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THE ROLE OF NUCLEAR ENERGY IN REDUCING CARBON DIOXIDE EMISSIONS

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Abstract:
Nuclear energy plays an important role in reducing carbon dioxide (CO_2) emissions since it allows the production of large amounts of electricity without the direct combustion of fossil fuels. Unlike coal and gas-fired power plants, nuclear power plants do not emit CO_2 during the operation, making them a significant factor in the fight against climate change. Furthermore, unlike renewable sources that depend on weather conditions, nuclear energy provides a stable and reliable source of electricity generation. Although there are challenges, such as solutions for radioactive waste and high initial costs, advancements in technology, particularly the development of fourth-generation reactors and small modular reactors, could further enhance the sustainability of this energy source. In combination with renewable sources, nuclear energy can contribute to reducing global fossil fuel consumption and facilitate the transition to a low-carbon economy.
Keywords: *Nuclear energy, CO_2 emissions, Climate change, Renewable sources, Fourth generation reactors.*

Introduction

Climate change is one of the most significant challenges that modern society faces. Global warming, primarily caused by carbon dioxide (CO_2) emissions and other greenhouse gases, can lead to major changes in ecosystems worldwide. These include rising sea levels, increasingly frequent and extreme weather events, and a range of other negative consequences for the environment and human society. In the effort to reduce CO_2 emissions and ensure a sustainable energy future, nuclear energy is gaining increasing importance as one of the key solutions. One of the main advantages of nuclear energy is that it does not produce direct CO_2 emissions during operation, making it significantly more favorable compared to traditional power plants that rely on fossil fuels. The aim of this paper is to analyze the role of nuclear energy in reducing CO_2 emissions, considering its advantages and limitations. Through a review of relevant literature, the study explores how nuclear energy can contribute to global efforts to mitigate climate change, as well as the challenges it faces in this process.

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This analysis enables an understanding of how nuclear energy can play a significant role in the fight against climate change while also identifying key challenges that must be addressed to maximize its benefits.

1. Nuclear Energy and CO_2 Emission Reduction

When comparing different sources of electricity based on their total life-cycle CO_2 emissions, nuclear energy stands out as one of the options with the lowest carbon emissions. On average, a nuclear power plant produces approximately 12 grams of CO_2 equivalent per kilowatt-hour of electricity (g CO_2e/kWh), which is comparable to wind power and significantly lower than solar panels, which emit around 45 g CO_2e/kWh. In comparison, coal-fired power plants release between 820 and 1,000 g CO_2e/kWh, while natural gas plants emit around 490 g CO_2e/kWh [1]. This exceptionally low emission level makes nuclear energy a potentially key element in the fight against climate change [2].

Countries that have successfully implemented nuclear energy as a significant part of their energy mix demonstrate impressive results in reducing CO_2 emissions. France, which generates approximately 70% of its electricity from nuclear power plants, has one of the lowest per capita CO_2 emissions among developed countries [3]. Similarly, Sweden has successfully combined nuclear energy with hydropower to drastically reduce its dependence on fossil fuels. Historical data show that the rapid expansion of nuclear energy during the 1970s and 1980s in France, Sweden, and several other countries enabled the fastest reduction in the carbon intensity of the energy sector ever recorded [4].

Figure 1 shows the map of nuclear energy in the European Union for the year 2023, with a total production of 619,601 GWh. France is the largest producer, generating 338,202 GWh. Countries marked in yellow represent those that produce nuclear energy, while those marked in blue do not.

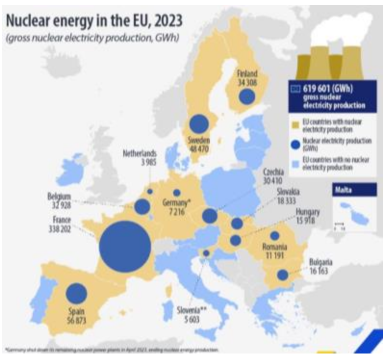

Figure 1. *Nuclear Energy in Europe in 2023 [5]*

Long-term projections by the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) indicate that achieving the goals of the Paris Agreement will most likely require a significant increase in the share of nuclear energy in the global energy mix. Most scenarios that predict successful limitation of global warming to 1.5 °C or 2 °C include a doubling or even tripling of global nuclear energy capacity by mid-century. These projections recognize the challenges associated with nuclear energy expansion, including high initial costs, lengthy construction processes, and public acceptance issues. However, they also emphasize its irreplaceable role as a stable, high-capacity electricity source with low CO_2 emissions [6].

Nuclear energy also has the potential to contribute to decarbonization beyond the electricity sector. The high-temperature heat generated in nuclear reactors can be used to produce hydrogen through thermochemical processes or high-temperature electrolysis, enabling low-emission transportation and industry. Advanced technologies, such as small modular reactors (SMRs), promise greater flexibility and lower costs, potentially facilitating the broader adoption of nuclear energy. Additionally, existing nuclear power plants can be utilized for synthetic fuel production when electricity demand is not at its peak, further reducing reliance on fossil fuels in sectors where direct electrification is challenging [7].

