A Review of Nuclear Energy: Sustainability and Environmental Friendliness for the Future

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Abstract: Nuclear energy is important for its low greenhouse gas emissions and provision of reliable, baseload power in the transition to a sustainable and resilient energy future. This review paper critically examines nuclear power's role in transitioning to cleaner energy sources. The review discusses that nuclear energy, recognized for its low greenhouse gas emissions and high energy density, offers a compelling option for addressing environmental concerns.. This article covers the significance of nuclear energy in achieving climate goals and meeting rising energy demands, provided that these challenges are effectively managed. It stresses the necessity of maintaining a balanced energy mix that incorporates renewables to secure a sustainable and environmentally friendly future. This review contributes valuable insights into the potential and challenges associated with nuclear energy in the context of environmental sustainability.

Keywords: Climate Change, Environmental Sustainability, Nuclear Energy

1. Introduction

Sustainable development is a comprehensive idea that aims to fulfill the current generation's needs without jeopardizing the ability of future generations to meet their own requirements. It necessitates a delicate balance of environmental, social, and economic aspects, taking into account equity across nations and generations as shown in Figure 1 [1]. While sustainability in the context of energy supply used to revolve around fuel availability compared to consumption rates, recent concerns about climate change and environmental degradation have added complexity to the equation.

The link between energy consumption and human development is evident. A country can significantly enhance the well-being of its populace by increasing energy consumption up to about 100 gigajoules (GJ) per capita, a milestone yet to be reached by 80% of the world's population. Therefore, a fundamental aspect of advancing toward a more equitable and sustainable future is ensuring that everyone has access to modern, affordable, and dependable energy services. However, achieving this will result in a rise in global energy demand.

The primary challenge lies in how to meet this growing demand for energy. Currently, more than 80% of our energy comes from burning fossil fuels, a situation that hasn't changed significantly since 1990. The unregulated emissions from this practice are contributing to climate change, environmental harm, and the premature deaths of around 7 million people annually. This dual challenge – the necessity to reduce harmful emissions while providing more energy to an expanding population – places the energy sector at the core of sustainable development efforts.

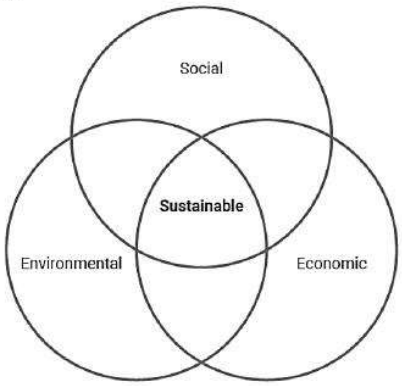

Fig. 1: The three 'pillars' of sustainability [1]

It's crucial to recognize that no energy technology is entirely devoid of risks to people or the environment. For example, low-carbon energy sources might not release carbon dioxide during use, but they do generate emissions and waste during their construction, production, and decommissioning phases. As such, the suitability of any energy technology for achieving sustainable development objectives must be evaluated in relative terms, considering its merits and demerits when compared to alternative options.

Nuclear power, the only proven, scalable, and reliable low-carbon energy source, will be crucial in reducing our reliance on fossil fuels to combat climate change and chronic air pollution. In a broader context, nuclear power stands as a sustainable energy option due to its inherent energy density and the fact that it incorporates the costs related to health and the environment. Utilizing nuclear energy offers various sustainability benefits compared to alternative energy generation methods. By expanding its usage, we can provide modern, affordable energy to those currently lacking access while lessening our impact on the environment. This, in turn, ensures that our pursuit of other sustainable development goals remains unhampered.

As shown in Figure 2, at the end of the twentieth century, global energy demand was 5653 TW-hours, while at the end of the nineteenth century, it was 2.5 times that amount, and in 2021, global energy demand was 176,431 TW-hours [2]. The importance of energy and electrical power for economic development has thus increased.

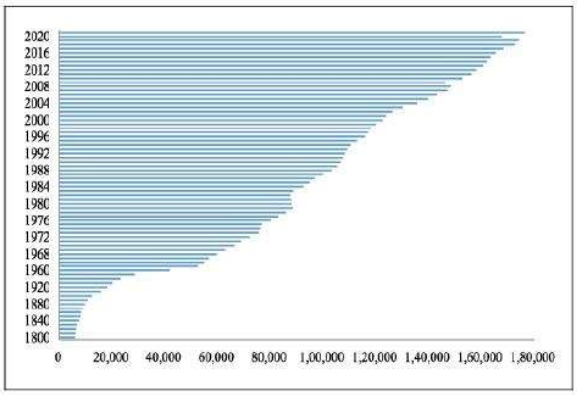

Fig. 2: Global energy consumption (terawatt-hour) [2].

