Guest Editorial

Nuclear Energy's Role in Sustainability and Environmental Protection in India

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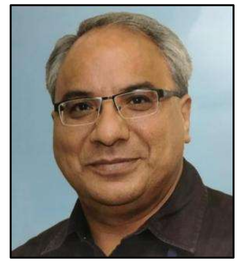

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The world today stands at a critical juncture, grappling with the profound and far-reaching impacts of climate change. The increasing frequency of extreme weather events, rising sea levels, and deteriorating ecosystems only serve to underscore the urgency of transitioning to a low-carbon economy. Governments across the globe are intensifying their climate policies, striving to meet the ambitious goals set forth in international agreements such as the Paris Agreement. Central to these efforts is the systematic decarbonization of national energy mixes [1], where nations are increasingly turning to green and clean technologies to power their economies and ensure sustainable electrification. In this global race to mitigate climate change, renewable energy sources like wind, solar, and hydropower are often highlighted as the vanguards of a sustainable future [2]. However, the challenge lies not only in generating sufficient clean energy but also in ensuring a reliable and continuous supply that can meet the growing demands of an energy-hungry world.

For India too, the stakes are particularly high. With a rapidly growing population and an expanding economy, the demand for energy is set to surge dramatically in the coming decades [3]. At the same time, India is committed to its nationally determined contributions (NDCs) under the Paris Agreement, aiming to reduce its greenhouse gas emissions intensity and increase the share of non-fossil fuel-based energy in its power generation capacity [4]. Balancing these competing priorities—meeting the burgeoning energy needs of its citizens and industries while adhering to climate goals—poses a formidable challenge.

In this context, nuclear energy offers a compelling solution. As a source of clean energy, nuclear power generates electricity with virtually no greenhouse gas emissions during operation [5]. Moreover, nuclear plants occupy less land and have a minimal ecological footprint compared to other large-scale energy sources [6]. With advancements in technology, modern nuclear reactors are safer, more efficient, and capable of playing a key role in India's energy mix. They can provide the continuous, large-scale power needed to support industrial growth, urbanization, and the rising aspirations of millions, all while contributing to the nation's climate objectives.

This editorial for the special issue on "Nuclear Energy for Sustainable Development and Environmental Management" highlights how nuclear power can push India toward a sustainable energy future, striking a balance between economic growth and environmental preservation.

Where does nuclear power stand in today's world?

To understand the role of nuclear energy today, it is essential to look at both global and national perspectives. Nuclear power currently generates 2,602 TWh of electricity, accounting for nearly 9% of global electricity production [7]. With approximately 440 nuclear power plants in operation across 31 countries, the world has accumulated around 20,000 reactor years of operational experience [7]. This has been achieved through a period of rapid growth in the 60s to 80s, followed be a gradual stagnation and decline since the 90s and early 2000s. But in recent times, nuclear energy has seen a resurgence, driven by the volatility in energy markets, especially in Europe following Russia's invasion of Ukraine. This situation is further intensified by rising fossil fuel prices and the global push to meet climate change targets.

While the revival of nuclear power in developed economies of the Global North has been gradual, it is the developing economies of the Global South that are expected to drive nuclear growth in the coming years [8]. India and China stand out as countries that have consistently pursued civilian nuclear power programs over the decades, positioning themselves as key players in the future expansion of nuclear energy [9].

In India, nuclear power currently contributes about 1.8% of the country's installed power capacity and nearly 3% of its national electricity needs [10]. The country operates 23 nuclear power plants with an average capacity factor of 83% and an availability factor of 86% [11]. Recently, the newly commissioned 700 MWe units, KAPS 3 and 4 in Gujarat, have begun full-power operations, supplying electricity to the grid [12]. India's nuclear energy outlook is further strengthened by the core loading of the Prototype Fast Breeder Reactor (PFBR) at Kalpakkam [13]and its regulatory permission for first approach to criticality [14], marking the beginning of the long-anticipated second stage of India's three-stage nuclear program. With multiple projects in various stages of development [15] and several uranium supply agreements signed with countries like Uzbekistan, Kazakhstan, Russia, Canada, and France [16] [17], India is poised to significantly expand its nuclear power program in the coming decades.

How does nuclear energy enable sustainable development?

Going forward in the nuclear journey, it is important to understand what makes this energy source so significant. Nuclear energy plays a crucial role in enabling sustainable development by offering a reliable, low-carbon energy source that supports economic growth, social well-being, and environmental protection (see **Error! Reference source not found.** for an illustrative understanding).

