

THE ROLE OF NUCLEAR ENERGY IN COMBATING CLIMATE CHANGE THROUGH DEVELOPING A SUSTAINABLE GLOBAL ENERGY INFRASTRUCTURE

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Received	Revised	Accepted	Published
15 August, 2024	15 September, 2024	30 September, 2024	14 October, 2024

ABSTRACT

Nuclear energy's low greenhouse gas emissions make it a promising solution to the climate change problem. To keep industrial development empowering, the increasing demand for more and more energy generally relies on processes that produce huge quantities of carbon dioxide (CO₂), contributing to pollution and triggering global warming. Nuclear power plants, on the other hand, generate electricity without producing CO₂ which helps in lowering the overall emissions and contributing to meeting energy demands while avoiding using fossil fuels. Furthermore, nuclear power plants operate around the clock, ensuring a regular and reliable supply of electricity which is an important component of grid stability. Moreover, nuclear power is particularly efficient due to its high energy density, which enables a very little amount of nuclear fuel to provide a large amount of energy. Advances in reactor design and safety measures have considerably improved nuclear energy's safety, efficiency, and environmental performance across the world. This article discusses how nuclear energy helps to reduce overall greenhouse gas emissions, initiatives to address challenges like waste management and public skepticism, and the steps needed to expand the use of this energy source.

Keywords: Nuclear energy, Climate change, Greenhouse gases, Base-load Power Generation, Economic Development, Energy Security, Waste management

INTRODUCTION

One of the most important issues of the twenty-first century is climate change, which is defined by long-term changes in temperature and weather patterns. It has caused serious environmental and socioeconomic upheavals and is mostly a consequence of human exploitation, including the combustion of fossil fuels, deforestation, and manufacturing operations. According to data provided by the Intergovernmental Panel on Climate Change (IPCC), global temperature has increased by around 1.2°C compared with the pre-industrial period and this trend is predicted to continue unless significant steps are taken to minimize greenhouse gas emissions (Paillere, H.2015). Climate change has far-reaching and intricate

consequences. Increases in global temperatures cause polar ice caps and glaciers to melt, leading to rising sea levels and an upsurge in the severity of catastrophic weather conditions including storms, droughts, and floods (NASA, 2021). Such modifications to the environment have serious implications for biodiversity, habitats, and human societies as a whole. As an illustration, the loss of ice habitats endangers polar bears and penguins, whereas shifting weather patterns harm agricultural output, resulting in food poverty and economic fragility. In order to satisfy global energy demands without aggravating environmental concerns, plans for energy production must take climate change into consideration. Fossil fuels are

currently responsible for more than half of the world's energy demands and are also the main source of greenhouse gas emissions. To ensure a sustainable future and lessen global warming, a shift to low- or zero-carbon energy sources is required. The Alternatives that use renewable energy sources like wind, solar, and hydropower have attracted a lot of interest and investment. However, intermittences, energy storage, and geographical restrictions pose challenges for these sources. Nuclear energy is a feasible alternative to maintain a steady energy supply and complement renewable energy sources because of its low greenhouse gas emissions, high energy density, and capacity to provide base-load power (Bandoc, G. 2018).

Nuclear Energy and Its Historical Context

The history of nuclear energy has been complicated and controversial. Its development started in the middle of the 20th century, first for military usage, but it rapidly expanded to civilian applications, most notably the production of electricity. The nuclear power era began in 1956 when the UK's Calder Hall became operational as the first commercial nuclear power station (World Nuclear Association, 2021). Since then, there have been major developments in reactor design, safety protocols, and waste management, leading to an evolution of nuclear technology. Despite its enormous potential, nuclear energy has faced a number of challenges, including a negative public perception, high initial expenses, and catastrophic accidents at Chernobyl and Fukushima, among others. These occurrences have sparked many concerns about the safety of nuclear power and its consequences on the environment. However, because of technical advancements and stringent safety regulations, the efficiency and safety of modern nuclear reactors have substantially improved (Sovacool, 2011).

