Nuclear Energy Future in Mitigating Climate Change and Achieving Sustainable Development

Samah Abdullah Abd El-Azeem
Physics Department, College of Sciences and Humanities, Prince Sattam Bin Abdulaziz University, Al-Kharj 11942, Saudi Arabia | Physics Department, Faculty of Women for Arts, Science and Education, Ain Shams University, Cairo 11757, Egypt
drsamah2020.sa@gmail.com (corresponding author)

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ABSTRACT

The growing global population and rising developmental demands have led to increased electricity consumption, primarily from fossil fuel-powered stations, contributing to climate change and necessitating urgent sustainable development. This situation, exacerbated by global warming and its adverse environmental impacts, highlights the escalating demand for energy. As the awareness of climate change has intensified, nuclear energy has gained renewed attention as a key player in mitigating its effects. With global energy consumption being expected to rise substantially, expanding nuclear power plants has become a priority. Nuclear energy presents an opportunity to reduce reliance on fossil fuels while providing a clean and reliable source of electricity. This study investigates the role of nuclear energy in electricity generation, emphasizing its potential as a low-carbon energy source. It underscores the critical need to advance technologies, foster innovation, and enhance safety protocols to ensure energy security. The current study also advocates for increased funding and investment, the establishment and enforcement of effective policies and regulatory frameworks, and the development of human resources and infrastructure. Additionally, it recommends that governments prioritize research into innovative nuclear technologies, collaborate internationally, and accelerate the development and deployment of nuclear energy to support sustainable development.

Keywords-nuclear energy; climate change; sustainable development; global warming; greenhouse gases; clean energy

I. INTRODUCTION

Electricity is fundamental to modern life, and ensuring a continuous, reliable supply remains one of the world's greatest challenges [1]. As global energy demand increases, alongside the need to reduce greenhouse gas emissions and mitigate climate change, the development of clean, sustainable energy sources that provide consistent electricity has become increasingly critical [2]. Transitioning to these cleaner energy sources is a complex process that requires a balanced approach, integrating technical innovation, economic strategies, and supportive policies to achieve a sustainable energy future. Establishing such a future involves addressing the environmental and energy crises caused by the extensive fossil fuel use through an energy revolution focused on renewable electricity generation [3]. However, despite the increasing adoption of renewables, their full potential is hindered by the lack of advanced energy storage technologies. Effective storage solutions, such as advanced batteries, are essential for integrating renewable energy into the power grid and ensuring a reliable electricity supply.

In addition to advancing storage solutions, all viable options for a reliable electricity supply, including nuclear energy, should be considered. Rising energy demand and increasing oil and gas prices have prompted many countries to revisit nuclear power as a viable energy source. For populous nations, like China and India, nuclear power is particularly critical to diversify energy sources and reduce vulnerabilities to political and economic instabilities. Additionally, countries, such as the United Arab Emirates, Belarus, and potentially Niger, Jordan, and Turkey, are considering nuclear technology as a long-term strategy to support sustainable development, reduce climate change, and address global warming [4]. While nuclear energy offers significant potential, it requires careful management to address risks, such as safety concerns and nuclear waste disposal.

The early 21st century experienced a renewed interest in renovating existing nuclear power plants and constructing new ones, driven by the demand for cleaner energy solutions, rapid industrial growth in emerging economies, and the necessity to replace outdated or decommissioned power generation facilities. Nuclear reactors, known for their high safety standards, low waste production, and cost-effectiveness, offer a cleaner alternative to fossil fuels, which contribute to emissions and climate change. Nuclear power emits the least carbon, with each gigawatt of nuclear capacity potentially preventing 5.6 million tons of carbon dioxide emissions annually. Unlike fossil fuels, nuclear operations do not release pollutants, such as sulfur dioxide or nitrogen oxides [4]. In 2007, 439 nuclear power reactors operated across 30 countries, providing approximately 15.2% of the global energy consumption. Although nuclear technology was primarily utilized in industrialized nations, the developing countries were increasingly embracing it. Of the 30 reactors under construction, around 16 were placed in developing countries, mostly in Asia, where countries, like China, India, and Japan, were expanding their nuclear energy capabilities [5]. Nuclear energy is utilized in over 50 countries and regions, providing more than 10% of the global electricity and is anticipated to remain a key component of future energy supplies [6]. Fourteen countries in 2023 produced at least one-quarter of their electricity from nuclear energy. France gets up to around 70% of its electricity from nuclear energy, while Ukraine, Slovakia and Hungary get about half of it from the latter. Japan was used to relying on nuclear power for more than one-quarter of its electricity and is expected to return to somewhere near that level [7]. This study underscores the critical role of nuclear energy in advancing a sustainable future, calling for interdisciplinary collaboration and strategic initiatives to foster public understanding and acceptance. By integrating diverse perspectives, this research provides a foundational resource for researchers, policymakers, and stakeholders in the energy sector, supporting efforts to develop impactful strategies that align with global sustainability goals.

