International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online) Volume 14, Issue 8, August 2025)

Nuclear Energy-Based Sustainable Development

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Abstract — **This paper's primary goal is to supply carbon-free power at a reasonable cost while reducing emissions and eliminating greenhouse gas emissions over their entire operating cycle. It can provide civilization with contemporary, reasonably priced energy. Achieving sustainable development goals—from ending poverty to improving health and education, promoting industrial development, and lowering greenhouse gas emissions—requires having access to inexpensive, dependable, and clean energy. The energy needed to attain high living standards, good health, a clean environment, and a sustainable economy can be supplied by nuclear power.**

Keywords— **Nuclear energy, Sustainable development, Greenhouse gases, Carbon-free power, Clean energy**

I. INTRODUCTION

Compared to thermal power from fossil fuel power plants, nuclear power is thought to have both economic and environmental benefits. Since nuclear power facilities don't release greenhouse gases like CO2 while they're operating, they don't significantly contribute to global warming, however some CO2 emissions are linked to other stages of the plants' life cycles. Because of their low operating costs, nuclear power plants are often able to generate base-load electricity at a lower cost than many other energy sources.

Recent years have seen improvements in nuclear power reactors' capacity factors, safety records, construction time, and cost. Development that satisfies current demands without jeopardizing the capacity of future generations to satisfy their own needs is known as sustainable development. It tackles a wide range of social, economic, and environmental problems, such as poverty, environmental degradation, and disasters, but it lacks a single, precise definition. However, pollutants are created, released, and disposed of along all energy value chains, from resource extraction to usage, harming the environment.

II. NUCLEAR ENERGY OVERVIEW

The regulated release of heat from the fission of heavy atomic nuclei, mainly uranium-235 and, to a lesser extent, plutonium-239, is known as nuclear energy. This heat turns water into steam in a commercial power plant, which powers turbines to produce electricity while producing no greenhouse gas emissions. Nuclear energy is one of the most resource-efficient energy sources accessible since modern reactors reach very high energy densities—a few metric tons of fuel may power a gigawatt-scale plant for more than a year.

Approximately 25% of low-carbon electricity and 10% of all electricity worldwide are produced by nuclear power. With the largest fleets in the US, France, China, and Russia, more than 400 reactors are in operation in more than 30 countries. Pressurized water reactors (PWR), boiling water reactors (BWR), pressurized heavy-water reactors (PHWR), and more recent designs like small modular reactors (SMRs) and Generation IV concepts that prioritize passive safety and enhanced fuel cycles are important reactor types.

Fig.1:Kudankulam Nuclear Power Plant

The main benefits of nuclear power over wind and solar electricity are its small land footprint, high capacity factor (typically over 90%), and low operating emissions. High upfront capital costs, lengthy licensing procedures, public opinion, and long-term spent fuel management are still obstacles, but new developments in advanced reactors, fuel recycling, and modular construction are working to overcome these problems and increase nuclear's contribution to a low-carbon, sustainable energy future.

III. Sustainability Dimensions Of Nuclear Energy

A. Environmental Sustainability

One of the cleanest possibilities for producing electricity on a large scale is nuclear energy. Nuclear reactors are essential to international efforts to fight climate change and reach carbon neutrality because, when in operation, they release very little greenhouse gas. Nuclear improves air quality and public health since it doesn't emit sulfur dioxide, nitrogen oxides, or particle matter like fossil fuels do.

Additionally, nuclear has a very small land footprint. In order to generate the same amount of electricity, a 1,000 MW nuclear power station needs just over one square mile, but solar and wind require about 75 and 360 square miles, respectively. This effectiveness contributes to biodiversity and agricultural land preservation.

B. Economic Sustainability

High capital expenditure and extremely low operational costs are characteristics of nuclear power. Reactors offer steady electricity pricing once they are up and running, independent of changes in the price of coal or natural gas fuels. Additionally, nuclear reactors run at capacity factors exceeding 90%, which means they provide steady, dependable power with little downtime—much higher than solar or wind.

From the standpoint of employment, nuclear energy sustains thousands of highly skilled positions in supply chain sectors, plant operations, and safety engineering. In order to ensure competitive long-term economics, long plant lifetimes—typically 40–60 years, with possible extensions—spread capital expenses across decades.

Although initial building costs are a deterrent, advancements like standardized reactor designs and Small Modular Reactors (SMRs) are meant to reduce financial risks and shorten construction times.

C. Social Sustainability

By improving national energy security and lowering reliance on imported fossil fuels, nuclear energy promotes social well-being. Digital infrastructure, healthcare systems, industrial expansion, and general economic progress are all supported by a steady supply of electricity.