Nuclear Energy Combating Climate Change

Nuclear energy is a crucial component in the fight against climate change due to its ability to generate large amounts of electricity without emitting carbon dioxide (CO₂). Unlike fossil

fuel power plants, which release significant amounts of CO₂ and other greenhouse gases into the atmosphere, causing global warming and ultimately endangering human life. This time according to the International Atomic Energy Agency (2021) the energy sector is responsible for nearly three-quarters of global greenhouse gas emissions which is, no doubt, an alarming situation. The Lifecycle emissions from nuclear power, which include emissions from mining, fuel processing, construction, and decommissioning, are negligibly lower compared to those from fossil fuel-based energy sources. According to the IPCC (2021), the median lifecycle emissions of nuclear power are 12g CO₂ eq /kWh, compared to 820g CO₂ eq /kWh for coal and 490g CO₂ eq /kWh for natural gas. This huge difference highlights nuclear energy's potential to reduce overall emissions intensely (Ahmad, P. 2021).

Nuclear energy's high energy density is another significant advantage. A small amount of nuclear fuel can produce a large amount of energy, making it extremely efficient. For instance, 1 kilogram of uranium-235 can produce approximately 24,000 MWh of electricity, compared to 2.5 MWh from burning 1 ton of coal. This high energy density means that nuclear power plants require less fuel and generate much less waste compared to fossil fuel plants. The compact nature of nuclear fuel also facilitates easier storage and transportation, reducing the environmental and logistical challenges associated with fuel supply chains (May, B. 2010).

One important aspect of Nuclear Power Plants is their capability to provide reliable and base-load electricity, which is essential for maintaining grid stability. Unlike renewable energy sources such as wind and solar, which are intermittent and depend on weather conditions, nuclear power can operate continuously, providing a stable and predictable energy supply. This reliability is critical for meeting constant electricity demands and supporting economic activities that require uninterrupted power. Moreover, the ability of nuclear power plants to run for extended periods without refueling typically 18 to 24 months enhances their role as

a dependable source of electricity (Maghyereh, 2022).

Technological Advancements

The topmost of the reservations raised regarding nuclear power plants are the safety and security of the plants and safe waste management but these concerns have significantly dissolved with the advancements in nuclear technology. Modern reactors, such as Generation III+ and upcoming Generation IV designs, incorporate advanced safety features, passive safety systems, and enhanced fuel utilization. The Small Modular Reactors (SMRs) represent a significant technological advancement in nuclear power. SMRs are designed to be more affordable, scalable, and safer than traditional large reactors. They can be deployed in smaller grids or remote locations and have the potential to complement renewable energy sources by providing flexible and reliable power (Zaman, K. 2024).

Furthermore, research into thorium reactors and nuclear fusion offers promising avenues for future energy production. Thorium reactors, for example, utilize thorium-232, which is more abundant and produces less long-lived radioactive waste compared to uranium. Nuclear fusion, though still in the experimental stage, has the potential to provide nearly limitless, clean energy if technical and economic challenges can be overcome (Novalianda, et al., 2021).

Economic Feasibility

While the initial expenditures associated with constructing nuclear power facilities are huge but the long-term economic rewards are significant too as they have minimal operating and maintenance expenses and can last for 60 years or more with good care and periodic modifications. The whole lifespan costs of nuclear energy must be taken into account when comparing costs with alternative energy sources. For example, although renewable energy sources such as solar and wind have lower initial costs but managing irregularities with them requires large investments in energy storage and system integration. On the other hand, the reliable production of nuclear power

minimizes the requirement for surplus infrastructure (Jewell, J. 2021).

Job Creation and Economic Development

The nuclear sector additionally contributes to promoting economic growth and employment creation. Nuclear power plants' development, operation, and maintenance create a large number of lucrative employment opportunities in the fields of construction, engineering, and management. Moreover, the nuclear supply chain, encompassing mining, fuel processing, and waste management, contributes to increased employment and economic activity. Particularly in areas with restricted access to energy supplies, investments in nuclear technology and infrastructure can promote growth in the economy. Nuclear power may boost economic stability overall, draw investment, and encourage business activities by offering an affordable and consistent energy supply (Sabie, O. M. 2022).

