India's Nuclear Energy Vision:

Strategic Pathways for SMR Deployment

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The Energy and Resources Institute
Creating Innovative Solutions for a Sustainable Future

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Foreword

India's demand for clean, reliable, and affordable energy is rising rapidly, driven by economic growth, expanding industrialization, digital transformation, and the aspirations of a young and growing population. As the country advances towards its Net Zero target by 2070 and its vision of Viksit Bharat by 2047, ensuring energy security while accelerating decarbonization has become a strategic imperative. This requires a calibrated expansion of the energy basket, anchored in clean and firm power sources. In this context, nuclear energy can play a critical role in strengthening long-term energy security and grid reliability.

This report examines India's evolving nuclear energy landscape, including legislative reforms, policy direction, and long-term capacity ambitions. The various aspects looked in the report include policy enablers, regulatory evolution, financing mechanisms, supply chain readiness, localization potential, and opportunities for public–private partnership. The report underscores the importance of a pragmatic and phased roadmap for nuclear capacity expansion leveraging both large conventional reactors for scale and small modular reactors (SMRs) for flexibility, distributed deployment, and industrial decarbonization.

Importantly, the analysis acknowledges that scaling nuclear energy in India will require addressing technological, financial, geopolitical, and institutional challenges. The report outlines practical pathways to navigate these complexities, with particular emphasis on human resource development, regulatory preparedness, and public engagement. By situating nuclear energy within India's broader clean energy transition, this report aims to contribute constructively to informed policy dialogue and long-term strategic planning.

Dr Vibha Dhawan

Director General, TERI

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List of Abbreviations

AERB – Atomic Energy Regulatory Board
AHWR – Advanced heavy water reactor
AKRUTI – Advanced knowledge for rural technology implementation
BARC – Bhabha Atomic Research Centre
BHAVINI – Bharatiya Nabhikiya Vidyut Nigam Limited
BSMR – Bharat small modular reactor
BSR – Bharat small reactors
CEA – Central Electricity Authority
CSR – Corporate social responsibility
DAE – Department of Atomic Energy
DTRI – DAE technologies for rural India
EDF – Électricité de France
EPC – Engineering, procurement, and construction
EPR – European pressurized reactor
FOAK – First-of-a-kind
GEN-III – Generation III reactors
GEN-IV – Generation IV reactors
GWe – Gigawatt (electric)
GW – Gigawatt
HBNI – Homi Bhabha National Institute
HTGR – High-temperature gas-cooled reactor
HTTR – High-temperature engineering test reactor
HWB – Heavy Water Board
IAEA – International Atomic Energy Agency

IGCAR – Indira Gandhi Centre for Atomic Research
IRRS – Integrated Regulatory Review Service
IREL – Indian Rare Earths Limited
ITI – Industrial Training Institute
LEU – Low-enriched uranium
LWR – Light water reactor
MWe – Megawatt (electric)
MWth – Megawatt (thermal)
MSR – Molten salt reactor
NDT – Non-destructive testing
NEA – Nuclear Energy Agency
NGO – Non-governmental organization
NPCIL – Nuclear Power Corporation of India Limited
NUWARD – Nuclear Forward Reactor
OECD – Organization for Economic Co-operation and Development
O&M – Operations and maintenance
OSART – Operational safety review team
PHWR – Pressurized heavy water reactor
PRIS – Power reactor information system
PSU – Public sector undertaking
QA – Quality assurance
R&D – Research and development
RAPP – Rajasthan Atomic Power Project
RfP – Request for proposal
RRCAT – Raja Ramanna Centre for Advanced Technology
SHANTI – Sustainable Harnessing and Advancement of Nuclear Energy for Transforming India
SMR – Small modular reactor
SCOPE – Science Communication, Outreach, and Public Engagement
TERI – The Energy and Resources Institute
TRISO – TRI-structural ISOtropic fuel
UCIL – Uranium Corporation of India Limited
UK – United Kingdom
USA – United States of America
VVER – Water–Water Energetic Reactor

Executive Summary

India's energy transition is closely linked to its development priorities. Rising electricity demand, rapid industrial growth, and the need for reliable and affordable power require an energy system that is scalable, resilient, and low carbon. In this context, nuclear energy plays a critical role in supporting a development-led transition, aligned with India's objective of achieving 100 GW of nuclear power capacity by 2047. Large reactors of 700 MW and above such as Pressurised heavy water reactors (PHWR), Light water reactors (LWRs) and Fast breeder reactors (FBRs), will remain central to achieving this target. Small modular reactors (SMRs) are emerging as an important complementary component of this long-term nuclear vision, particularly in applications where flexibility, phased deployment, and non-electric uses are critical.

India's nuclear programme is built on strong foundations developed over more than six decades, including a strong safety record, mature institutions, indigenous manufacturing capability, and an integrated closed fuel-cycle strategy. These strengths support the continued deployment of large nuclear power plants while also enabling the introduction of new reactor technologies. SMRs expand the scope of nuclear energy by enabling modular and standardized deployment, improved siting flexibility, and applications beyond grid electricity, including industrial process heat, hydrogen production, desalination, and captive power for energy-intensive industries. Realising this potential will require targeted development of human resources, including new skills in modular manufacturing, advanced digital systems, safety analysis, and multi-application operation, alongside enhanced regulatory and institutional capacity.

The global assessment in this report shows that SMR development is advancing across a wide range of reactor designs, fuels, and applications. Countries such as the United States, Canada, China, Russia, France, and the United Kingdom are actively adapting regulatory frameworks, licensing pathways, and industrial ecosystems to enable SMR deployment. International experience shows that SMRs encompass a broad spectrum of reactor concepts and deployment models, tailored to national priorities, industrial capabilities, and specific end-use applications. A consistent lesson is the importance of early regulatory engagement, design standardization, and coordinated public–private action to manage risk and accelerate deployment.

For India, SMRs represent a paradigm shift in nuclear deployment. Unlike conventional nuclear plants delivered as large, site-specific infrastructure projects, SMRs rely on factory-based manufacturing, modular construction, and repeat deployment. This shift necessitates new approaches to regulation, manufacturing, financing, and project structuring. A phased and roadmap-driven approach beginning with pilot and demonstration projects, followed by standardization and scale-up will be essential to integrate SMRs effectively into India's energy system while preserving safety, cost discipline, and public confidence.

From an economic perspective, the report recognizes that nuclear power remains capital intensive, with project outcomes strongly influenced by construction timelines, financing conditions, and risk allocation. Achieving the 100 GW target by 2047 will require investments of approximately ₹23–25 lakh crore. SMRs offer economic value primarily through smaller project sizes, phased investment, improved risk management, and learning effects, rather than immediate cost reductions. Early government support such as the use of project-specific Special Purpose Vehicles (SPVs) for capital pooling to de-risk first-of-a-kind projects is therefore a strategic economic intervention that can lower long-term system costs, enable private sector participation, and support the development of a competitive domestic supply chain.

