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India's Nuclear Energy Expansion Strengthens Energy Security, Decarbonisation, Indigenous Technology and the Vision of Viksit Bharat 2047

Published On: 01-09-2026

Recent Developments:

- India is positioning **nuclear energy** as a reliable, low-carbon and technology-intensive component of its long-term development strategy through the **Nuclear Energy Mission for Viksit Bharat**, indigenous reactor technologies and the **SHANTI Act, 2025**.
- The **Nuclear Energy Mission** targets **100 GW of nuclear power capacity by 2047** and aims to operationalise at least **five indigenous Small Modular Reactors by 2033**.
- India currently has **8.78 GW of nuclear power capacity**, which is projected to rise to about **22 GW by 2031–32** through progressive completion of projects already under implementation.
- The **500 MWe Prototype Fast Breeder Reactor at Kalpakkam** achieved **first criticality on 6 April 2026**, marking India's formal entry into the **second stage of its three-stage nuclear power programme**.
- The **SHANTI Act, 2025** seeks to facilitate wider participation of the private sector in the nuclear energy programme while supporting the expansion envisaged under the Nuclear Energy Mission.

Nuclear Energy: Basics and Significance:

How Nuclear Power Generation Works:

- A nuclear power plant generates electricity from the **heat released through controlled nuclear fission**.
- During fission, a neutron strikes a fissile nucleus such as uranium or plutonium, causing it to split and release **heat and additional neutrons**, thereby sustaining a controlled chain reaction.
- The released heat converts water into **steam**, which rotates a turbine connected to a generator and produces electricity.
- Nuclear power therefore provides **firm and dispatchable electricity**, making it particularly relevant for meeting base-load requirements alongside variable renewable energy.

Why Nuclear Energy Matters for India:

- Nuclear energy can provide large-scale electricity with **low lifecycle greenhouse-gas emissions**, thereby supporting India's **Net Zero target by 2070**.
- Its high capacity factor enables continuous generation without the intermittency associated with solar and wind power.
- Nuclear power can reduce dependence on imported fossil fuels and strengthen **energy security**.
- Expansion of indigenous nuclear technology can promote **strategic autonomy, industrial capability, skilled employment and technological self-reliance**.

Status of Nuclear Energy in India:

Current Capacity and Expansion:

- India has **24 nuclear power reactors with an installed capacity of 8.78 GW**, while additional reactors are at different stages of construction and implementation.
- The official roadmap envisages increasing capacity to approximately **22 GW by 2031–32**, followed by further expansion towards **100 GW by 2047**.
- The expansion strategy combines **large indigenous PHWRs, Light Water Reactors, Fast Breeder Reactors and Small Modular Reactors**.
- The government has approved pre-project activities for **two 500 MW Fast Breeder Reactors at Kalpakkam**, supporting the expansion of the second stage of India's nuclear programme.

Nuclear Energy Mission for Viksit Bharat:

- The **Nuclear Energy Mission**, announced in the **Union Budget 2025–26**, seeks to establish nuclear energy as an important source of reliable low-carbon electricity.
- The mission has earmarked **?20,000 crore** for research and development of indigenous **Small Modular Reactors**.
- The government aims to operationalise at least **five indigenous SMRs by 2033**, with applications including captive power generation, replacement of retiring fossil-fuel plants and electricity supply to remote locations.
- Indigenous SMR designs under development include the **220 MWe Bharat Small Modular Reactor, 55 MWe Small Modular Reactor and a High Temperature Gas Cooled Reactor for hydrogen production**.

India's Three-Stage Nuclear Power Programme:

Stage I — Pressurised Heavy Water Reactors:

- The first stage is based primarily on **Pressurised Heavy Water Reactors using natural uranium** as fuel.
- Spent fuel is reprocessed to recover **plutonium**, which becomes an important input for the second stage.
- India has developed substantial indigenous expertise in the design, construction, operation and fuel-cycle management of PHWR technology.

Stage II — Fast Breeder Reactors:

- The second stage uses **plutonium-based fuel** in Fast Breeder Reactors to generate electricity while producing additional fissile material.
- The **500 MWe PFBR at Kalpakkam achieved first criticality on 6 April 2026**, marking a major milestone in India's nuclear strategy.
- The PFBR uses **uranium-plutonium mixed oxide fuel** and a uranium-238 blanket to breed additional plutonium, thereby improving fuel utilisation.

Stage III — Thorium Utilisation:

- The third stage envisages the use of **uranium-233 derived from thorium** to exploit India's substantial thorium resources.
- Thorium-232 is **fertile rather than fissile**, meaning that it cannot sustain a conventional fission chain reaction by itself but can be converted into fissile uranium-233 through neutron irradiation.
- India's long-term three-stage strategy therefore seeks to transform its relatively limited uranium resources and substantial thorium resources into greater **energy security and fuel-cycle sustainability**.

Applications Beyond Electricity:

Healthcare:

- Nuclear technology supports **medical imaging, cancer diagnosis, radiotherapy and radiopharmaceutical development**.

- Institutions such as **BARC, IGCAR, Tata Memorial Centre and TIFR** contribute to indigenous nuclear medicine and advanced medical technologies.
- Radiation technology also supports the sterilisation of medical equipment, strengthening infection-control practices.

Agriculture:

- **Radiation-induced mutagenesis** can help develop crop varieties with desirable characteristics such as higher yield, early maturity and greater tolerance to drought, salinity, heat and diseases.
- Nuclear techniques can therefore contribute to **climate-resilient agriculture and food security**.

Food Preservation:

- **Food irradiation** can extend the shelf life of agricultural commodities, fish and spices by controlling microorganisms, insects and other spoilage agents.
- Longer shelf life can reduce post-harvest losses and facilitate transportation over longer distances.