II. GLOBAL ENERGY DEMAND

Global energy demand is sharply rising due to the increasing world population, higher living standards, and continuous industrialization [8]. The International Energy Agency (IEA) projects that by 2050, energy demand will have doubled [9]. Currently, more than 80% of the world's energy supply relies on fossil fuels, including petroleum, coal, and natural gas [10-16]. However, beyond the concern of depleting fossil fuel resources, their extraction, processing, and use contribute significantly to environmental pollution. Therefore, it is crucial to develop and adopt energy-efficient, environmentally friendly technologies across various economic sectors [10].

TABLE I. ELECTRICITY PRODUCTION ACCORDING TO THE WORLD ENERGY COUNCIL

Region	Electricity production forecasts (TWh))				
	2010	**2020**	**2030**	**2040**	**2050**
Sahara region-Africa	414	612	996	1867	3087
Southeast Asia/Pacific	996	1549	2106	3123	4024
north America	5214	6152	6903	7727	8024
Middle East/North Africa	1150	1445	1951	2693	3644
Latin America	1147	1648	2422	3131	3701
Europe	5104	5932	6869	7803	8493
South Asia	6121	8761	11070	13064	14298
East Central Asia	1331	1861	2881	5055	8424
Total	21477	27960	35198	44454	35646

Table I presents data on the global electricity production in 2010, along with future projections until 2050, as outlined in the World Energy Council's studies. These regional forecasts highlight the global shift towards a more diverse and sustainable energy mix, emphasizing renewable energy sources and the need to meet the growing electricity demand worldwide.

III. THE PRESENT STATE OF NUCLEAR ENERGY

TABLE II. NUMBER OF NUCLEAR REACTORS IN OPERATION AND UNDER CONSTRUCTION IN SEVERAL COUNTRIES OF THE WORLD [17]

Country	**Operational (2020)**		**Under Construction (2020)**		**Nuclear Electricity Production in 2019**	
	Number of units	Net capacity (MWe)	Number of units	Net capacity (MWe)	TWh	% total
World	443	393,068	52	54,515	2,657	10.4
Argentina	3	1,641	1	25	7.9	5.9
Armenia	1	423	-	-	2.0	27.8
Bangladesh	-	-	2	2,160	-	-
Belarus	1	1,110	1	1,110	-	-
Belgium	7	5,930	-	-	41.3	47.6
Brazil	2	1,884	1	1,340	16.1	2.7
Bulgaria	2	2,006	-	-	16.5	37.5
Canada	19	13,554	-	-	95.4	14.9
China	50	47,518	14	13,175	348.3	4.9
Czechia	6	3,932	-	-	28.6	35.2
Finland	4	2,794	1	1,600	22.9	34.7
France	56	61,370	1	1,630	379.5	70.6
Germany	6	8,113	-	-	71.1	12.2
Hungary	4	1,902	-	-	15.4	49.2
India	23	6,885	6	4,194	40.7	3.2
Iran	1	915	1	974	5.9	1.8
Japan	33	31,679	2	2,653	65.6	7.5
Korea	24	23,150	4	5,360	138.6	26.2
Mexico	2	1,552	-	-	10.8	4.5
Netherlands	1	482	-	-	3.7	3.1
Pakistan	6	2,332	1	1,014	9.0	6.6
Romania	2	1,300	-	-	10.3	18.5
Russia	38	28,578	3	3,459	208.8	19.7
Slovakia	4	1,837	2	880	15.3	53.9
Slovenia	1	688	-	-	5.5	37.0
South Africa	2	1,860	-	-	13.6	6.7
Spain	7	7,121	-	-	55.8	21.4
Sweden	6	6,859	-	-	55.8	34.0
Switzerland	4	2,960	-	-	16.5	23.9
Turkey	-	-	3	3,342	-	-
Taiwan	4	3,844	-	-	31.1	13.4
Ukraine	15	13,107	2	2,070	83.0	53.9
UAE	1	1,345	3	4,035	-	-
UK	15	8,923	2	3,260	51.0	15.6
USA	93	95,523	2	2,234	809.4	19.7