Nuclear initiatives promote technological research, create specialized education programs, and create long-term job prospects. Local investment, training, and infrastructure development are advantageous to communities that house nuclear reactors.

Public perception is still a major social issue, though. Nuclear safety is a major worry due to past incidents like Fukushima (2011) and Chernobyl (1986). Transparent communication, a solid safety culture, strict regulatory control, and an obvious dedication to environmental conservation are all necessary to maintain social approval.

D. Technological Sustainability

Nuclear energy is becoming more sustainable due to ongoing innovation. The designs of advanced generation IV reactors place a strong emphasis on built-in safety mechanisms, economical fuel use, and the potential to recover spent fuel. Modularity, shorter building times, and the possibility of deployment in remote or smaller grid regions are also benefits of SMRs.

Furthermore, nuclear energy can be used for purposes other than producing power. For industries that are typically challenging to decarbonize, such as steel, cement, and chemical manufacturing, high-temperature reactors can supply process heat. Another viable route that supports clean transportation and industrial transitions is nuclear-driven hydrogen production.

Nuclear can also act as a stabilizing backbone of future energy systems by integrating with renewable sources, guaranteeing grid dependability and facilitating the broader penetration of intermittent sources like solar and wind.

IV. Environmental Issues And Sustainable Growth

Since actions that continuously harm the environment are not sustainable, environmental issues and sustainable development are related. These activities' long-term cumulative effects on the environment frequently result in a range of ecological, health, and other issues. Since energy is essential to sustaining and raising living standards globally, the relationship between humans and the environment has become more obvious in recent years.

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It's possible that the extensive usage of fossil fuels had a big effect on the environment. The greenhouse gases produced by burning fossil fuels are thought to be a significant contributor to global warming, in addition to the effects of drilling and mining for these resources and the release of waste from processing and refining activities. Flooding, extreme weather, and disruptions to the food chain are all consequences of global warming and extensive climate change. In both urban and rural locations, as well as in industrialized and developing nations, nuclear energy can assist minimize environmental harm and promote sustainability. Nuclear energy development and use should be given top priority.

Nuclear energy can contribute to sustainable development in several ways:

Zero greenhouse gas emissions: Unlike fossil fuels, nuclear power plants emit no greenhouse gases while in operation, making them a cleaner energy source.

Reliability: Nuclear energy supports economic growth and development by offering a steady and dependable source of electricity.

Fig.2 Nuclear Energy Agency(NEA)

Scalability: Nuclear energy can lower carbon emissions while meeting the world's growing energy needs.

Diversification: By lowering reliance on fossil fuels, nuclear energy can provide energy security and variety in several ways:

Low waste production: The goal of next-generation nuclear technology is to increase fuel efficiency while reducing waste production.

Carbon capture and storage (CCS): To cut emissions from industrial sources, nuclear energy can be used in conjunction with CCS.

Nuclear-renewable hybrid systems: For the best energy output, hybrid systems can be created by combining nuclear energy with renewable resources like solar or wind power.

Energy storage: Hydrogen can be produced using nuclear energy for transportation and energy storage.

Applications in medicine and industry: Nuclear energy helps with industrial operations, food irradiation, and medical treatments.

III. HUMAN HEALTH AND NUCLEAR POWER

There is an indirect connection between SDG7 (Sustainable Development Goal 7) and well-being. Medical facilities require dependable and reasonably priced energy, and converting to contemporary, sustainable energy sources can lower the number of illnesses and deaths brought on by pollution. An estimated 7 million premature deaths are caused each year by indoor and outdoor particle pollution from fuel combustion, according to WHO estimates. Animal diseases can be monitored using nuclear techniques before they infect humans. Vaccines against animal-to-human illnesses like influenza and malaria can be developed using radiation technology. Without heating or changing the food's nutritional value, radiation can eliminate dangerous germs from it.

Compared to conventional food-preservation techniques, it also uses less energy and eliminates the need for refrigeration and chemical additives. Cancer is diagnosed and treated using nuclear methods. Nutrition in infants and young children, childhood obesity, nutrition in mothers and adolescents, nutrition and aging, meal quality, and environmental health are all evaluated using nuclear techniques. The part of the patient's body that needs to be treated is either inside or next to the radiation source.

Toxic emissions (such metal leaching from coal mines) and particle emissions from combustion are the primary causes of health problems in the power industry. The health costs associated with fossil fuel generation alternatives are the highest per unit of output, and carbon capture systems score especially poorly because of their reduced efficiency, use of hazardous solvents, and compound release during the capture process.