Sustainable development is about meeting the needs of the present without compromising the ability of future generations to meet their own needs [18]. In this context, nuclear energy is a key player, particularly in mitigating climate change. Nuclear power plants generate electricity with minimal direct emissions of carbon dioxide (CO_2) [19], making them essential in strategies aimed at decarbonizing the energy sector. As countries transition away from fossil fuels, nuclear energy provides a stable and consistent power source that complements intermittent renewable energy sources like wind and solar, ensuring a reliable supply of electricity while reducing the overall carbon footprint.

The reliability and stability of nuclear power are significant advantages [20], especially when compared to some renewable energy sources that depend on weather conditions. Nuclear power plants operate continuously, providing a consistent and stable supply of electricity essential for supporting industrial activities, economic development, and essential services like healthcare and education. Furthermore, nuclear energy enhances energy security by reducing dependence on imported fossil fuels [21], thereby reducing vulnerability to global energy market fluctuations and geopolitical risks, supporting long-term economic stability.

Nuclear energy also contributes to economic development and job creation [22]. The nuclear industry creates high-skilled jobs in engineering, construction, operations, and maintenance, offering higher wages and long-term career opportunities. This, in turn, drives economic expansion, increases productivity, and improves living standards. Additionally, nuclear power supports industrial growth by providing a reliable and affordable electricity source, critical for infrastructure development and overall economic growth.

From an environmental perspective, nuclear energy is beneficial due to its minimal land use and efficient resource utilization [6]. Nuclear power plants require significantly less land than many renewable energy sources, which helps preserve natural habitats and ecosystems, supporting biodiversity. Moreover, nuclear energy is highly energy-dense, meaning it produces a large amount of energy from a small amount of fuel, reducing the environmental impact associated with mining and resource extraction.

In the long term, nuclear energy supports sustainable development by future-proofing energy needs. As populations grow and energy demands increase, nuclear power offers a viable solution that can meet these demands without exacerbating environmental problems. Advances in technology have also led to effective waste management practices, including long-term storage solutions [23] and the potential for recycling nuclear fuel [24], ensuring that waste is managed safely and sustainably.

Finally, nuclear energy accommodates technological innovation. Continued research and development in nuclear technology, such as Small Modular Reactors (SMRs) and Generation IV reactors, are leading to safer, more efficient, and more flexible nuclear power options. These innovations address some challenges associated with traditional nuclear energy, such as high capital costs and safety concerns, making nuclear power an even more sustainable option. Moreover, nuclear energy can work synergistically with renewable energy sources, providing the consistent power needed to balance the intermittency of renewables, supporting the development of a more resilient and sustainable energy grid.

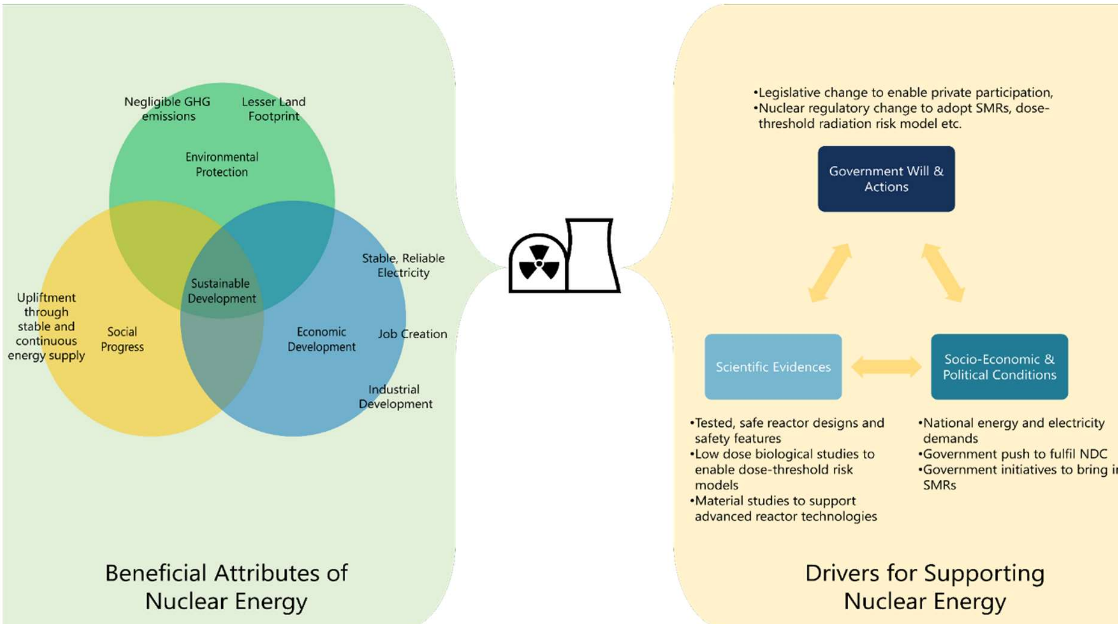

Figure 1. Illustrating the beneficial attributes of nuclear energy and what it would take to support its growth

How does nuclear energy support environmental protection?