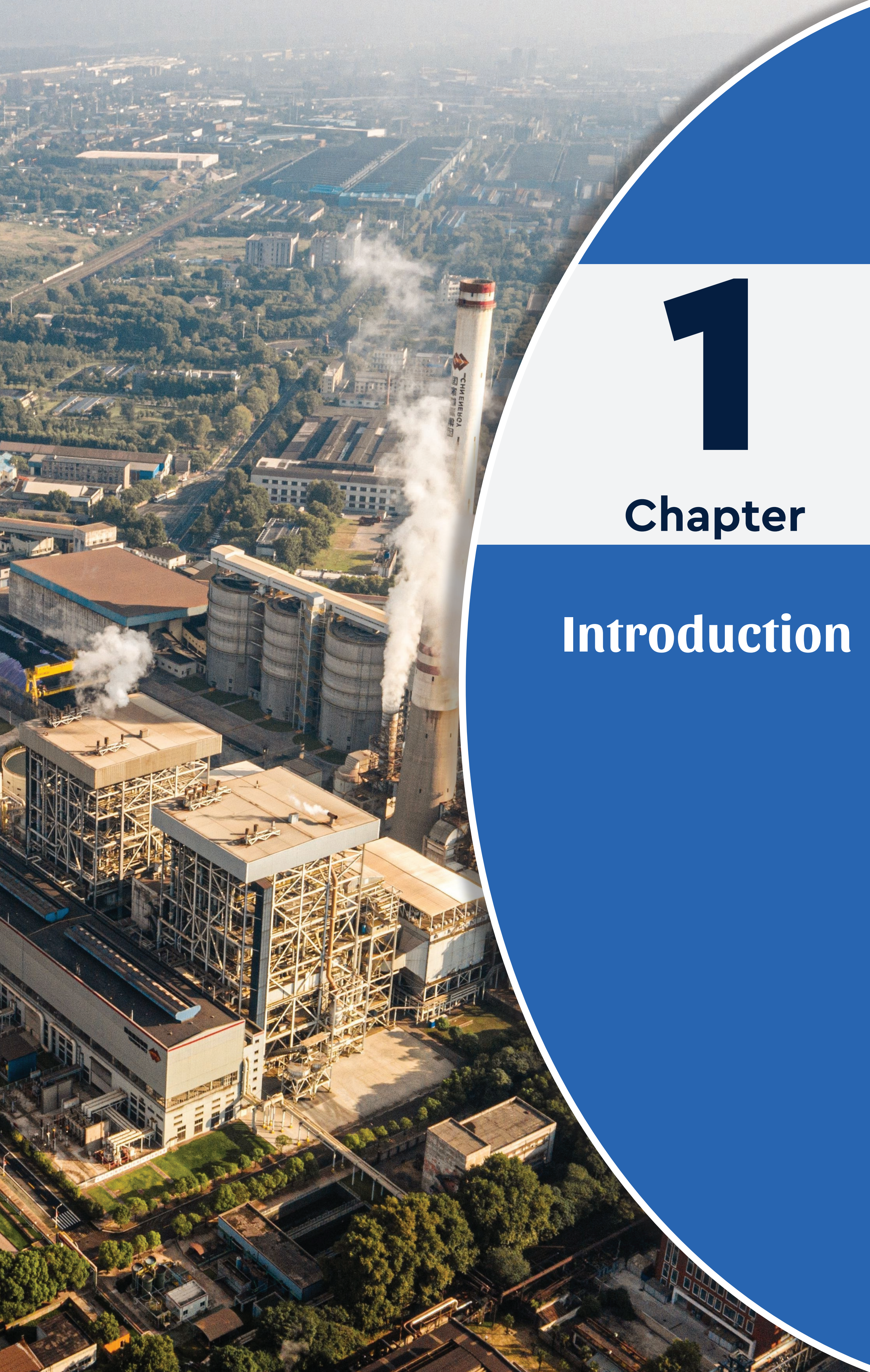
The report further highlights the importance of regulatory readiness, standardized reactor designs, skilled human resources, coordinated fuel supply and waste management systems, and sustained public outreach. Scaling up nuclear capacity and introducing SMRs will require a substantial expansion of trained professionals across design, construction, operations, regulation, safety oversight, and communication functions. Strengthening education, training, and certification frameworks, along with industry–academia collaboration, is essential to ensure that human capital development keeps pace with technological and deployment ambitions.

Based on the analysis, the report presents a set of policy and institutional recommendations aimed at enabling a credible and orderly expansion of nuclear energy in India. These include reforming licensing and regulatory frameworks to accommodate SMR-specific deployment models, reinforcing the role of the state in fuel cycle and waste management responsibilities, enabling structured and transparent private sector participation, and institutionalizing mechanisms for public engagement and trust-building. Over the long term, India's SMR pathway should remain aligned with its thorium-based nuclear strategy to enhance fuel security and strategic autonomy, while fostering healthy domestic competition to identify scalable and resilient solutions.

To operationalize these recommendations, the report outlines a phased implementation roadmap aligned with India's nuclear vision to 2047. The roadmap prioritizes near-term consolidation through completion of ongoing projects and regulatory preparedness, medium-term scale-up through

serial deployment of large reactors and early SMR commercialization, and long-term integration of advanced and thorium-based reactor systems. This phased and disciplined approach ensures that technology deployment, institutional capacity, and public confidence evolve in a coordinated manner, enabling nuclear energy to serve as a reliable, low-carbon backbone of India's energy system well beyond mid-century.

Overall, the report concludes that SMRs represent a strategic opportunity for India. When integrated through a disciplined, phased, and development-oriented roadmap supported by early policy intervention, human capital investment, and regulatory readiness SMRs can complement large reactors, support industrial decarbonization, enhance system flexibility, and reinforce nuclear energy as a reliable low-carbon backbone of India's energy system well beyond mid-century.



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Chapter

Introduction

"To build a truly self-reliant India, we must achieve energy independence. In the last 11 years, our solar energy capacity has increased by 30 times. We are constructing new dams, and India is now focusing actively on nuclear energy. We have brought huge reforms in the field of nuclear energy to expand the country's nuclear power production capacity by 12 times by 2047."

- Shri Narendra Modi, Hon'ble Prime Minister

The value of nuclear energy in achieving net-zero energy emission targets is increasing worldwide. This is reflected in the renaissance of nuclear power in many countries. Technological advancements, policy support, rapidly growing demand, and associated alarming climate changes are driving this, alongside a conducive international environment.

The Indian government has also stressed the critical role of nuclear power in building a truly self-reliant India and achieving energy independence. An interim target of achieving 100 GW, which includes both large conventional and smaller nuclear power sources, by 2047, has also been envisioned. Small modular reactors (SMRs),[1] typically of capacity 300 MW and below, are gaining special attention these days as they offer enhanced safety features and can play a key role in decarbonizing hard-to-abate industries, providing a stable power supply to remote areas, serving captive power requirements, and for hydrogen production. India is designing and developing three types of SMRs; 200 MWe Bharat small modular reactors (BSMR), 55 MWe SMRs, and 5 MWth high-temperature gas-cooled reactors indigenously. International cooperation and private sector participation (for both conventional reactors and SMRs) are also on the horizon. Existing plants use uranium. Efforts are continuing for optimization of uranium and for the prospective utilization of thorium, which is indigenously available. India has also over 60 years of experience in development of nuclear energy and in the process has achieved a significant level of indigenous expertise managing nuclear power establishments to international level of safety. These augur well for realizing India's nuclear energy vision. It is, however, important to note that SMRs are relatively new entrants into the nuclear family and have not much commercial operating experience in the world.

India's development strategy for SMRs should, therefore, pay special attention to the legal, policy, and regulatory framework. The current policy and regulatory framework for nuclear, which is designed for large reactors, must evolve to accommodate the unique characteristics of SMRs. This includes streamlined licensing, technology-neutral safety standards, enabling provisions for private sector participation, promoting *Atmanirbharta* in supply chain procurement, human resources development, etc. Concerted efforts are also required to address the likely concerns of policymakers and the public about human safety and environmental impacts.

This report aims to assess India's current nuclear power landscape and long-term nuclear vision in the context of emerging global developments, with a particular focus on SMRs. It examines international trends in nuclear technologies, identifies key regulatory, technical, institutional, and market-related challenges for SMR deployment in India, and reviews ongoing policy and regulatory initiatives to address these issues. Based on this assessment, the report outlines priority action areas

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[1] The SMRs are nuclear fission reactors with a power capacity typically up to 300 MWe per unit, smaller than conventional large reactors. They are termed "modular" because their components are factory-fabricated and assembled on-site.
For the purpose of this report, the term SMR is used broadly to include both small reactors (SRs) and small modular reactors, unless specified otherwise. This allows for a comprehensive assessment of reactors within the small-capacity range, irrespective of whether they are modular in design or conventionally constructed.

to support the accelerated deployment of SMRs in alignment with India's energy transition and net-zero objectives.

Chapter 2 provides a brief overview of the present status of nuclear power in India and the long-term nuclear vision.

Chapter 3 covers global trends on the development of nuclear technology, especially SMR.

Chapter 4 outlines the key challenges in advancing nuclear energy in India, including regulatory gaps, private sector participation, fuel management, siting, and institutional issues.

Chapter 5 reviews global experience in addressing nuclear deployment challenges, focusing on regulation, licensing, safety, and public–private models.

Chapter 6 examines the economics of nuclear power, including costs, tariffs, financing, and viability of large reactors and SMRs.

Chapter 7 focuses on human resource development and public outreach in the nuclear sector.

Chapter 8 presents policy recommendations to strengthen India's nuclear programme.

Chapter 9 provides the conclusion and a roadmap for achieving nuclear capacity targets by 2047.

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Chapter

India’s Nuclear Energy Vision

"....for the continuation of our civilization and its further development, atomic energy is not merely an aid, it is an absolute necessity."