Environmental Benefits

Nuclear energy has numerous environmental advantages in addition to its low greenhouse gas emissions. When considering renewable energy installations such as wind and solar farms, which require huge amounts of land for wide-scale deployment, nuclear power stations require comparatively smaller land areas (Union of Concerned Scientists, 2013). Air pollution, a serious health risk linked to the burning of fossil fuels, is another benefit of nuclear power. According to the Environmental Protection Agency (2020), nuclear energy might reduce the incidence of respiratory diseases and other health problems brought on by air pollutants including sulfur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter by taking the place of coal and gas plants (Kim, S. 2020).

Enhancing Energy Security and Contribution to Climate Goals

Nuclear energy enhances energy security by diversifying the energy mix and reducing reliance on imported fossil fuels. Many countries, particularly those with limited

domestic energy resources, benefit from the stability and predictability of nuclear fuel supply. Uranium, the primary fuel for nuclear reactors, is abundant and can be sourced from stable geopolitical regions, reducing the risk of supply disruptions. Furthermore, advanced nuclear technologies, such as breeder reactors, have the potential to utilize existing nuclear waste as fuel, further enhancing energy security and sustainability. By recycling nuclear waste, these technologies can extend the lifespan of nuclear fuel and reduce the environmental impact of waste disposal (Woods, J. 2017).

In order to reach global climate targets, nuclear energy is essential. With attempts to keep the increase to 1.5°C, the 2015 Paris Agreement seeks to keep global warming far below 2°C over pre-industrial levels. Reducing greenhouse gas emissions quickly and significantly is necessary to meet these objectives in all industries, including the energy sector (UNFCCC, 2015). Since nuclear power can provide enormous amounts of low-carbon electricity, it is a vital part of any deep DE carbonization plan. A substantial increase in nuclear capacity is required to accomplish climate objectives while maintaining energy security and economic stability, according to a number of studies (Scheffran, J. 2015).

Challenges and Concerns

Most of the time, when discussing about nuclear energy, various concerns and challenges arise primarily due to of the explosive nature of nuclear material, previous mishaps, and widespread misconceptions. Some of the most vital challenges are discussed here.

- **Safety and accidents**

Nuclear accidents like Chernobyl (1986) and Fukushima (2011) have rightly aroused major safety concerns. However, it is critical to acknowledge that contemporary nuclear reactors have achieved significant advances in safety measures and risk management procedures to avoid and reduce such catastrophes (IAEA, 2021). For example, the Nuclear Regulatory Commission (NRC) in the United States has put

in place severe safety standards. Modern US reactors have several independent safety systems, and emergency response processes have been greatly enhanced since Fukushima. France, which relies on nuclear power for over 70% of its electricity, employs advanced safety processes and performs frequent safety exercises to maintain readiness for any potential mishaps (World Nuclear Association, 2021). The strict rules for nuclear safety set out by the Office for Nuclear Regulation (ONR) have been implemented by the United Kingdom. These guidelines include the ongoing evaluation and improvement of safety measures. The UK's strategy places a strong emphasis on learning from global best practices and ongoing improvement (ONR, 2020). While, the Pakistan Nuclear Regulatory Authority (PNRA) makes ensuring that stringent safety guidelines, are followed by nuclear plants in Pakistan. For instance, in 2021, new safety mechanisms were included in the Chashma Nuclear Power Plants along with training the staff on new lines to enable them to manage situations with effectiveness (PNRA, 2021).