2. Challenges and Limitations of Nuclear Energy

Nuclear energy is considered a significant source of electricity worldwide today, but it comes with numerous challenges and limitations that affect its broader adoption. One of the most important issues is the safety aspects of nuclear power plants, especially after disasters such as Chernobyl and Fukushima. These accidents demonstrated that, despite advanced safety systems, the combination of human errors, technical failures, and natural disasters can have severe consequences for the environment and human health. The issue of nuclear waste disposal is one of the most complex aspects of nuclear energy, as highly radioactive waste must be safely stored for thousands of years, raising technical, political, and ethical questions [8].

The economic challenges associated with nuclear energy are becoming increasingly significant. The initial costs of building nuclear power plants are very high, and the construction period can take over a decade. When adding the costs of insurance, maintenance, and eventual decommissioning of the plants, nuclear energy often becomes economically less competitive compared to renewable energy sources, whose prices are continuously falling. This has led to a reassessment of the economic viability of new nuclear projects in many countries [9].

In addition, the proliferation of nuclear weapons presents an additional risk associated with nuclear energy. The technologies used for uranium enrichment in civilian nuclear programs can be misused for the development of nuclear weapons. The international nonproliferation regime aims to prevent such misuse, but challenges remain, especially in politically unstable regions. Even when there is no direct link to military programs, the spread of nuclear technology increases global security risks, including the possibility of terrorist attacks on nuclear facilities or theft of nuclear materials. Public opinion plays a significant role in the future development of nuclear energy, as public support has significantly declined in many developed countries following major nuclear incidents [10].

3. The Future of Nuclear Energy in Decarbonization

Nuclear energy is considered one of the most controversial sources of energy in the context of global decarbonization. While it does not produce direct CO_2 emissions during its operation, there are serious issues such as radioactive waste management, safety risks, and high investment costs, which often overshadow its benefits. However, interest in nuclear technology is once again rising, partly in response to the increasing need for reliable energy sources that can complement and support intermittent renewable sources like solar and wind energy. The development of advanced fourth-generation reactors has the potential to overcome many traditional barriers and offer a technically feasible solution for reducing CO_2 emissions in the energy sector [11].

The current energy situation shows that many countries are reassessing their nuclear policies, especially in light of rising climate goals and the need for energy security. For example, China, Russia, and the United Arab Emirates are actively expanding their nuclear energy capacities, while France and the United Kingdom continue to develop new projects despite the challenges. In contrast, Germany and Switzerland have decided to gradually phase out nuclear energy, reflecting the social and political tensions surrounding this technology. These different developmental paths highlight the complex relationship between technical, economic, and socio-political factors influencing the future role of nuclear energy [3].

SMRs are considered one of the most promising directions for the development of nuclear energy. Unlike traditional large reactors, SMRs offer many advantages, such as prefabricated manufacturing, reduced capital costs, more flexible implementation, and improved safety features. These systems may prove particularly useful for remote communities, industrial sites with high energy demand, or in combination with renewable energy sources to provide stable power. Some countries, including the U.S., Canada, and the United Kingdom, actively support the development and commercialization of SMR technology, with the first commercial projects already nearing realization. However, challenges remain regarding regulatory approvals, economic competitiveness, and public acceptance of these new technologies [12].

In addition to technical innovations, the future of nuclear energy in the context of decarbonization will significantly depend on economic factors. Historically, nuclear projects have often faced cost overruns and delays, which has impacted their competitiveness compared to alternatives such as natural gas and increasingly renewable energy sources. When considering the costs of energy storage, grid expansion, and backup capacity required for systems with a high share of renewables, the economic equation becomes more complex. Moreover, carbon pricing mechanisms and recognition of the value of CO_2-free electricity generation could significantly improve the economic position of nuclear energy. The success of future nuclear projects will likely depend on the industry's ability to reduce costs through standardization, supply chain optimization, and improved project management practices [13].

4. Conclusions

Nuclear energy has significant potential in global efforts to reduce CO_2 emissions, thanks to its extremely low carbon footprint during the operation of power plants. This means that nuclear energy can generate electricity without direct CO_2 emissions, which is crucial in the fight against climate change.

The successful implementation of nuclear energy in countries like France and Sweden has significantly reduced carbon dioxide emissions, but its broader use remains limited due to safety risks, challenges in managing radioactive waste, high initial costs, long construction periods, and concerns about the proliferation of nuclear weapons.

The development of advanced nuclear technologies, such as fourth-generation reactors and SMRs, offers promising solutions for decarbonization by enhancing safety, reducing costs, and enabling more flexible implementation. By providing stable base-load power, nuclear energy can complement intermittent renewable sources like solar and wind, ensuring a more reliable energy supply. A balanced integration of nuclear and renewable energy, along with effective management of existing challenges, is essential for a successful transition to a low-carbon economy and mitigating climate change.

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