Nuclear energy plays a significant role in supporting environmental protection in several ways, primarily by reducing greenhouse gas (GHG) emissions, minimizing air pollution, conserving natural resources, and enabling land preservation.

Nuclear power plants generate large amounts of electricity with almost no direct GHG emissions. During operation, nuclear reactors emit negligible amounts of carbon dioxide (CO_2) [19], making them one of the most effective tools for mitigating climate change. In India, the operating nuclear power plants have generated nearly 411 billion units of electricity, averting nearly 353 million tonnes of CO_2 equivalent to the environment [25]. This is particularly important as the global community and India strive to reduce carbon emissions to meet targets like those set by the Paris Agreement. Although nuclear energy does produce some emissions during the construction, operation, and decommissioning of plants, these emissions are comparable to those of renewable energy sources like wind and solar, and far lower than those from fossil fuel-based power generation [26].

Unlike coal, oil, or natural gas plants, nuclear power does not involve the combustion of fossil fuels. Therefore, it does not release harmful pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NOx), or particulate matter into the atmosphere. These pollutants are major contributors to air pollution, which can cause respiratory problems, cardiovascular diseases, and other health issues in humans, as well as harm ecosystems. By preventing the emission of SO_2 and NOx, nuclear power helps reduce the formation of acid rain and smog, both of which have detrimental effects on the environment, including damage to forests, soils, and water bodies.

Being a highly energy-dense source, nuclear power produces a large amount of energy from a small amount of fuel. For example, a single uranium fuel pellet, about the size of a fingertip, can produce as much energy as one ton of coal or 149 gallons of oil [27]. This efficiency reduces the need for extensive mining and extraction activities, which can have significant environmental impacts, including habitat destruction and water contamination. Therefore, the extent of mining and extraction activities for nuclear power is far less than for coal-based plants.

Nuclear power plants also require less land than renewable energy sources such as wind or solar farms. For example, a nuclear plant can produce the same amount of electricity as a solar farm covering hundreds of times more land area [28]. This means that nuclear energy can provide large-scale power without requiring large tracts of land, preserving natural habitats and ecosystems. Furthermore, with the advent of SMRs, the land requirement for nuclear power is further reduced.

Finally, though nuclear power generates radioactive waste, modern waste management techniques allow for its safe containment and storage. The volume of nuclear waste is relatively small compared to the waste produced by fossil fuel plants [29], which includes vast quantities of ash, sludge, and other byproducts that often end up in landfills or are released into the environment. Further, since India follows a closed fuel cycle, it is considered more sustainable in terms of waste management than open fuel cycle technologies in other countries [30]. And through advanced waste management techniques these wastes are stored deep below the earth’s surface to minimize their environmental impact [31]. Also, efforts towards transmuting the radionuclides in these wastes to further reduce their harm, is being pursued in India [32].

What can be done to support nuclear's growth in India?

The Indian government maintains a positive outlook on nuclear energy's role in facilitating a sustainable and clean transition away from fossil fuels. National economic models evaluating future energy needs across various human development scenarios emphasize the importance of nuclear power, alongside renewable sources, in replacing fossil-fuel-based plants [33]. Recent advancements, such as the addition of two new high-capacity nuclear power plants to the grid and the initiation of the second stage of India's three-stage nuclear program, highlight this commitment. Furthermore, increased governmental support for Small Reactors and Small Modular Reactors [34] highlights nuclear energy's anticipated critical role in driving India's future growth and development [33].

Therefore, it is now important to focus on the steps required to accelerate this growth. To ensure that the expansion of the domestic nuclear power industry aligns with the country's development needs, a range of supportive technological, economic, social, and policy-level changes are necessary (see for **Error! Reference source not found.** an illustrative understanding).

On the technological front, Pressurized Heavy Water Reactor (PHWR) technology is likely to remain the backbone of India's domestic nuclear expansion [35]. However, a few upcoming projects aim to introduce large-capacity Light Water Reactor technologies from international vendors [25]. To ensure a seamless and timely integration of these new technologies, it will be crucial to develop the necessary expertise within India's nuclear engineering and science communities. With the announcement of the Bharat Small Reactor (BSR) and Bharat Small Modular Reactors (BSMRs) [36], the Indian government is also emphasizing a shift towards advanced, Generation VI reactors aimed at delivering nuclear energy directly to industrial and residential users. For BSRs, the existing, proven 220 MWe PHWR technology will likely be adapted [37] with suitable modularity to enable factory fabrication. In the case of BSMRs, extensive research and planning will be required to select the most suitable design from the over 70 SMR options available globally [38], tailored to meet India's specific needs.