As of early 2020, there were 443 operational nuclear reactors worldwide, with a total installed capacity of 393 GWe. An additional 54 reactors, with a combined capacity of 54.5 GWe, were under construction, as displayed in Table II [17, 18]. Nuclear power plants generated 2,657 TWh, accounting for 10.4% of the global electricity production. Although nuclear power production saw a 3.7% increase in 2019 compared to 2018, it remained below its 2006 peak of 2,761

TWh [19]. In 2019, the United States, France, China, Russia, and South Korea collectively produced 70% of the world's nuclear energy, with the U.S. and France alone contributing 45% of the total [18, 20-21].

Following the connection of the first nuclear reactor to the grid in June 1954 in Obninsk, near Moscow, the industry experienced growth, peaking with 26 and 33 new connections in 1974 and 1984, respectively. However, after the Chernobyl disaster, the industry faced a decline, and by 1989, reactor closures surpassed the new connections for the first time. From 2012 to early 2020, following the Fukushima incident, 55 new reactors were linked to the grid, with 34 of them having been located in China [17, 22]. Without significant new construction initiatives, the average age of nuclear reactors worldwide increased to 30.7 years by mid-2020. Of the reactors currently operational, 270, which make up two-thirds of the global total, have been running for over 30 years, as observed in Figure 5. This includes 81 reactors, representing 20% of the total, that have been in operation for over 40 years [22, 23].

IV. FUTIRE PROJECTIONS OF NUCLEAR ENERGY

Currently, 52 nuclear reactors are under construction worldwide, including 14 in China, with a combined net capacity of 54,515 MWe. However, many of these projects face construction delays, mainly due to high costs, with some experiencing significant postponements. For instance, the construction of the Bushehr-2 reactor in Iran, which began in 1976, was halted for nearly 40 years before resumed in 2019 [22].

According to forecasts from the International Atomic Energy Agency (IAEA) in 2020, the nuclear power generation capacity could have decrease by about 7% in the low scenario and have increased by up to 80% in the high scenario by 2050, as can be seen in Table III [21]. Regardless of these projections, the proportion of nuclear energy in the overall power generation mix is expected to decline. However, the power output from nuclear plants is anticipated to rise by 10% in the low scenario and 100% in the high scenario by 2050 [24].

TABLE III. FUTURE PROJECTIONS OF NUCLEAR ENERGY GENERATING AND PRODUCTION CAPACITY [21]

	2019	2030		2040		2050	
		Low	High	Low	High	Low	High
Nuclear Electrical Generating Capacity (GWe)	392	369	475	349	622	363	715
Nuclear as % of the Electrical Capacity	5.3	3.4	4.4	2.6	4.7	2.3	4.5
Nuclear Electrical Production (TWh)	2,657	2,872	3,682	2,774	4,933	2,929	5,762
Nuclear as % of the Electricity Production	10.4	8.2	10.5	6.4	11.4	5.7	11.2