Nuclear Waste Disposal

Managing nuclear waste remains a significant challenge, but it is manageable with existing and emerging technologies. Current methods involve storing spent nuclear fuel in secure, deep geological repositories. Countries like Finland have pioneered the use of such repositories; the Oncology repository is designed to safely contain nuclear waste for thousands of years (Posiva, 2021). The United States is exploring deep geological repositories, such as the proposed Yucca Mountain site, and is currently managing waste through dry cask storage systems, which have proven safe and effective. France reprocesses a significant portion of its nuclear waste, reducing the volume that requires long-term storage. In the United Kingdom, the government is investing in geological disposal facilities (GDFs) to ensure safe, long-term containment of nuclear waste. The UK also engages in public consultations to address concerns and increase transparency. Pakistan, though newer to the nuclear energy

sector, follows international guidelines for waste management. The country collaborates with the International Atomic Energy Agency (IAEA) to adopt best practices for waste storage and disposal (IAEA, 2021).

Public Perception and Political Issues

Public concerns and political issues regarding nuclear energy are significant but addressable through education, transparency, and robust policies. The fear of nuclear accidents and the stigma from past incidents contribute to public apprehension. However, countries with successful nuclear programs have demonstrated that these challenges can be overcome with proper communication and regulatory frameworks. For instance, France's successful nuclear program owes much to public education and transparent communication about nuclear safety and environmental benefits (World Nuclear Association, 2021). In the United States, the NRC actively engages with the public to address safety concerns and provide accurate information about nuclear energy's role in reducing carbon emissions (Vanina, S. 2024). The United Kingdom's ONR regularly publishes reports and conducts public meetings to maintain transparency and build public trust in nuclear energy (ONR, 2020). Similarly, Pakistan's PNRA engages with local communities and stakeholders to inform them about nuclear safety measures and the benefits of nuclear energy (PNRA, 2021).

In addition, robust policy frameworks are crucial. For example, the European Union's Euratom Treaty provides a comprehensive regulatory framework for nuclear energy, ensuring high safety standards across member states (European Commission, 2021). In Japan, despite the setback from Fukushima, the government has made significant strides in rebuilding public trust. Enhanced safety regulations and transparent communication have been pivotal in this process. The restart of several nuclear reactors under stringent new safety standards is a testament to overcoming political and public challenges (METI, 2020).

V. Case Studies

United States:

The United States has made significant advancements in nuclear safety, particularly after the Fukushima disaster. The U.S. Nuclear Regulatory Commission (NRC) has implemented rigorous safety measures, including continuous oversight and regular upgrades to plant safety systems. These measures include the installation of passive cooling systems, which ensure that reactors remain cool even without power, significantly reducing the risk of overheating. For example, the Vogtle Electric Generating Plant in Georgia has incorporated advanced passive safety systems in its new reactors. These systems use natural forces like gravity and convection to maintain cooling without relying on active mechanical components, thereby enhancing safety and reliability.

France:

France, which generates about 70% of its electricity from nuclear power, has implemented comprehensive safety protocols and regular safety drills to ensure high preparedness levels. France's approach to nuclear safety involves stringent regulatory oversight by the Nuclear Safety Authority (ASN) and the adoption of advanced safety technologies (World Nuclear Association, 2021).

Additionally, France excels in waste management through its reprocessing program at La Hague, which significantly reduces the volume of high-level waste that needs to be stored long-term. This process recovers usable materials from spent nuclear fuel, thereby reducing both waste and the need for fresh uranium (Orano, 2021).

United Kingdom:

The United Kingdom has adopted stringent safety guidelines through the Office for Nuclear Regulation (ONR), ensuring that all nuclear facilities adhere to the highest safety standards. The UK government has also invested in Geological Disposal Facilities (GDFs) for long-term waste management, exemplifying a proactive approach to nuclear safety and waste

disposal (ONR, 2020).

The Sellafield site, for instance, is undergoing a major decommissioning and waste management program, which includes the safe storage of spent nuclear fuel and other radioactive waste. This initiative demonstrates the UK's commitment to addressing historical waste challenges and ensuring future safety (Sellafield Ltd, 2021).

Finland:

Finland's Oncology deep geological repository is a global example of effective long-term nuclear waste disposal. The repository, managed by Posiva, is designed to safely contain spent nuclear fuel for thousands of years. Finland's transparent and participatory approach, involving local communities in decision-making processes, has built public trust in its nuclear program (Posiva, 2021).