To support the expansion of India's nuclear power program, significant advancements in technology will be necessary within the domestic nuclear supply chain. Key components of the nuclear value chain, including manufacturers, suppliers, and service providers, will need to enhance their capabilities to handle increased demand and align with international standards [39]. This involves adopting cutting-edge technologies and implementing rigorous international quality assurance measures and certifications [40]. Improving technological capabilities will ensure that domestic suppliers can meet the growing needs of the nuclear program efficiently and reliably. It will also be crucial for these entities to stay competitive on a global scale by adhering to international best practices in quality and safety. This includes investing in state-of-the-art manufacturing processes, advanced materials, and precision engineering to produce components that meet global standards. Additionally, fostering strong partnerships with international organizations and participating in global supply chains can provide valuable insights and support in achieving these objectives.

The expansion of India's nuclear power program will also require substantial financial investments, as demonstrated by the recent budget allocation of nearly trillion rupees toward research and development in the domestic nuclear sector [41]. However, there is considerable potential for private investment in nuclear power production, which will likely materialize only after legislative changes are implemented. An example of this is the joint venture between Nuclear Power Corporation of India Ltd (NPCIL) and the National Thermal Power Corporation (NTPC) to develop the nuclear power project at Mahi Banswara in Rajasthan [42].

Additionally, the BSR and BSMR programs are expected to be largely funded through private investments [36], reflecting a growing trend towards leveraging private sector capital in the nuclear energy domain.

From an environmental perspective, it is crucial to reclassify the nuclear power industry based on its actual pollution emissions, in order to foster nuclear growth. Currently, the industry's classification as 'Red' in the Central Pollution Control Board's (CPCB) color-coded environmental permitting scheme [43] imposes unnecessary strictness and negatively impacts public perception. Given the decades of safe operation of domestic nuclear power plants and their minimal conventional and radiological emissions [44], it is appropriate to categorize them as 'Orange' or 'Green' under the CPCB framework. This reclassification would enhance public perception and facilitate the influx of both domestic private and international investment through sustainable financing frameworks. The existing practices of conducting environmental impact assessments (EIAs) and submitting periodic emissions reports to environmental and nuclear regulators will continue to ensure that nuclear power plants operate safely and within environmental standards, even under a revised classification.

As far as nuclear regulations are concerned, an expanding nuclear programme would mean greater more regulatory oversight. The introduction of new reactor technologies, such as SMRs necessitates evolving regulations to accommodate these advancements. But a specific area of concern is radiation health risk regulations. Currently, the framework is based on the linear no-threshold (LNT) radiation risk model, which is scientifically flawed [45]. Research has shown that low levels of radiation do not cause the harm predicted by the LNT model; rather, there may be a threshold below which health effects are minimal [46]. Updating regulations to incorporate a dose-threshold based approach could support the nuclear expansion program by relaxing several operational and design requirements [45]. This change would also enhance public perception by aligning regulations with current scientific understanding of low-dose radiation. Additionally, directing scientific research towards studying the effects of low doses of radiation on biological systems, through both experimental and theoretical approaches, would provide a more accurate basis for risk assessment and regulation [47]. This would go a long way in grounding the nuclear expansion in scientific principles and evidences.

Finally, public consensus on nuclear power projects is crucial. Achieving this consensus requires a comprehensive approach involving nationwide public awareness campaigns at local, state, and national levels. An effective strategy would be to integrate information about nuclear energy into school curricula at both state and central levels. This can help educate students from a young age about the benefits and safety of nuclear power, fostering a more informed and open-minded future generation. Additionally, hosting district-level meetings and community forums is crucial for directly addressing public concerns and dispelling misconceptions about nuclear energy. These meetings should be designed to provide clear, accurate information and offer a platform for residents to ask questions and express their views. Efforts should also include the development of transparent communication techniques and risk communication tools that simplify complex information. This approach helps convey the importance of having a nuclear power plant in the vicinity and addresses potential concerns about safety and environmental impact. By using accessible language and visual aids, public outreach can demystify nuclear energy and highlight its benefits, such as its role in reducing carbon emissions and ensuring a reliable energy supply.

Conclusion

In summary, nuclear energy is poised to be a crucial component of India's clean energy transition. To fully realize its potential, it is essential to provide robust support across technical, economic, legislative, social, regulatory, and policy dimensions. This special issue on "Nuclear Energy for Sustainable Development and Environmental Management" aims to offer valuable insights and timely information on these aspects. It will guide policymakers, technocrats, researchers, and students in developing a thorough understanding of why nuclear energy and its varied applications is vital for India’s future energy landscape.

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