- Dr Homi J. Bhabha, Father of the Indian Nuclear Programme

2.1
Introduction

India's nuclear energy vision is guided by the need to expand clean, reliable, and secure electricity supply while strengthening technological self-reliance. SMRs represent a key focus area for future expansion, aimed at complementing the conventional pressurized heavy water reactor (PHWR) fleet and supporting the country's long-term energy transition goals.

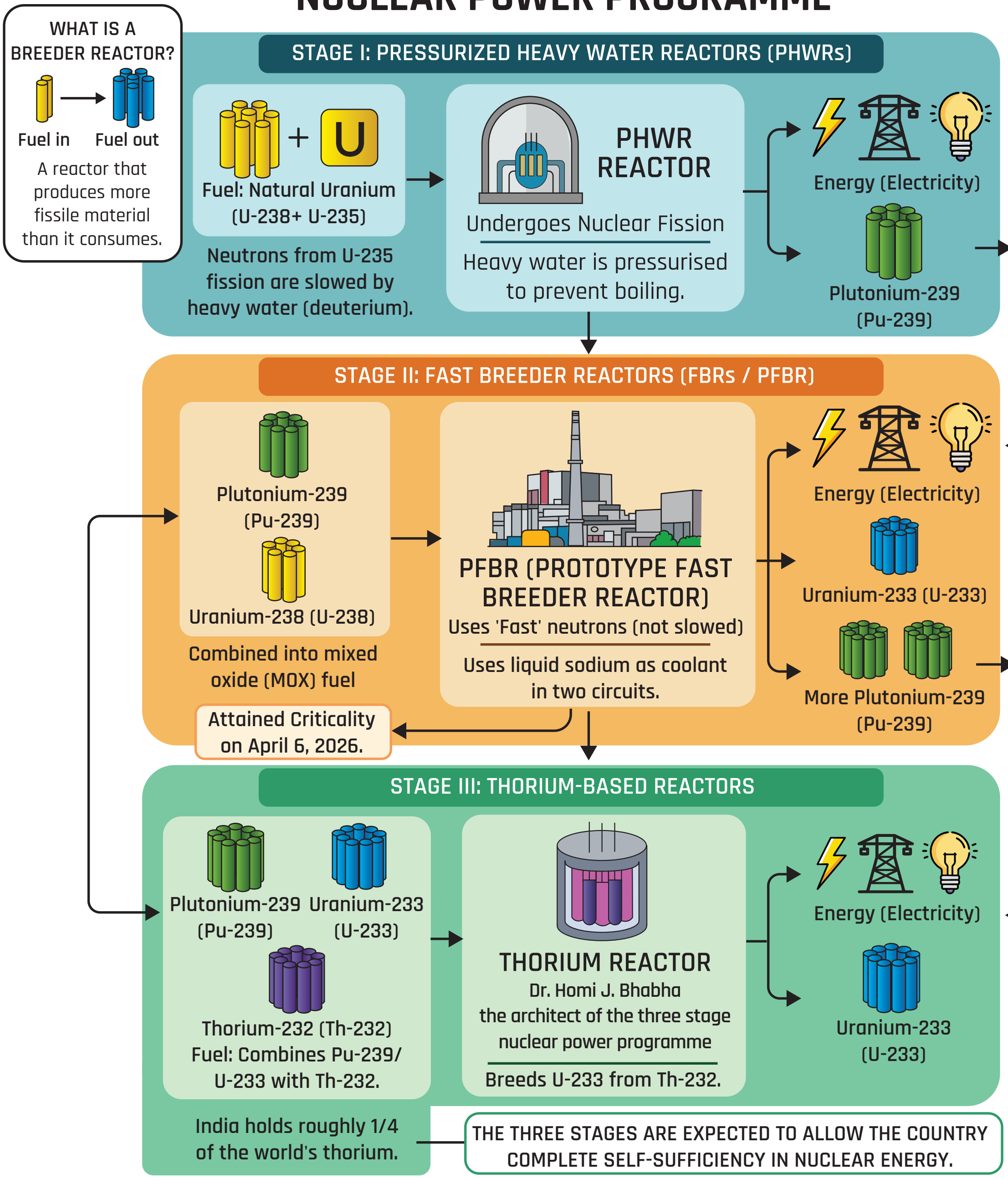
This chapter outlines the evolution of India's nuclear programme from the foundational three-stage strategy to the policy, institutional, and regulatory reforms underway to enable the future deployment of SMRs.

2.2
India's Nuclear Programme: The Three-stage Strategy

India's three-stage nuclear strategy emerged from a unique combination of resource constraints, geopolitical conditions, and long-term energy security considerations. At the time of programme inception, India faced limited domestic uranium availability, restricted access to international nuclear markets, and a need to build an indigenous technological base. These factors led to the formulation of a phased approach that prioritized efficient use of natural uranium in the near term, progressive development of fuel recycling capabilities, and eventual transition to thorium-based systems. Conceived under the leadership of Homi Bhabha, this strategy enabled India to pursue nuclear energy development despite external constraints, while laying the foundation for long-term fuel sustainability and technological self-reliance.

India currently operates in Stage I, with Stage II under demonstration (FBR at Kalapakkam achieved critically, the first step in a sustained chain reaction on 6 April 2026, commercial operation remains pending) and Stage III in research. India's step-wise three-stage programme has developed strong domestic expertise. With this established foundation, traditional reactors and SMRs can be deployed in parallel to align nuclear growth with net-zero and energy security objectives.

INDIA'S THREE-STAGE NUCLEAR POWER PROGRAMME



WHAT IS A BREEDER REACTOR?

Fuel in → Fuel out

A reactor that produces more fissile material than it consumes.

STAGE I: PRESSURIZED HEAVY WATER REACTORS (PHWRs)

Fuel: Natural Uranium (U-238+ U-235)

Neutrons from U-235 fission are slowed by heavy water (deuterium).

PHWR REACTOR

Undergoes Nuclear Fission

Heavy water is pressurised to prevent boiling.

Energy (Electricity)

Plutonium-239 (Pu-239)

Fuel for Stage II

STAGE II: FAST BREEDER REACTORS (FBRs / PFBR)

Plutonium-239 (Pu-239)

Uranium-238 (U-238)

Combined into mixed oxide (MOX) fuel

PFBR (PROTOTYPE FAST BREEDER REACTOR)

Uses 'Fast' neutrons (not slowed)

Uses liquid sodium as coolant in two circuits.

Attained Criticality on April 6, 2026.

Energy (Electricity)

Uranium-233 (U-233)

More Plutonium-239 (Pu-239)

Fuel for Stage III

STAGE III: THORIUM-BASED REACTORS

Plutonium-239 (Pu-239)

Uranium-233 (U-233)

Thorium-232 (Th-232)

Fuel: Combines Pu-239/ U-233 with Th-232.

THORIUM REACTOR

Dr. Homi J. Bhabha the architect of the three stage nuclear power programme

Breeds U-233 from Th-232.

Energy (Electricity)

Uranium-233 (U-233)

India holds roughly 1/4 of the world's thorium.

THE THREE STAGES ARE EXPECTED TO ALLOW THE COUNTRY COMPLETE SELF-SUFFICIENCY IN NUCLEAR ENERGY.

Fig 2.1: India's Three-Stage Nuclear Power Programme and the Role of Fast Breeder Reactors

(Image inspired by an article published in The Hindu, April 9, 2026)*

The figure **2.1** illustrates India's three-stage nuclear power programme, highlighting the progression from PHWRs to FBRs, and eventually to thorium-based reactors. It underscores the strategic role of fast breeder reactors in enabling fuel sustainability and advancing long-term energy security.

2.3

Current Status of Nuclear

India presently (as of Jan 2026) operates 25 nuclear reactors[1] with a total installed capacity of about 8.8 GW[1] located across seven sites and is dominated by PHWRs.[2] The list of nuclear plants with their locations are depicted in Figure **2.2** and **2.3** shows how India's nuclear power generation has gradually increased over the years forming the pillar of India's civilian nuclear programme due its established robust domestic manufacturing ecosystem, proven operational experience, and its compatibility with the country's uranium resource profile. Over the decades, India has progressed indigenously from 220 MW to 540 MW and now 700 MW PHWRs which are already successfully commissioned, with earlier commissioning challenges fully resolved.