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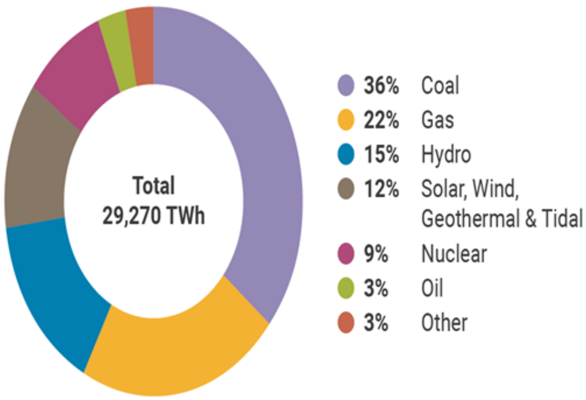

Fig.3 World Nuclear Association reference

Solar, wind, and hydropower have less of an influence on health than nuclear power, which is one of the best performers.

IV. Renewable Energy Vs Non Renewable Energy

With more than 50% of its installed electrical capacity coming from non-fossil fuel sources as of mid-2025, India has made great progress toward renewable energy. The installed capacity from renewable sources (solar, wind, hydro, and bioenergy) is increasing quickly and now surpasses non-fossil fuel sources like large hydro and nuclear combined, even if non-renewable sources like coal still account for a significant amount of energy generation. India has a high capacity for renewable energy worldwide and is quickly implementing new wind and solar projects, helped by affordable prices and growing interest from investors and the government.

The installed capacity is around 484.82 GW.

Non-Fossil Fuel Sources: More than half of the entire capacity, a pre-planned milestone. The capacity for renewable energy is about 184.62 GW, or 38.08% of the overall capacity.

Non-Renewable Energy: Coal contributes significantly to India's non-renewable energy production, though precise numbers differ.

A. Renewable Energy in India:

With notable capacity installation increases in recent years, the renewable energy sector is expanding rapidly.

Sources: India's renewable energy mix is varied, with solar and wind power dominating, followed by biofuels and huge hydro.

Cost: With a 24/7 clean energy supply available at costs that are competitive worldwide, renewable energy is getting cheaper.

India wants to have 500 GW of non-fossil fuel-based energy capacity by 2030. This goal is backed by a lot of encouragement from policymakers and a lot of confidence from investors.

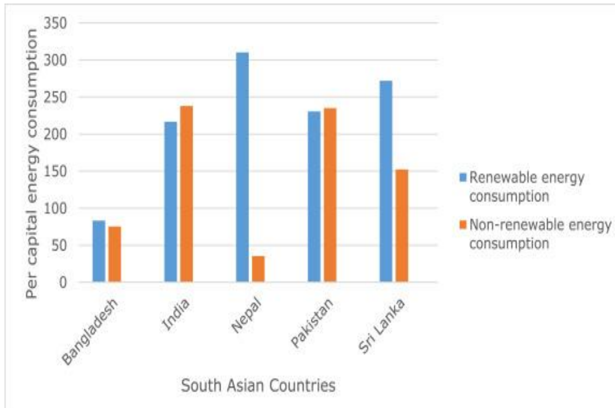

Fig.4 Renewable Energy Vs Non Renewable Energy

B. Non-Renewable Energy in India:

India's electricity generation has traditionally been dominated by non-renewable resources, especially coal.

Environmental Impact: The high carbon emission levels of non-renewable sources, particularly fossil fuels, have an effect on human health and air quality.

Costs: Although coal power used to be less expensive, its fuel costs have since increased dramatically, making renewable energy sources more feasible from an economic standpoint.

V. Clean Energy

One clean energy source with no emissions is nuclear. Fission, the mechanism by which uranium atoms split to produce energy, is how it produces power. Without the toxic consequences of fossil fuels, energy is produced by using the heat released by fission to create steam that turns a turbine. The United States prevented over 471 million metric tons of carbon dioxide emissions in 2020, according to the Nuclear Energy Institute (NEI). More than all other sustainable energy sources put together, this is the equivalent of taking 100 million automobiles off the road.

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Additionally, it maintains clean air by eliminating thousands of tons of dangerous air pollutants annually, which are linked to smog, acid rain, lung cancer, and heart disease.

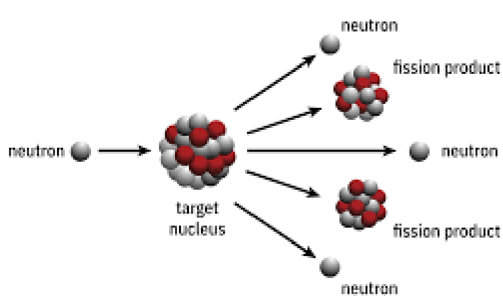

Fig.5: Nuclear Fission

VI. Land Efficiency of Nuclear Power

Nuclear energy generates more electricity on less area than any other clean air source, even though it provides enormous amounts of carbon-free power. It takes a little over one square mile to run a conventional 1,000-megawatt nuclear plant in the United States.