This review paper takes a close look at how nuclear power can contribute to the shift towards cleaner energy sources. The paper explores that nuclear energy, known for its minimal greenhouse gas emissions and substantial energy output, presents a convincing choice for addressing environmental issues. It also covers the mix of nuclear energy with renewable energy.

3. Comparison of Nuclear Energy with Other Energy Sources

3.1 Climate Change

The United Nations recognizes climate change as "the most systemic threat to humankind". As such, addressing it is generally considered the most significant and urgent sustainability challenge. Climate change is resulting from increasing concentrations of CO_2 in the Earth's atmosphere. Given that three-quarters of anthropogenic CO_2 emissions result from the burning of fossil fuels for energy, the main focus should be on deploying energy technologies that emit only small amounts of CO_2 per unit of energy, as shown in Figure 3. On a life-cycle basis, nuclear power emits just a few grams of CO_2 equivalent per kWh of electricity produced. A median value of 12g CO_2 equivalent/kWh has been estimated for nuclear – similar to wind and lower than all types of solar [3].

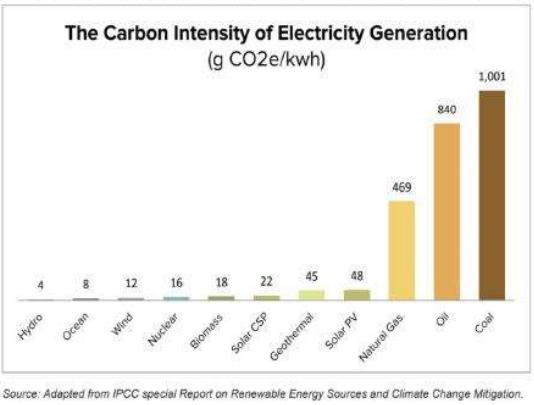

Fig. 3: CO_2 equivalent/kWh from various energy sources [4]

Environmental deterioration, climate change, and the need for energy consumption are now major concerns for human rights worldwide. Growing energy consumption and demand are major problems in reducing atmospheric emissions during economic expansion [5]. Nuclear energy has become a possible solution to reduce carbon emissions and encourage better energy practices to address this issue [6]. For instance, Kim [7] looked at the inspiration of nuclear energy on CO_2 emission and proposed that it is a more practical and long-term method of lowering carbon emissions in clean energy systems. Danish et al. [8] established that increasing investment in nuclear energy promotes energy efficiency, which boosts environmental sustainability and reduces CO_2 emissions in India. Similarly, Saidi and Omri [9] advised that OECD countries implement nuclear energy conservation to decrease the adverse environmental effects of energy usage by optimizing energy efficiency.

3.2 Land Requirement

Nuclear power plants produce huge amounts of low-carbon power and require less land than any other energy source. The UN expects two-thirds of people to live in urban areas by 2050 – an additional 2.5 billion individuals – where land is at a premium. Coupled with the need to preserve land to prevent loss of biodiversity, it is likely that nuclear energy's unique land-use advantages will prove increasingly determinative in the future as shown in Figure 4 [10].

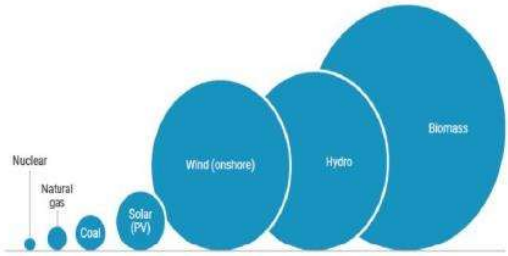

Fig. 4: Relative land use (fuel mining and generating footprint) of electricity generation options per unit of electricity [11].

3.3 Water Requirement

Fresh water is a valuable resource in most parts of the world. Apart from proximity to main load centers, there is no reason to site nuclear power plants away from a coast, where they can use once-through seawater cooling.

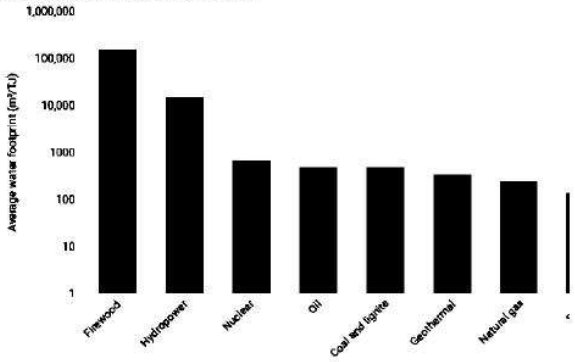

Fig. 5: Water consumption per unit of electricity and heat produced 2008-2012 [12].