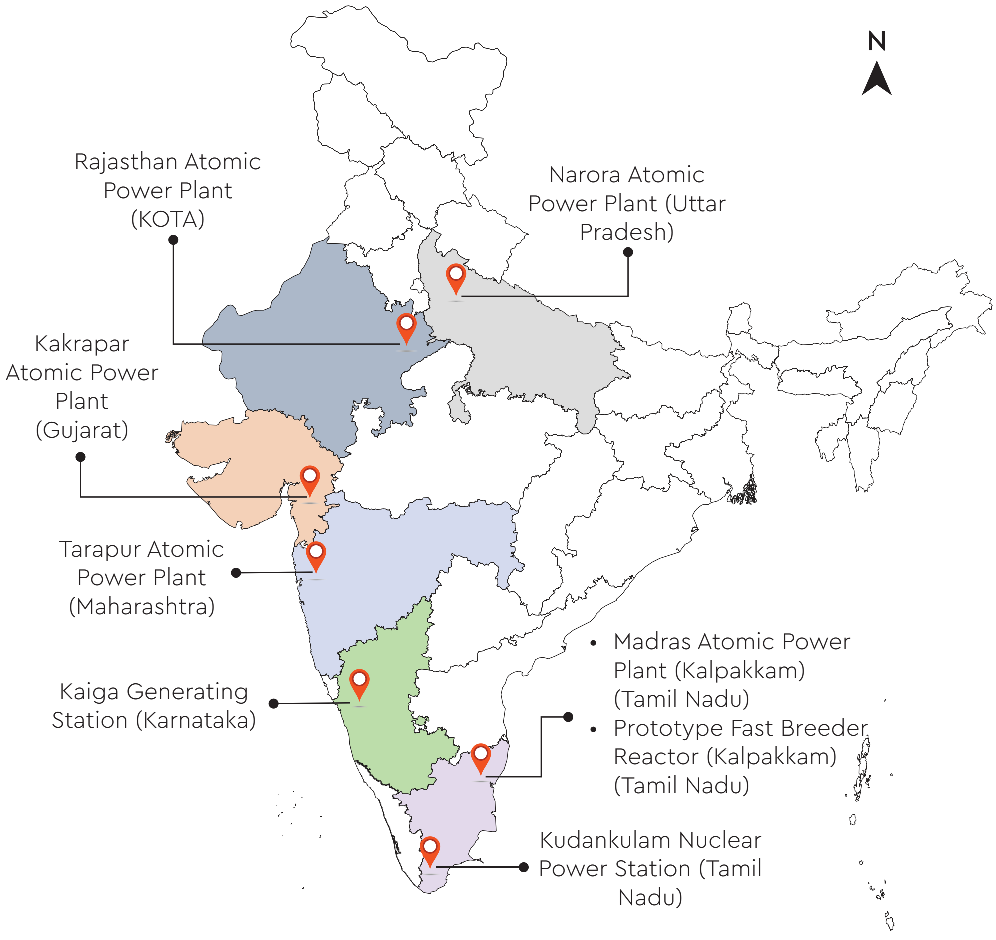


Fig. 2.2: Nuclear power plants in India

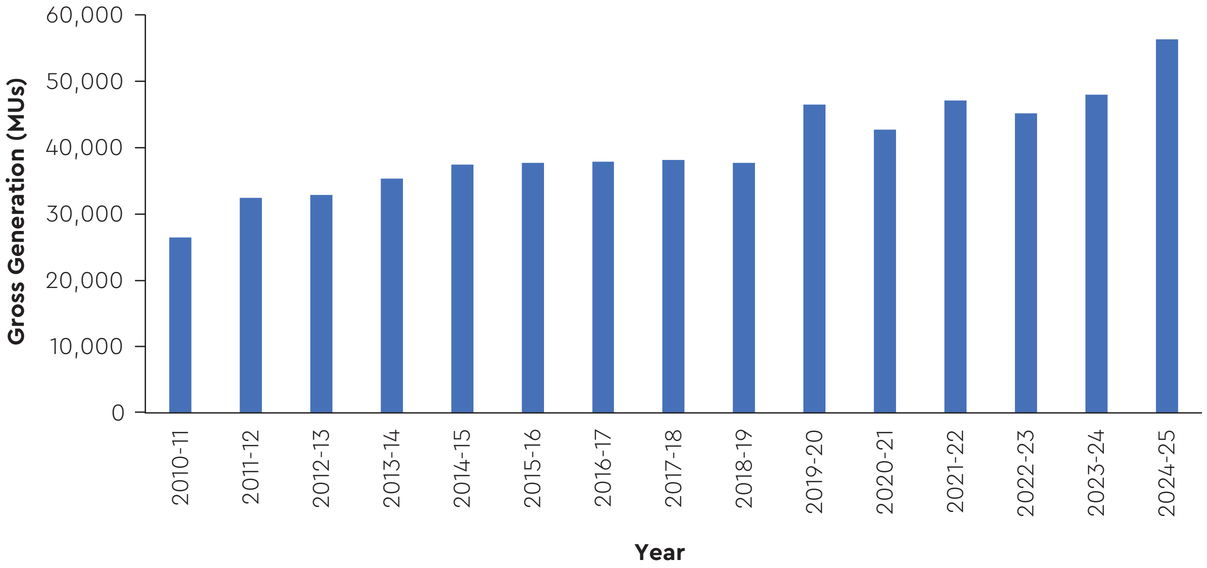


Fig 2.3: Gross generation of nuclear power

Source: NPCIL

Building on this technological maturity, PHWR units currently under construction or in advanced planning at Kakrapar, Rawatbhata, Kaiga, Gorakhpur, and Chutka are expected to raise installed capacity to nearly 22 GW by 2032.[3] Ongoing nuclear expansion includes the development of Kudankulam Units 3–6 in collaboration with Russia, together with the construction of 13 indigenous 700 MW PHWRs under the fleet-mode strategy. NPCIL has set a target to commission at least one reactor every year, reinforcing the steady expansion of the nuclear fleet.

2.4

Long-term Vision to 2047

Looking beyond 2032, India aims to expand its nuclear capacity to 100 GW by 2047. Achieving this ambitious goal will require moving from a primarily PHWR-based programme to a broader mix of technologies that can scale up quickly and support long-term energy security.

India will follow a path, combining domestic strengths with strategic international partnerships:

- **Large PHWRs:**

These reactors will remain the backbone of India's baseload capacity. Their proven performance and strong domestic manufacturing base make them central to sustained growth. In this context, new greenfield sites such as **Mahi Banswara in Rajasthan**, proposed for **four indigenously developed 700 MWe PHWR units**,[4] represent a significant step towards scaling up nuclear capacity rapidly while strengthening regional energy security.

- **Imported large reactors (French and American technologies):**

  In addition to Russian VVERs, two already operating and four under construction at Kudankulam,[5] India is actively working with France (EDF) on the Jaitapur project[6] and Westinghouse (USA) on the Kovvada project.[7] Technical and commercial discussions are progressing. These large, imported reactors will be essential to meeting the 2047 capacity target, especially for adding high-capacity units quickly.

- **Small modular reactors (SMRs):**

  SMRs are expected to provide flexibility, faster deployment, and suitability for new locations such as industrial hubs and remote areas. Their modular design will help expand capacity at a much quicker pace.

- **Systems (fast breeder reactors and thorium-based designs):**

  These technologies support India's long-term goals of fuel sustainability and strategic resource independence, especially by enabling efficient use of plutonium (Pu-239 used fuel from stage 1) and thorium.

- **Bharat small reactors:**

  this approach ensures that reactor maturity is with aggressive target. SMR integration is complementary, it is recognized as the structurally essential component required to transition the sector and achieve the magnitude of the 2047 national capacity goal and beyond.

2.5

Uranium Resources and Fuel Security Considerations

India's nuclear power programme has evolved under the constraint of limited domestic uranium resources, a factor that has shaped reactor choice, fuel strategy, and international engagement. As highlighted in studies by BARC, India's known uranium reserves are modest relative to projected long-term nuclear capacity requirements, making efficient fuel utilization and diversification of supply sources a major consideration.[8]

Domestic uranium production supports a portion of current PHWR requirements and has expanded gradually through mining operations in Jharkhand, Andhra Pradesh, and Telangana. India's uranium production remains modest at ~600 tonnes annually (1–2% of global output), constrained by low-grade and dispersed deposits. Despite a sizable resource base of ~4,25,000–4,33,800 tonnes of U_3O_8, mining capacity remains limited, with planned expansion to ~1,095 tonnes per year. However, indigenous production alone is insufficient to meet the fuel demands of an expanding nuclear fleet. This has led India to adopt a dual approach: strengthening domestic exploration and mining while securing uranium imports through long-term international agreements.[9]

These constraints underpin India's emphasis on PHWR technology, which uses natural uranium efficiently, and reinforce the strategic importance of the three-stage nuclear programme, particularly the transition towards thorium-based systems. In parallel, assured access to imported uranium has enabled higher plant load factors and more predictable reactor operations in recent years.