V. NUCLEAR ENERGY AND GREENHOUSE GASES

Research by the IEA reveals that electricity and heat production contribute to 43.89% of the CO_2 emissions from fuel combustion, with fossil fuels, such as coal, natural gas, and oil, being the largest contributors to these emissions [25]. Achieving net-zero emissions requires the urgent and complete decarbonization of electricity and heat generation, utilizing low-carbon energy sources [26]. As technology progresses and the urgency to reduce greenhouse gas emissions intensifies, renewable energy is progressively taking a larger share of the global energy consumption [27, 28]. Currently, the wind power leads among the renewables, with solar energy quickly catching up. Transitioning to these cleaner, sustainable energy sources is essential for addressing climate change challenges and meeting the energy demands of a growing global population [29-32]. In 2019, renewables in the United States surpassed nuclear energy in electricity generation for the first time, underscoring the increasing potential of renewables to replace fossil fuels as primary power sources [33]. However, it is important to acknowledge that, at present, renewables alone may not be sufficient to fully replace fossil fuels due to technological constraints. Their energy output is variable and dependent on the weather conditions, which limits their ability to completely meet energy demands. Thus, achieving a decarbonized energy sector will require the integration of diverse clean energy solutions and technologies [34-37].

Nuclear energy generates electricity through controlled nuclear reactions that do not produce carbon emissions, a major contributor to climate change. It is a reliable energy source with minimal CO_2 emissions, ranging from 15 to 50 gCO_2/kWh, compared to the approximately 450 gCO_2/kWh from gas-fired power plants and 1050 gCO_2/kWh from coal-fired plants [38]. The high energy density of nuclear fuel allows for substantial electricity generation with a relatively small amount of material [8]. For instance, in France, nuclear energy power generates electricity with a lifecycle carbon footprint of just 12 g CO_2/kWh, representing only 1.18% of the 1011.5 g CO_2/kWh produced by coal power plants [25]. When compared to renewable energy sources, nuclear energy demonstrates comparable or superior carbon emission reduction performance. The emissions per kWh are similar to those of onshore and offshore wind power (12.4–14.2 g CO_2/kWh) and significantly lower than those of solar energy (21.7–42 g CO_2/kWh) [39]. Globally, nuclear energy accounts for approximately 25% of all low-carbon electricity generation, underscoring its critical role in the transition to a decarbonized energy sector [26]. The IAEA estimates that nuclear power plants have cumulatively prevented over 70 gigatons of CO_2 emissions over the past 50 years. Currently, existing nuclear reactors continue to annually reduce emissions by more than 1 gigatons of CO_2 [40]. Due to its low carbon emissions, countries, such as China, the United States, Canada, and Russia, have recognized nuclear energy as a key element of their carbon-neutral strategies. According to [41], nuclear electricity generation must double over the next 30 years to meet the net-zero emission targets, with the addition of approximately 550 GW of new nuclear capacity by 2050.

In addition to its low carbon footprint, nuclear energy does not emit sulfur dioxide or nitrogen oxides, which cause acid rain, nor does it release toxic metals, such as lead or mercury. This makes nuclear power one of the cleanest and least polluting energy sources available, positioning it as a highly effective solution to combat the global climate change [42, 43].

VI. CHALLENGES IN NUCLEAR ENERGY

Nuclear energy has long been recognized as a powerful source of electricity, offering a high energy density and low greenhouse gas emissions. However, despite these advantages, it faces significant challenges that impact its development and acceptance worldwide. Addressing these challenges is crucial to realizing nuclear energy's potential as a vital component of a sustainable energy future.

A. Safety Concerns

One of the foremost challenges in nuclear energy is ensuring reactor safety. The catastrophic accidents in Chernobyl in 1986 and Fukushima in 2011 profoundly impacted public perception, highlighting the severe environmental, health, and social consequences of nuclear incidents [44]. Despite these risks, nuclear energy is carefully monitored by international organizations, such as the IAEA and national regulators. Any new nuclear projects require extensive approvals and permits before they can proceed.

B. Nuclear Waste Management

Another significant challenge in nuclear energy is the management of nuclear waste, which remains hazardous for thousands of years. Addressing this issue necessitates the development of safe, long-term storage solutions. Geological repositories, designed to securely house waste deep underground, present a promising approach, though their implementation involves intricate technical and societal considerations. Moreover, advancing recycling and reprocessing technologies to extract usable materials from spent fuel while minimizing waste is crucial, but requires careful management to mitigate proliferation risks. A comprehensive planning strategy is essential to enhance the safe and efficient management of nuclear waste. Such a strategy should encompass all waste generated -past, present, and future- and account for every phase of the waste lifecycle, from its generation to its final disposal [45].