Though nuclear power plants require significant quantities of water for cooling as shown in Figure 5 [12], their ability to provide large amounts of power is increasingly being used to secure water supplies in areas of scarcity. Where potable water cannot be obtained from streams and aquifers, desalination of seawater, mineralized groundwater is required. Most desalination is powered by fossil fuels, but nuclear desalination has been used for many years in countries such as Japan, India and Kazakhstan.

3.4 Waste Production and Nuclear Energy

Zhang et al. [13] suggested that careful waste management is crucial for sustainability, as it prevents harm to people and the environment. All energy technologies produce waste, but the quantity, risk, and management methods vary. The energy density of the fuel used plays a significant role in waste production and manageability. Nuclear energy, with its high energy density, requires a small amount of fuel per unit of energy, resulting in manageable waste streams. Unlike some other energy sources, nuclear energy contains its emissions, effluents, and waste, making it the only electricity generation method to do so. Nuclear energy incorporates waste management, disposal, and decommissioning costs into its electricity cost, minimizing external costs for society. This internalization of costs allows for rational decision-making when comparing energy sources.

3.5 Safety Aspect

When comparing energy sources from a safety perspective, it is evident that each source has its own set of advantages and drawbacks. Nuclear energy, while having low greenhouse gas emissions, carries the risk of catastrophic accidents and long-term radioactive waste management. Fossil fuels, including coal, oil, and natural gas, are reliable but contribute to air pollution and health hazards. Renewable energies like wind and solar are generally safer during operation but face challenges in integrating into the grid and have some environmental impacts in manufacturing and disposal. Hydropower, biomass, geothermal, and natural gas each have unique safety considerations, highlighting the importance of carefully evaluating energy sources based on location and specific context to ensure the highest level of safety.

Although legacy nuclear energy has been the safest form of electricity generation, it has been demonized as unsafe since the 1960s. The three well-known nuclear accidents, Three Mile Island, Chernobyl, and Fukushima, were legacy nuclear designs. Even with the best safety record of all types of electricity generation, it is time to move away from legacy nuclear to reap the benefits of a truly renewable source of safe clean energy, advanced nuclear.

4. Technological Enhancement in Nuclear Energy

The advancement in the nuclear energy from technical point of view is required because of to prevent the accidents (Three Mile Island, Chernobyl, and Fukushima) and to provide safer electricity generation using nuclear energy.

Application of this nuclear energy for industrial process heating; recycling legacy nuclear 'waste' to provide fuel for advanced reactors; integration of the hydrogen economy into nuclear plant design and operation; improvement in moving pebble-bed advanced reactor technology; mining improvements for uranium and thorium, including mining uranium from seawater; molten salt storage systems for improving load following functionality and to provide process heat functionality; resolving corrosion challenges in molten salt reactors; and retrofitting existing oil-and-gas-based refineries to operate as nuclear bio refineries[14].

5. Challenges for Nuclear Energy

Nuclear energy, while offering benefits in terms of low greenhouse gas emissions and high energy density, is not without its challenges. The most

significant concern is the potential for nuclear accidents, as exemplified by disasters like Chernobyl and Fukushima. These accidents can have long-lasting environmental and health consequences. Another challenge is managing radioactive waste, which remains hazardous for thousands of years and requires secure storage and disposal solutions [15]. Nuclear proliferation, where materials or technology for peaceful nuclear energy purposes are misused for weapons, is a security concern. Additionally, the high capital costs of nuclear power plants and public apprehension about safety further complicate the widespread adoption of nuclear energy. Addressing these challenges is crucial for the continued development and safe utilization of nuclear energy in the global energy mix.

6. Hybrid Nuclear-Renewable Energy System

. In terms of cleaner production, the most popular and practiced way of power generation is renewable energy sources which are intermittent in nature, require large land area, and also dependent on geographic positions and climatic conditions. Besides, nuclear energy is also having some limitations including government policies and public apprehensions. To overcome these hurdles, these two carbon-free technologies can be integrated and form a Hybrid Nuclear-Renewable Energy System system (HNRES) [16].

HNRES differ from combined heat and energy generation systems in that the objective is not only to generate heat and power for use in regional industrial plants but also to transmit as much low-carbon energy as possible to industrial processes. This system also ensures grid flexibility, emission reduction, and economic viability [17].

7. Conclusion

The following conclusions can be drawn based on this literature review:

- With less emissions of CO_2, less requirement of land, and a high availability factor compared to other energy resources, nuclear energy should be the preferred choice for the next generation.
- Though there are safety concerns (radiation exposure, radioactive waste management) associated with Nuclear energy. But these challenges can be handled with the advancement in technologies. As radioactive waste can be used in next-generation nuclear power plants.
- Integration of nuclear energy with renewable energy is providing the future energy systems by mitigating the limitations of each other at some extent.

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