As India plans capacity expansion towards 2047, uranium availability remains a key planning parameter. In the near term, it reinforces the role of PHWRs, imported reactor technology, and uranium-fuelled SMRs. Over the longer term, it strengthens the case for advancing fast reactors and thorium-based technologies to reduce dependence on external fuel supplies and enhance long-term energy security.

From 2008–09 till 2024–25, a total of 18842.60 MTs of Uranium in the form of Uranium Ore Concentrate, Natural UO2 pellets and Enriched UO2 pellets was imported for reactors under the International Atomic Energy Agency (IAEA) Safeguards in India.

Further, uranium enrichment considerations have also played an important role in shaping India's nuclear technology choices. India's nuclear programme has historically emphasized reactor designs that minimize dependence on enriched uranium, most notably PHWRs, which operate on natural uranium. This approach reduced vulnerability to external fuel supply constraints and supported indigenous fuel-cycle development. While access to imported enriched uranium has improved in recent years through international cooperation, enrichment availability remains a strategic planning factor rather than a primary expansion pathway. As India scales its nuclear capacity toward 2047, enrichment-related constraints reinforce the continued relevance of PHWRs and imported reactor technology in the near term, while strengthening the long-term case for fast reactors and thorium-based systems that reduce reliance on externally supplied enriched fuel.

2.6

Financial Support from Government in Addition to Private Sector Participation

The Union Budget 2025–26 earmarked ₹20,000 crore for research, design, and deployment of SMRs, with a goal of having five indigenously designed reactors operational by 2033. These efforts are being coordinated by the DAE through institutions such as the BARC and the NPCIL.

Ongoing designs include BSMR-200, 55 MWe modular unit, and a 5 MWth high-temperature gas-cooled reactor (HTGCR). These designs intend to serve distributed industrial loads and smaller grids. BSRs (SMRs) are expected to enable shorter construction schedules, reduced capital requirements in the long run, and improved siting flexibility, while maintaining the high safety standards characteristic of nuclear generation.

To facilitate wider participation, the government has also initiated policy measures like introducing the Request for Proposal (RfP) for private players to establish 220 MW Nuclear to involve private entities in SMR design, component manufacturing, and co-development under a regulated framework marking an important evolution in India's historically state-led nuclear sector.

A significant milestone was achieved in 2024, when the Rajasthan Atomic Power Project's Unit-7 (RAPP-7),[10] one of the country's largest and third indigenous nuclear reactors, reached criticality, marking the beginning of controlled fission chain reaction. This signifies India's growing capability in building and operating indigenous nuclear reactors, contributing to a future powered by homegrown technology.[11]

2.7

Institutional Framework

India's nuclear programme operates through a coordinated institutional architecture led by the Department of Atomic Energy (DAE), which reports directly to the Prime Minister's Office.[12] The DAE provides overall policy direction and oversees research, international cooperation, and programme implementation.

Within this structure, NPCIL manages the construction and operation of nuclear power plants, while BARC and Indira Gandhi Centre for Atomic Research (IGCAR) drive reactor development and fuel-cycle research. The Nuclear Fuel Complex[13] supports the programme through fuel fabrication and component manufacturing, while domestic uranium mining is undertaken by the Uranium Corporation of India Limited (UCIL).[14] Regulatory oversight is carried out independently by the Atomic Energy Regulatory Board (AERB), which sets safety standards, licenses facilities, and monitors compliance across the nuclear lifecycle.

For the fast breeder programme, Bharatiya Nabhikiya Vidyut Nigam Limited (BHAVINI)[15] plays a dedicated role in deploying and operating breeder reactors, aligning with India's long-term closed fuel cycle strategy and the vision of long-term fuel sustainability.

Together, these institutions create an integrated system that links policy, research, technology development, and regulatory supervision, enabling coherent and coordinated growth of India's nuclear sector. The present institutional framework for nuclear regulation is presented in Figure 2.4.

Department of Atomic Energy (DAE)

- Policy direction • R&D oversight • International cooperation

Nuclear Power Corporation of India Limited (NPCIL)

- Construction & operation of nuclear power plants

Bhabha Atomic Research Centre (BARC)

- Reactor design • Materials research • Fuel-cycle innovation

Indira Gandhi Centre for Atomic (IGCAR)

- Fast breeder and advanced reactor system research

Atomic Energy Regulatory Board (AERB)

- Independent safety oversight & licensing

Fig 2.4: Institutional framework for nuclear regulation

(Refer to Annexure 3 for detailed functional structure and working)

India's civilian nuclear sector operates under a well-established framework of engagement with the International Atomic Energy Agency (IAEA). The IAEA safety review team at designated facilities, conducts periodic peer-review missions, such as Operational Safety Review Team (OSART)[16] and Integrated Regulatory Review Service (IRRS),[17] and provides internationally benchmarked safety standards that inform AERB's regulatory processes. This cooperation strengthens India's safety culture, enhances transparency, and ensures that future SMR designs, and deployment strategies remain aligned with global norms.

2.8

International Cooperation and Strategic Partnerships

International cooperation plays a supporting role in India's nuclear programme by enabling technology access, fuel security, and safety benchmarking. Table 2.1 provides an overview of India's key bilateral and multilateral nuclear partnerships relevant to both large reactor deployment and the emerging SMR roadmap.

Table 2.1: Overview of India's bilateral and multilateral nuclear cooperation

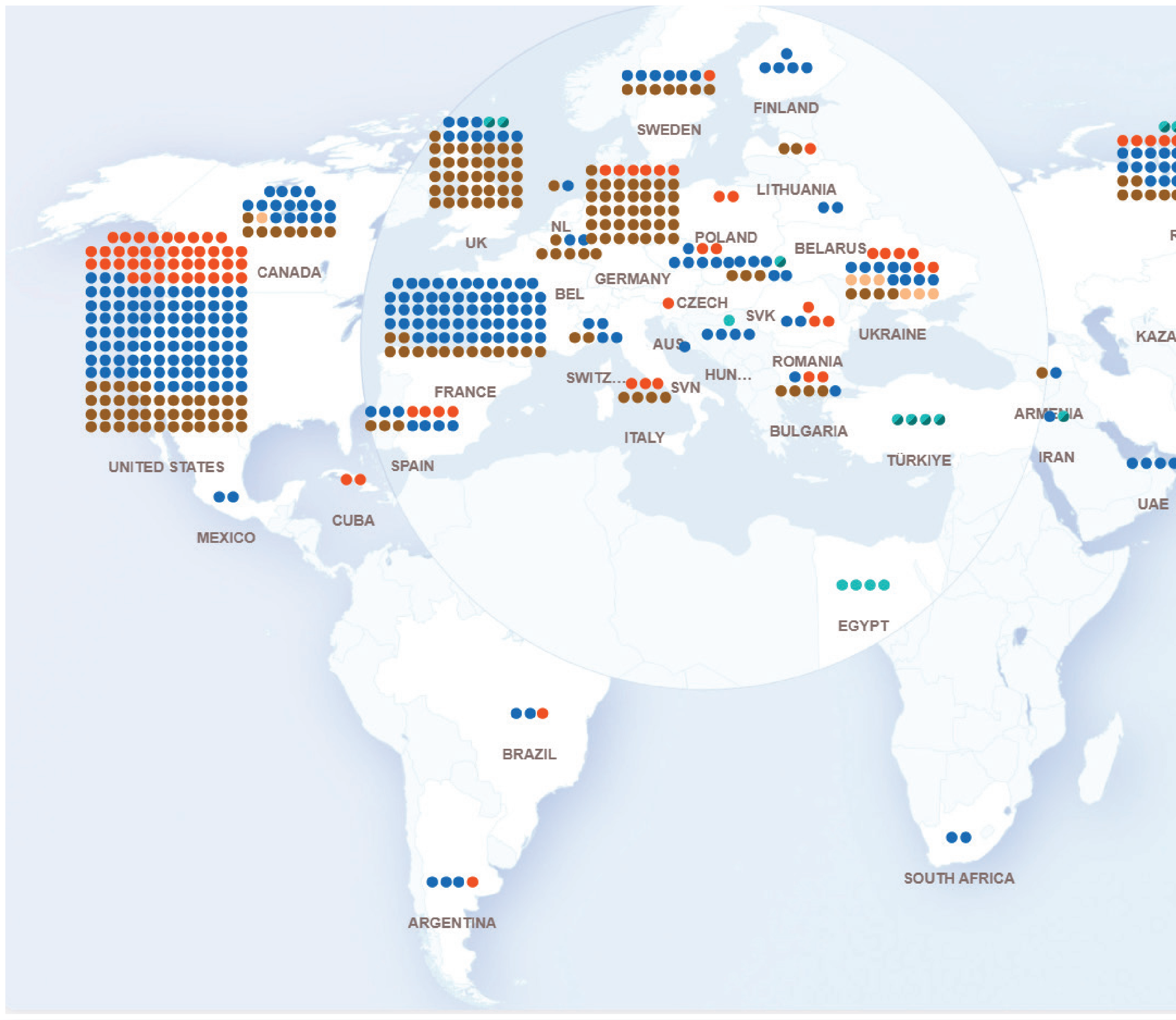
Partner Country / Organization	Nature of Cooperation	Key Areas Covered
Russia [18]	Strategic bilateral partnership	VVER reactors (Kudankulam), construction, fuel supply, O&M support
France[19]	Strategic civil nuclear cooperation	EPR reactors (Jaitapur), engineering, safety standards
United States[20]	Civil nuclear cooperation agreement	Large reactors (AP-type), SMR collaboration, fuel assurance
Canada[21]	Nuclear cooperation agreement	Uranium supply (10,000 tonnes between 2027–35), R&D collaboration
Australia[22,23]	Nuclear cooperation agreement	Uranium supply
Kazakhstan[24]	Nuclear cooperation agreement	Uranium supply
Namibia[25]	Nuclear cooperation agreement	Uranium supply
Japan[26]	Civil nuclear cooperation	Components, manufacturing collaboration, safety practices
South Korea[27]	Nuclear cooperation (submarines)	Engineering services, components, R&D
United Kingdom[28]	Nuclear cooperation	R&D, SMR engagement, safety standards
Argentina[29]	Nuclear cooperation	Heavy water reactors, research collaboration
International Atomic Energy Agency	Multilateral engagement	Safeguards, OSART, IRRS, safety standards
World Association of Nuclear Operators	Multilateral operational network	Peer reviews, operational benchmarking
Generation IV International Forum[30]	Multilateral R&D platform	Advanced reactors, fast systems, fuel cycles
ITER Organization [31]	Multilateral megaproject	Fusion research and engineering
OECD Nuclear Energy Agency[32]	Participant	Policy analysis, safety, economics