C. Economic Challenges

The economic viability of nuclear energy presents a significant challenge. The construction of nuclear power plants entails substantial initial costs and extended timelines, making them less attractive investments compared to the relatively cheaper and quicker deployment of renewable energy technologies. To ensure nuclear energy's competitiveness in a diversified energy market, innovative financing models, cost reductions through technological advancements, and streamlined regulatory processes are imperative. Furthermore, the operational costs of nuclear plants, including maintenance, fuel procurement, and the considerable expenses associated with decommissioning at the end of their lifecycle, further affect their economic feasibility. The growing availability and declining costs of alternative energy sources, such as natural gas, renewable energy, and advanced battery storage, have intensified economic pressures on nuclear power in some markets.

To address these challenges, the nuclear industry is exploring Small Modular Reactors (SMRs) as a cost-effective solution with lower upfront costs and greater deployment flexibility. Enhancements in construction techniques, supply chain efficiency, and advancements in fuel recycling and waste management also hold promise for improving the nuclear energy's economic competitiveness [46].

D. Proliferation Risks

Proliferation risks remain a significant challenge for the nuclear energy industry, as civilian nuclear technology and materials can be diverted for military purposes. The dual-use nature of nuclear processes, like uranium and plutonium enrichment, heightens the risk of their mismanagement in creating nuclear weapons. This issue is particularly acute in geopolitically volatile regions, where civilian nuclear programs might be suspected of masking weapon development efforts. The global dissemination of nuclear technology and expertise further exacerbates these risks, especially in cases where international safeguards and oversight by organizations like the IAEA are insufficient.

Mitigating proliferation risks requires robust international agreements and regulatory frameworks to ensure that the nuclear materials are exclusively used for peaceful purposes. Key measures include stringent oversight, enhanced transparency, and the enforcement of comprehensive non-proliferation treaties, which are vital for building trust among nations. Effectively addressing these risks is critical for the sustainable expansion of nuclear energy, as proliferation concerns significantly influence public perception, international relations, and global security [47].

E. Public Perception and Acceptance

Public perception plays a crucial role in the development of nuclear reactors. The Fukushima disaster significantly eroded public confidence in nuclear energy, leading to a prolonged stagnation in the global expansion of nuclear power plants. Over the past decade, the nuclear electricity generation capacity increased by only 59 GW, while 48 GW were decommissioned due to reactor shutdowns. A post-Fukushima survey conducted in 23 countries revealed that only 22% of the respondents supported expanding nuclear energy, while 30% of them called for the immediate closure of nuclear plants [48].

Public acceptance has therefore become a critical factor in the adoption of nuclear technology. In Germany, where nuclear energy once supplied a quarter of the electricity, eight reactors were permanently shut down immediately after the Fukushima incident, with plans to have phased out the remaining 17 by 2022. Similarly, the South Korea’s government, elected in 2017, opted to cancel new nuclear plant projects and reject lifetime extensions for the existing reactors [49]. However, the retreat from nuclear energy poses challenges for meeting carbon emission reduction targets and has contributed to rising electricity costs. For example, Germany reported the highest electricity prices in Europe during the first half of 2020 as a result of abandoning nuclear energy. Consequently, countries, like France and Japan, have revised their strategies, have emphasized the development of SMRs, and have been committed to increasing the nuclear capacity [40].

F. Regulatory Challenges

Regulatory challenges represent a significant barrier for the nuclear energy industry, arising from the intricate and evolving nature of nuclear technology. Ensuring safety, security, and environmental protection demands rigorous oversight, resulting in lengthy, documentation-heavy approval processes that often delay the construction and operation of nuclear plants. Moreover, inconsistent regulatory frameworks across countries complicate international projects and collaboration. As nuclear technologies, such as SMRs, continue to advance, regulatory bodies face the challenge of updating their frameworks to address the emerging safety and operational concerns. This includes conducting comprehensive safety assessments, engaging in public consultations, and adhering to international standards, all of which further add to project complexity and costs.