The construction and operational safety measures at Oncology are rigorously tested and monitored, ensuring that the repository remains secure over its entire lifespan. This approach has set a benchmark for other countries considering similar waste disposal solutions (IAEA, 2020).

Sweden:

Sweden's nuclear waste management program is considered one of the best globally, primarily due to its extensive use of deep geological storage and community engagement. The Swedish Nuclear Fuel and Waste Management Company (SKB) oversee the safe disposal of nuclear waste, ensuring that it is securely stored away from the biosphere (SKB, 2021).

Sweden's approach involves comprehensive environmental impact assessments and regular public consultations, which help maintain public support and transparency. The Forsmark site, for example, is a key facility for interim storage of spent nuclear fuel before it is moved to a permanent repository (Mestneer, 2023).

Japan:

After the Fukushima disaster, Japan overhauled its nuclear safety regulations, with the Nuclear Regulation Authority (NRA) enforcing stringent

new standards. The country has since restarted several reactors under these enhanced safety protocols, reflecting improved safety and public trust. The safety measures include the installation of additional backup power supplies, enhanced cooling systems, and more robust containment structures. These improvements ensure that reactors can withstand extreme natural events and prevent similar incidents in the future (Bandoc, G. 2018).

Canada:

Canada's Nuclear Waste Management Organization (NWMO) is developing a deep geological repository for long-term waste management. The NWMO's approach involves extensive public consultation to address concerns and ensure community involvement in decision-making processes. The Adaptive Phased Management (APM) plan includes robust safety measures, environmental assessments, and ongoing community engagement. This participatory approach has been crucial in building public confidence and ensuring the project's success (Hillerbrand, R. 2015).

Pakistan:

Pakistan's Pakistan Nuclear Regulatory Authority (PNRA) ensures that nuclear facilities operate under strict safety regulations, with continuous staff training and international cooperation to adopt best practices. The Chashma Nuclear Power Plant, for example, adheres to modern safety standards and receives regular safety assessments and upgrades (PNRA, 2021). Pakistan collaborates with the IAEA to enhance its regulatory framework and safety measures, ensuring that its nuclear program operates safely and efficiently. This cooperation includes adopting international safety standards and engaging in peer reviews to continuously improve safety protocols (IAEA, 2021).

VI. The Future of Nuclear Energy Innovations in Nuclear Technology

Recent advancements in nuclear technology are setting the stage for a more sustainable and environmentally friendly future. Key

innovations include the development of advanced reactors and nuclear fusion technology, both of which promise to enhance the safety and efficiency of nuclear power.

1. **Advanced Reactors:** Advanced reactor designs, such as Generation IV reactors and Small Modular Reactors (SMRs), offer significant improvements in safety, efficiency, and waste management. Generation IV reactors, including fast reactors and molten salt reactors, are designed to use fuel more efficiently and produce less long-lived radioactive waste. These reactors incorporate passive safety features that automatically shut down the reactor in case of an emergency, reducing the risk of accidents (World Nuclear Association, 2023).
2. **Small Modular Reactors (SMRs):** SMRs are compact, scalable nuclear reactors that can be deployed incrementally to match energy demand. They are designed with inherent safety features and can be constructed more quickly and at a lower cost compared to traditional large reactors. Countries like the United States, Canada, and the United Kingdom are investing in SMR development, seeing them as a crucial component of their future energy mix (IAEA, 2023).
3. **Nuclear Fusion:** Nuclear fusion, the process of combining atomic nuclei to release energy, has the potential to provide nearly limitless clean energy with minimal environmental impact. Unlike nuclear fission, fusion produces no long-lived radioactive waste and has a much lower risk of catastrophic accidents. The International Thermonuclear Experimental Reactor (ITER) project is making significant strides toward achieving practical fusion energy, with experimental results expected in the coming years (ITER, 2023).