2.9

Summing Up

India's nuclear programme aims to progress through a structured pathway strengthening its PHWR base, demonstrating advanced breeder technologies, and preparing for modular reactor deployment. The combined focus on indigenous design, institutional coordination, and regulatory modernization provides the foundation for sustained capacity growth through mid-century.

By progressively integrating new and proven technologies and implementation models, India is positioning nuclear power as a secure, low-carbon, and reliable component of its future energy mix supporting both national energy security and long-term sustainability goals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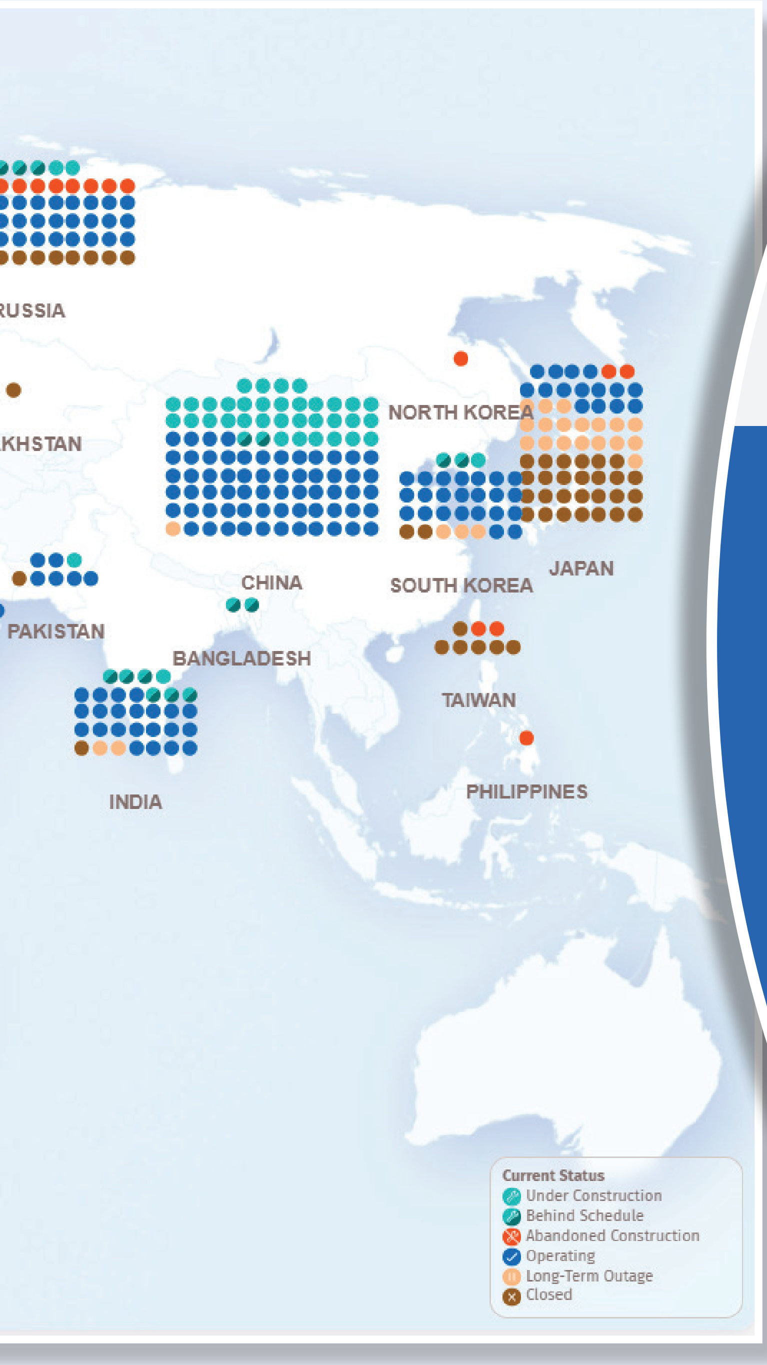


3

Chapter

Global Scenario in SMR Development

As countries seek reliable, low-carbon power sources to complement the variability of renewables and ensure long-term stability, nuclear energy is experiencing significant resurgence. Central to this renewed interest is the advancement of small modular reactors (SMRs). The SMRs represent a fundamental shift in nuclear design, offering inherent safety features, greater deployment flexibility, and a smaller environmental footprint. Their diverse capabilities, spanning across a wide range of reactor designs, fuel systems, and potential applications, position them as critical and versatile technology for the future of global power generation. Their development is progressing at different speeds across countries, shaped by national priorities, regulatory frameworks, and industrial capabilities. This chapter provides an overview of these global developments, regional trends, design classification, fuel management, and several applications that are shaping the trajectory of SMR deployment.

3.1

Present Status

3.1.1

Nuclear deployment status

As of 31 October 2025, the global nuclear fleet comprises 417 reactors in operation, with a combined net installed capacity of approximately 377 GWe.[33] Figure 3.1 presents this capacity alongside the regional distribution of reactors, showing that global nuclear power remains concentrated in a limited number of regions with long-standing nuclear programmes. Northern America, Western Europe and the Asia–Far East together account for the nearly 80% of operating reactors and installed capacity, reflecting early and sustained nuclear deployment, established regulatory frameworks, and accumulated operating experience in these regions.

Further, a small group of countries like the United States, France, China, Russia, and South Korea together operate nearly 71% of global nuclear capacity.[34] Their long-running nuclear programmes continue to influence global operational practices, regulatory approaches, and technology development. Other regions, including Central and Eastern Europe, the Middle East and South Asia, Latin America, and Africa, account for a smaller share of global operating capacity, reflecting variations in the scale and timing of nuclear deployment across countries.

While Northern America and Western Europe retain the largest operational fleets, more than 70% of new nuclear construction is now concentrated in Asia and the Far East as shown in Figure 3.1. In experienced nuclear regions like Europe and North America, capacity additions remain limited, with greater emphasis on extending the operation of existing reactors and developing frameworks to enable modular reactor deployment. This evolving pattern reflects a broader transition in global nuclear development, in which future capacity growth is increasingly associated with more flexible reactor technologies like small and advanced modular reactors.