According to the NEI, solar photovoltaic plants need 75 times more space and wind farms need 360 times more land area to generate the same quantity of electricity.

To put it into perspective, the same amount of power as a typical commercial reactor would require more than 430 wind turbines or more than 3 million solar panels (capacity factor not included).

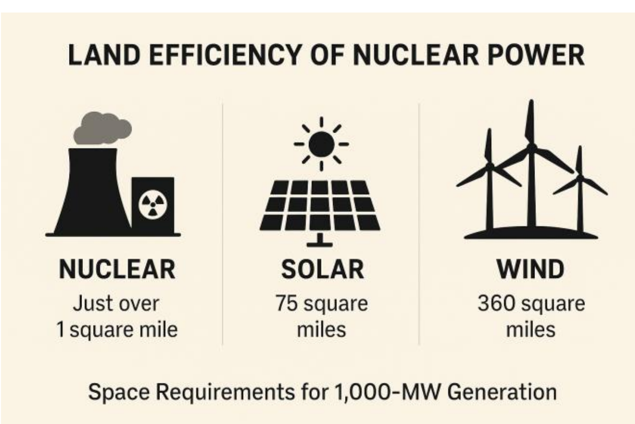

Fig.6 Comparison for Land Efficiency of Nuclear Energy

VII. Minimal Fuel Requirement

The density of nuclear fuel is very high. The amount of nuclear fuel utilized is not as high as one might anticipate because it is around a million times higher than that of other conventional energy sources. Over the past 60 years, the U.S. nuclear energy industry has produced enough spent nuclear fuel to fill a football field less than 10 yards deep.

Additionally, waste can be recycled and reprocessed, albeit this is not currently done in the US. Nonetheless, some of the most sophisticated reactor designs under development might run on spent fuel.

FUEL NEEDED & WASTE PRODUCED
PER 1,000 MW

	FUEL NEEDED	WASTE PRODUCED
Nuclear	26 tons	3,9 million lbs
Coal	2.1 million tons	6.3 million lbs
Gas	2.1 billion cubic feet	9 million lbs

Fig.7 Comparison for Fuel needed & Waste Produced

VIII. Source Of Baseload Electricity

Baseload and dispatchable generators (including nuclear, hydro, coal, and gas) and storage devices that can react to variations in power load or help with frequency management ensure a dependable supply of electricity. With a high capacity factor (about 90%), nuclear power generating also produces consistent and dependable electricity. On the other hand, intermittent generating sources like solar and wind pose extra demands on the electrical system for backup and load balancing; the system costs for these technologies can rise significantly with market share and can be three to ten times greater than those for conventional generators. It may be less expensive in some circumstances to integrate small-scale intermittent renewables than to extend the transmission and distribution infrastructure, despite these increased costs.

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IX. Nuclear Energy Growth

In the 1950s, the first commercial nuclear power plants went online. Currently, about 440 power reactors generate about 9% of the world's electricity from nuclear energy. About 25% of the low-carbon electricity produced worldwide comes from nuclear energy.

The second-largest source of low-carbon energy in the world is nuclear power. About 220 research reactors in more than 50 countries use nuclear energy. These reactors are utilized not just for research but also for training and the generation of industrial and medicinal isotopes.

Fig.8 Grafenrheinfeld Nuclear Power Plant

X. Conclusion

One of the most effective methods for producing large amounts of dependable, low-carbon electricity is still nuclear energy. Large amounts of power may be generated with relatively little material and space needs thanks to its exceptionally high energy density and small land footprint, and it is a crucial ally of renewable energy sources in the fight against climate change because of its nearly zero operating greenhouse gas emissions. Nuclear power may boost energy security, stimulate economic growth through skilled employment and technological innovation, and provide decades of reliable output when maintained under strict safety, regulatory, and waste-handling frameworks.

Constant attention is needed to address issues like public perception, waste management, and large upfront costs. Rapid advancements in closed-fuel cycles, tiny modular reactors, and sophisticated reactor designs, however, are resolving these problems and creating new avenues for deployment that is both flexible and safe. Countries may create robust, decarbonized energy systems that are in line with the global Sustainable Development Goals by combining nuclear with renewable energy, storage, and cutting-edge uses like hydrogen production.

In conclusion, nuclear energy is an essential component of a varied, sustainable energy mix rather than a stand-alone remedy. Its effectiveness in addressing the twin imperatives of global energy access and climate mitigation will depend on international cooperation, open communication, and strategic policy support.

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