Minerals and Rare Earth Elements:

- Nuclear analytical techniques support the **exploration, characterisation and quality assessment of mineral resources**.
- India has developed indigenous reference materials and analytical capabilities relevant to the **rare earth element ecosystem**, strengthening critical-mineral security.

Semiconductors and Advanced Materials:

- Nuclear research contributes to the production of **high-purity materials and specialised isotopes** required in advanced electronics and semiconductor applications.
- Indigenous materials capabilities can strengthen technological self-reliance in strategically important industries.

Green Hydrogen:

- Nuclear reactors can potentially support **low-carbon hydrogen production** by combining reliable electricity with high-temperature process heat.
- Nuclear-powered hydrogen could complement renewable-based electrolysis and reduce dependence on fossil-fuel-based hydrogen production.

Nuclear Safety and Regulation:

Defence-in-Depth:

- Indian nuclear facilities follow the principle of **Defence-in-Depth**, involving multiple physical barriers, redundant systems and independent safety layers.
- Nuclear plants are designed with safeguards against external hazards such as **earthquakes, floods, cyclones and tsunamis**.
- Emergency shutdown, cooling, radiation monitoring and emergency preparedness systems provide additional protection.

Radiation Protection:

- Radiation exposure is managed through the **ALARA principle**, which requires exposure to be kept **As Low As Reasonably Achievable**.

- Radiation safety also involves prescribed dose limits, shielding, protective equipment, trained personnel and dedicated health-physics systems.
- The **Atomic Energy Regulatory Board** plays a central role in regulatory oversight and safety assessment of nuclear installations.

Radioactive Waste Management:

- Radioactive waste is treated, conditioned and disposed of under prescribed safety standards to minimise risks to humans and the environment.
- India has developed indigenous technologies for the **vitrification of high-level radioactive waste**, converting it into stable glass forms suitable for long-term management.

Major Challenges:

High Capital Cost and Long Construction Periods:

- Nuclear projects require large upfront investments, complex regulatory processes and long construction periods.
- Delays can increase project costs and postpone the expected contribution to the energy mix.

Safety and Public Acceptance:

- Nuclear accidents, although rare, can have severe consequences, making **safety culture, transparent regulation and public communication** essential.
- Public acceptance also depends on credible emergency preparedness and effective radioactive-waste management.

Fuel and Technology Constraints:

- India's uranium resources are relatively limited and require supplementation through domestic exploration and international cooperation.
- The transition towards advanced reactors and thorium utilisation requires sustained **research, development, fuel-cycle innovation and skilled human resources**.

Financing and Private Participation:

- Achieving **100 GW by 2047** requires substantial investment and institutional capacity.
- Wider private participation under the **SHANTI Act, 2025** can mobilise additional capital and technology, but must operate within a robust framework of **liability, regulation, safeguards and public accountability**.

Way Forward:

Accelerating Indigenous Capacity:

- India should expand domestic manufacturing of **reactor components, nuclear-grade materials, fuel-cycle technologies and safety systems**.
- Indigenous PHWRs and SMRs can reduce technology dependence and strengthen domestic industrial capabilities.

Expanding SMRs:

- **Small Modular Reactors** can complement large reactors because of their modular construction, flexible deployment and potential suitability for captive and remote applications.

- Their deployment can support decarbonisation of **hard-to-abate industrial sectors** while reducing dependence on fossil-fuel-based captive power.

Strengthening Safety and Governance:

- Nuclear expansion must remain anchored in **independent regulatory oversight, transparent safety assessments, emergency preparedness and effective radioactive-waste management**.
- Private-sector participation should therefore be accompanied by strong institutional safeguards and clear accountability mechanisms.

Integrating Nuclear Energy with Renewables:

- Nuclear power should complement, rather than replace, renewable energy in India's clean-energy transition.
- **Firm nuclear generation** can provide grid stability while solar and wind generation expands, thereby supporting a diversified low-carbon electricity system.

Conclusion:

- India's nuclear programme has evolved from a long-term strategic vision into an increasingly important pillar of **energy security, decarbonisation and technological self-reliance**.
- The **Nuclear Energy Mission for Viksit Bharat**, the **SHANTI Act, 2025**, indigenous PHWRs, SMRs and the successful first criticality of the **PFBR** collectively mark a new phase in India's nuclear development.
- The ultimate challenge is to expand nuclear capacity rapidly without compromising **safety, environmental responsibility, economic viability and regulatory credibility**.
- A balanced combination of nuclear energy, renewables, storage, grid modernisation and energy efficiency can strengthen India's pathway towards **Viksit Bharat 2047 and Net Zero emissions by 2070**.

Value Addition for UPSC:

Key Concepts:

- **Nuclear Fission:** Splitting of a heavy atomic nucleus into smaller nuclei with the release of energy.
- **Nuclear Fusion:** Combining light atomic nuclei to release energy; it powers the Sun and remains under development for commercial electricity generation.
- **Fissile Material:** Material capable of sustaining a nuclear fission chain reaction, such as uranium-235 and plutonium-239.
- **Fertile Material:** Material that can be converted into fissile material after neutron absorption, such as thorium-232 and uranium-238.
- **Breeder Reactor:** A reactor designed to produce more fissile material than it consumes.
- **SMR:** A nuclear reactor generally designed with a smaller electrical capacity and modular construction for flexible deployment.
- **Defence-in-Depth:** A nuclear safety philosophy based on multiple independent and redundant protective barriers.
- **ALARA:** The principle of keeping radiation exposure as low as reasonably achievable.