The next section presents a comprehensive overview of the status of SMR design and deployment worldwide.

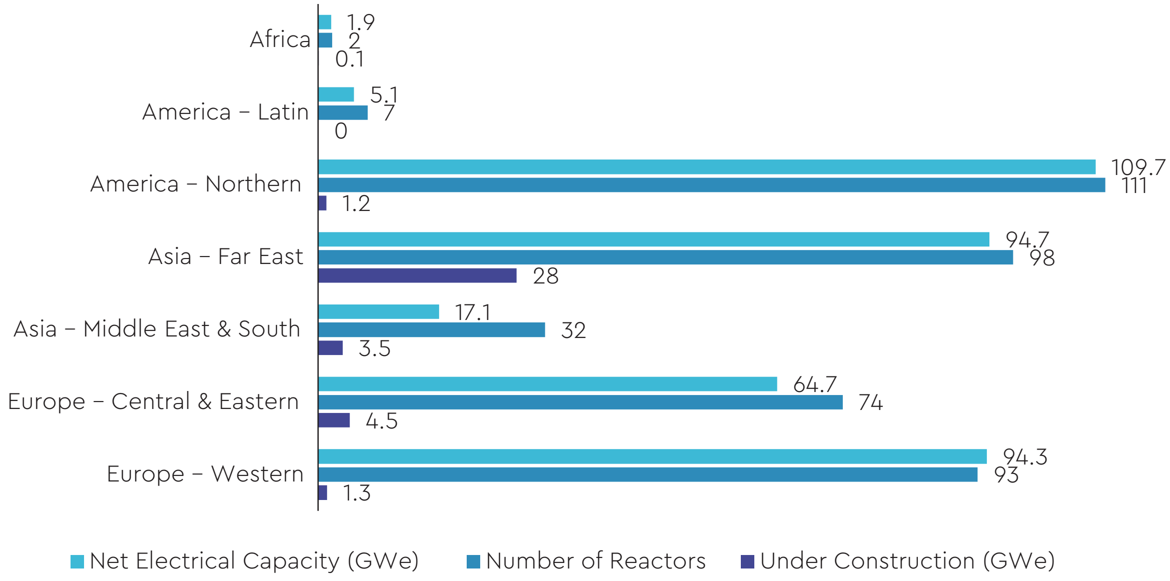


Fig 3.1: Regional distribution of nuclear power capacity and reactors (operating and under construction)- as on 31st october 2025

Source: IAEA; PRIS[35]

3.1.2

SMRs status

Globally, more than 120 SMR designs are currently under various development stages across different countries.[36] Figure 3.2 categorizes these designs by their stage of development—operational, under construction, near-term advanced deployment, and early-stage design. This distribution reflects the growing global engagement with SMR technologies and the wide range of approaches being pursued.

As of October 2025, only seven SMRs are currently operational. These include HTR-PM and CNP-300 (MWe)[37] in China, PHWR-220 (220 MWe)[38] in India, HTTR (thermal)[38] in Japan, EGP-6 (11 MWe)[39] in Argentina, and the marine-based KLT-40S (35 MWe)[38] and RITM-200 (50 MWe)[38] in Russia. Together, these projects represent the first set of SMRs that have transitioned from design to operation across both land-based and marine applications.

A limited but growing group of SMRs has progressed to the construction stage, marking the transition from design and licensing to physical deployment. Key projects in this category include CAREM-25 (30 MWe) (Argentina),[37] Linglong-1/ACP100 (125 MWe) (China),[40] BREST-OD-300 (300 MWe) (Russia),[41] and the KP-FHR (140 MWe), eVinci (5 MWe), and MARVEL (0.015 MWe) reactors in the United States[42] as shown in Figure 3.2. These projects indicate that selected SMR designs are beginning to translate technical readiness into on-site implementation.

Alongside these, a larger set of SMR designs remains at advanced or early development stages, where detailed engineering, licensing preparation, and technology validation are still underway. This segment encompasses the widest diversity of reactor technologies and applications and reflects continued international engagement with modular nuclear concepts. Taken together, this distribution highlights how SMR deployment is unfolding through a gradual progression from experimentation to construction.

At the same time, these SMRs differ widely in their underlying reactor technologies and design approaches, which shape their performance, fuel use, and potential applications. All these classifications and applications are detailed in the subsequent section.

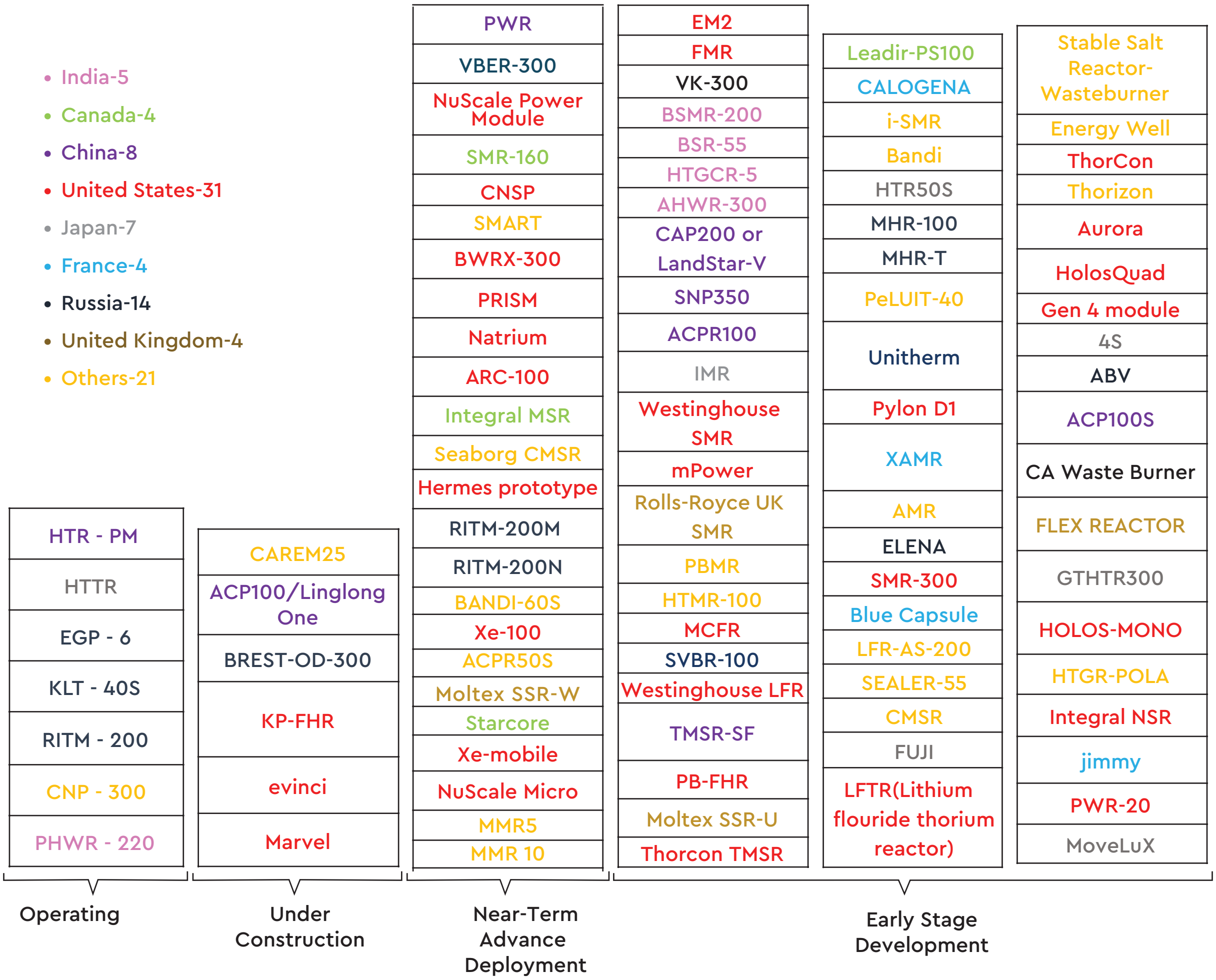


Fig 3.2: Global Distribution of SMR designs by stage of development

Source: TERI analysis (refer Annexure 1 & 2)

3.2

Overview of Global SMR Technologies and Their Types

SMR designs can be grouped into five broad technology categories based on reactor type, coolant system, and operating characteristics, as illustrated in Figure 3.3.[43] This classification reflects the diversity of design approaches being pursued globally and helps clarify how different SMR technologies are being developed to serve distinct power systems and industrial applications.

