regulators is also essential. By enhancing the exchange of operational experiences and utilizing advanced technology for clear reporting, both parties can address challenges more effectively. This will improve operational efficiency, create responsive policies, and foster stronger cooperation, ultimately supporting global nuclear safety.

International collaboration is crucial for tackling nuclear safety challenges through innovation and advanced technology. By sharing knowledge and resources, countries and research institutes can enhance global efforts to improve safety standards. Collaborative initiatives focus on safer materials, advanced reactor control systems, and risk mitigation strategies. Countries with limited resources can benefit from the expertise of more advanced nations, accelerating innovation. Such partnerships help develop global safety standards, reduce risks from inconsistent regulations, and foster policies that support nuclear safety while addressing national needs. This collaboration ensures the development of safe, sustainable nuclear technology for the future.

CONCLUSION

The study concludes that nuclear energy plays a crucial role as a stable and environmentally friendly energy source, offering advantages over fossil fuels and renewables. It ensures continuous energy supply, supporting grid stability during peak demand or when renewable production drops, with minimal carbon emissions. However, challenges such as safety, radioactive waste, and high costs of nuclear plants remain. Advancements in nuclear technology, such as improved reactor designs and cooling systems, could enhance efficiency and safety. International cooperation and oversight by organizations like the IAEA and NEA are vital for global nuclear safety.

Further research is needed to innovate the management of radioactive waste, improve reactor design, and enhance nuclear power plant efficiency. Strategies to reduce costs should focus on expanding nuclear energy use. Strengthening the IAEA's role and improving transparency in nuclear safety oversight are essential for better public understanding. Strategies to extend the operational life of aging nuclear plants should be developed to ensure continued safe and efficient operations.

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