To address these issues, fostering collaboration between industry stakeholders and regulatory authorities is crucial. Such partnerships can help balance innovation with safety, streamline regulatory processes, and support the integration of nuclear energy into the global energy mix [49].

G. Technological Development

The advances in reactor technology hold the potential to enhance both safety and efficiency, yet they necessitate substantial investment in research, development, and testing. Next-generation reactors, such as SMRs and thorium-based systems, offer promising improvements but encounter challenges in terms of demonstration and large-scale deployment. Additionally, ensuring a sustainable supply of nuclear fuel requires continuous exploration and the development of alternative resources, which is crucial for long-term viability and security in the nuclear energy sector [50].

VII. DISCUSSION

A carbon-free energy system is a complex, ongoing effort that requires the adoption of multiple strategies to accelerate the transition. One key approach is reducing reliance on fossil fuels by incorporating alternative energy sources, such as nuclear power, especially when renewable options are not readily accessible. It is also essential to decrease carbon emissions from the electricity grid beyond the capacity of conventional clean energy technologies. This can be achieved by facilitating the rapid implementation of innovative solutions and phasing out fossil fuel usage. Additionally, supporting the electrification of buildings, transportation, and other sectors with carbon-free energy sources is substantial to the success of this transition. [51-58] .

Currently, fossil fuels account for 62% of the global electricity generation, while renewables contribute 28% and nuclear energy only 10%. This heavy reliance on fossil fuels continues to drive greenhouse gas emissions. Although there is a gradual progress toward the adoption of low-carbon technologies and improved utilization of renewable resources, the pace of this transition is insufficient to meet the urgent need for decarbonization. Energy efficiency also plays a vital role in this process, allowing for the same energy output with less energy consumption, which reduces waste, lowers emissions, and offers significant economic benefits, including lower energy costs at both the household and national levels. These factors are all critical for mitigating climate change [59-60].

The ongoing use of fossil fuels presents an immediate threat to climate stability and is not sustainable in the long run due to the finite resources. As a result, there is growing emphasis on developing renewable energy sources as alternatives. These sources are increasingly seen as solutions to the depletion of fossil fuels, attracting significant investment and advancing rapidly. However, there is a notable trend toward reducing the reliance on nuclear energy due to the perceived risks, including safety concerns and public opposition. In light of the current energy crisis and the pressing need for sustainable energy solutions, moving away from nuclear power may not be a prudent decision [61].

Although renewable energy sources are often regarded as the future of energy generation, existing technological limitations, particularly in energy storage, highlight the necessity for supplementary emission-free power sources. Nuclear energy, as a reliable and efficient option, could effectively support and enhance electricity production from renewables. Moreover, the substantial investment directed towards developing renewable energies, like solar and wind, may not be the most effective approach due to their lower efficiency and reliability. Therefore, increasing investment in nuclear energy is essential not only to bridge knowledge gaps, but also to advance the field, ensuring a dependable source of emission-free energy [62-64].

VIII. CONCLUSIONS

Nuclear energy plays a critical role in the global transition to a sustainable, low-carbon future. Its ability to generate significant amounts of electricity with minimal greenhouse gas emissions makes it an essential tool in combating climate change. Even though challenges, such as safety concerns, waste management, public perception, and economic considerations are visible, the advantages of nuclear power, particularly its high energy density and ability to diversify the energy mix, cannot be ignored. The advancements in technology, regulatory improvements, and international collaboration are crucial to unlocking the full potential of nuclear energy. Through increased investment in research and development, enhanced safety protocols, and greater public engagement, nuclear power can effectively contribute to achieving carbon neutrality. As the world moves towards decarbonization, an integrated energy strategy that combines the strengths of nuclear energy with renewable sources is critical for ensuring a resilient and environmentally sustainable energy future. Publications and transparent communication can help bridge the gap between nuclear energy experts and the broader public. By providing accurate, balanced information, these efforts can combat misconceptions and foster trust, ultimately building greater public support for nuclear initiatives. Encouraging dialogue and disseminating knowledge is essential to promoting the understanding and acceptance of nuclear energy as a viable solution for sustainable energy.

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