Integration with Renewable Energy Sources

The future of nuclear energy also involves its integration with renewable energy sources to create a balanced and resilient energy mix. Hybrid energy systems that combine nuclear and renewables can optimize energy production and storage, ensuring a stable and reliable power supply.

1. **Hybrid Energy Systems:** Hybrid systems can leverage the continuous power generation capability of nuclear energy with the intermittency of renewable sources like wind and solar. For instance, during periods of low renewable output, nuclear plants can ramp up production to meet demand, while excess renewable energy can be stored or used to produce hydrogen for later use (IEA, 2023).
2. **Energy Storage Solutions:** Advanced energy storage technologies, such as battery storage and pumped hydro storage, are essential for managing the variability of renewable energy. Integrating nuclear power with these storage solutions can provide a more flexible and resilient energy grid, capable of meeting demand at all times.
3. **Policy and Regulatory Support:** Effective policies and regulations are crucial for the successful integration of nuclear and renewable energy. Governments need to create supportive frameworks that encourage investment in both nuclear and renewable technologies, streamline regulatory processes, and promote public acceptance (World Nuclear Association, 2023).

Policy Recommendations

To harness the full potential of nuclear energy, it is essential to implement policies that promote innovation, investment, and international cooperation. Several key recommendations include:

1. **Investment in Research and Development:** Governments and private sectors should increase funding for R&D in advanced nuclear technologies, such as SMRs and fusion, to accelerate their development and deployment.
2. **Public Engagement and Education:** Building public trust and acceptance is crucial for the expansion of nuclear energy. Transparent communication about the safety, environmental benefits, and economic advantages of nuclear power can help mitigate public concerns and misinformation.

3. **International Collaboration:** International cooperation on nuclear technology, safety standards, and waste management can enhance the global nuclear energy landscape. Collaborative efforts, such as those facilitated by the IAEA and other international bodies, are vital for sharing knowledge and best practices.
4. **Streamlined Regulatory Frameworks:** Simplifying and harmonizing regulatory processes across countries can reduce the time and cost associated with deploying new nuclear technologies. This includes updating regulations to accommodate the unique characteristics of advanced reactors and SMRs (World Nuclear Association, 2023).

Conclusion

The Nuclear energy offers a powerful tool in the fight against climate change, providing a reliable and low-carbon energy source. Innovations in reactor design and nuclear fusion promise safer and more efficient nuclear power, while integration with renewable energy sources can create a balanced and resilient energy mix. By addressing safety concerns, fostering public acceptance, and implementing supportive policies, nuclear power can play a pivotal role in achieving a sustainable energy future. However, to fully realize its potential, challenges related to public perception, regulatory frameworks, and the management of nuclear waste must be addressed. By investing in research, safety improvements, and integrated energy strategies, nuclear power can work in harmony with renewables to create a resilient, low-carbon energy system. Global collaboration, policy support, and public engagement will be key to unlocking the full benefits of nuclear energy in combating climate change. In conclusion, nuclear energy, when strategically incorporated, offers a powerful tool in the global effort to achieve carbon neutrality and build a sustainable energy future for all. Nuclear energy holds substantial promise in the global fight against climate change by providing a reliable and large-scale source of low-carbon electricity. Its ability to operate continuously, unlike many renewable sources, makes it a crucial component of a sustainable and resilient energy

infrastructure. As nations strive to meet decarbonization goals and reduce their reliance on fossil fuels, nuclear power can complement renewable energy technologies, providing a consistent energy supply to bridge intermittency gaps.

The future of nuclear energy lies in overcoming key challenges, such as waste management, public concerns, and financial barriers, while leveraging advancements like small modular reactors (SMRs) and next-generation nuclear technologies. By addressing these issues through policy frameworks, innovation, and public engagement, nuclear energy can play a decisive role in achieving a sustainable, low-carbon future. A balanced approach that integrates nuclear with renewables is essential for a comprehensive solution to the climate crisis, ensuring energy security, economic growth, and environmental sustainability on a global scale.

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