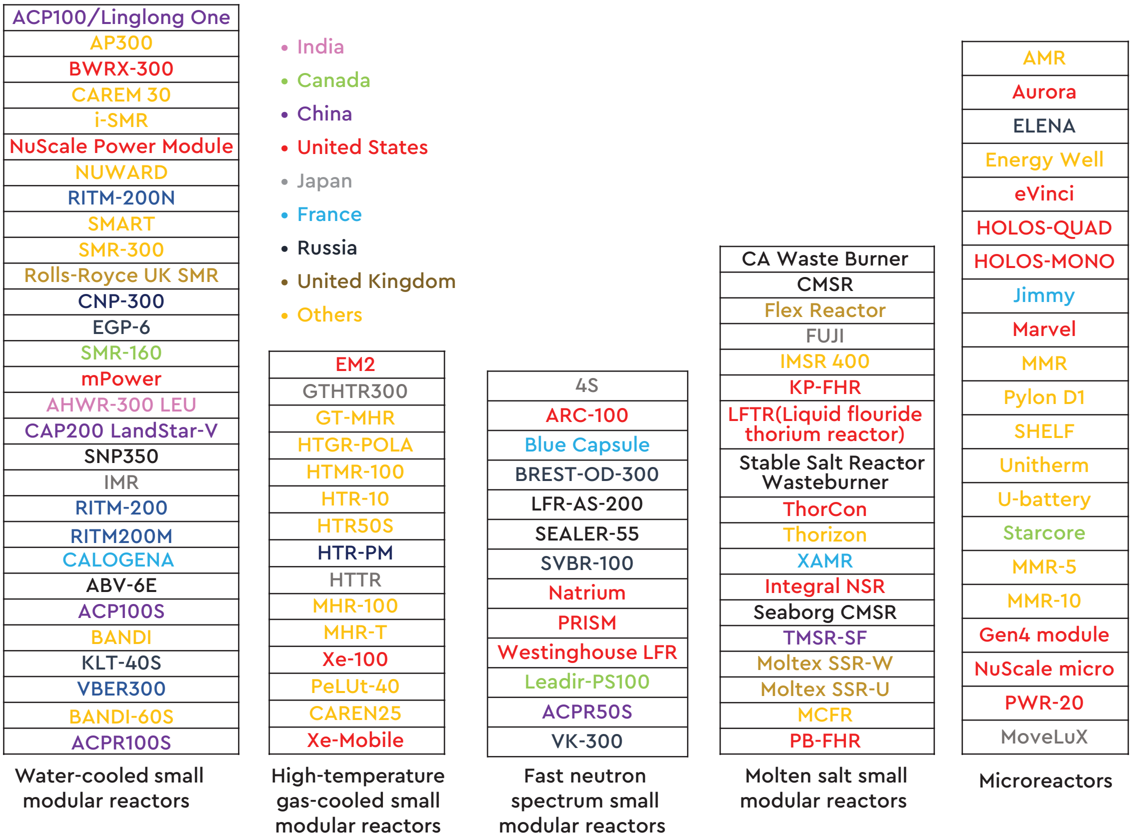


Fig 3.3: Classification of SMR technologies by reactor type and coolant (Annexure 1 & 2)

Water-cooled SMRs represent the most mature and widely developed category, drawing directly from light- and heavy-water reactor technologies that have been used for decades. These designs are typically deployed in compact, modular configurations and benefit from established regulatory familiarity. Land-based water-cooled SMRs form the largest subgroup, with around 14[44] designs currently under development. Examples include CAREM in Argentina and ACP100 in China, alongside prominent commercial designs such as NuScale VOYGR (USA), Rolls-Royce SMR (UK), and NUWARD (France). Due to their technological maturity and well-understood safety features, water-cooled SMRs are widely regarded as strong candidates for early deployment.

A subset of water-cooled SMRs includes **marine-based and floating reactors**. These systems are designed for deployment on barges or floating platforms and are particularly suited for remote or islanded regions. Russia's KLT-40S represents the first grid-connected floating SMR in operation, while additional floating units based on the RITM-200 design are under construction. These projects demonstrate how SMRs can be adapted to challenging geographical and infrastructure conditions.

High-temperature gas-cooled SMRs (HTGRs) operate at significantly higher temperatures, typically above 750°C, allowing them to support applications beyond electricity generation. These reactors are well suited for industrial process heat, hydrogen production, and cogeneration.[45] It also has the potential for online refuelling. Around 14 HTGR designs are under development globally, with China's HTR-PM already connected to the grid. In addition, HTGR test reactors in Japan and China have accumulated over two decades of operating experience[46]. Together, these developments highlight the role of HTGRs in expanding SMR applications towards industrial decarbonization and integrated energy systems.

Liquid metal-cooled fast neutron SMRs use coolants such as sodium, lead, or lead-bismuth in liquid form and operate in the fast neutron spectrum. These designs offer high-fuel efficiency and the potential to reduce long-term waste through advanced fuel utilization. Approximately 13 such designs are currently under development, including Russia's BREST-OD-300 and SVBR-100. These reactors are often linked to long-term sustainability objectives and closed fuel-cycle strategies.[47]

Molten salt SMRs represent a newer generation of reactor concepts. They use molten salt as a coolant, and in some cases as a fuel carrier, enabling low-pressure operation and passive safety features. About 13 molten salt SMR designs are in early licensing or development stages across countries such as Canada, Denmark, the United Kingdom, and the United States. These designs illustrate how SMRs could support both electricity generation and high-temperature industrial applications in the future.[48]

Finally, **microreactors** form a distinct category of ultra-compact SMRs, typically producing up to 10 MWe. These reactors are intended for remote, off-grid, or specialized uses, such as mining operations, defence installations, and isolated communities. A variety of coolant types are being explored, including water, helium, molten salt, and liquid metals. Licensing activities in the United States and Canada indicate growing interest in microreactors as flexible and rapidly deployable energy solutions.[49] Examples include U-battery (4 MWe); Gen 4 module (5 MWe); NuScale Micro (10 MWe).

Taken together, this technology classification shows that SMRs are not a single, uniform solution, but a set of reactor designs tailored to different energy needs, system sizes, and application contexts. The SMR designs classification based on generation are discussed in the following section.

3.3

Technological Maturity of SMRs: Evolutionary and Revolutionary Designs

SMR design scan broadly divided into evolutionary and revolutionary categories.[50]

Evolutionary SMRs are derived from established Generation II and Generation III+ light water reactor technologies. They rely on familiar systems such as light water coolants, conventional fuels, and proven safety features that have benefited from decades of operational experience. Because these designs align closely with existing regulatory frameworks and industrial supply chains, they are well suited for near-term deployment. Evolutionary SMRs are primarily designed for electricity generation, with some variants adapted for marine or floating applications. Their technological continuity and standardized engineering approaches make them an important pathway for early commercial deployment.

Revolutionary SMRs represent a more advanced stage of technological development. These designs incorporate features commonly associated with Generation IV concepts (involving passive shutdown and residual heat-removal systems), including molten salt, liquid metal, or helium cooling, along with advanced fuel cycles and higher operating temperatures. Such characteristics enable a broader range of applications beyond electricity, including industrial heat supply, hydrogen production, and cogeneration. By supporting these uses, revolutionary SMRs expand the potential role of nuclear energy within future low-carbon energy systems. Their development involves new materials and operating conditions, and regulatory frameworks are being progressively evolved to support these innovations.

Together, evolutionary and revolutionary SMRs reflect complementary development pathways. Evolutionary designs support early deployment and system reliability, while revolutionary designs broaden the scope of nuclear energy applications over the longer term. This dual-track approach allows countries to address immediate energy needs while gradually building capabilities for more advanced nuclear technologies.

3.4

Fuel Source and Waste Management

To understand the role of fuel technologies in shaping the design, safety, and deployment timelines of SMRs, it is important to compare the characteristics of the major fuel options currently under consideration. Fuel choice directly influences reactor performance, operating temperature, refuelling frequency, waste generation, regulatory complexity, and supply-chain readiness. Table 3.1 compares the various fuel types with respect to enrichment requirements, along with their key advantages and deployment status.

Table 3.1: Comparison of nuclear fuel types and enrichment requirements for various SMR designs

Fuel Type	Typical Enrichment	Reactor Types Using the Fuel	Key Advantages	Current Policy and Deployment Status
Conventional LEU (UO_2)	< 5% U-235[51]	Water-cooled SMRs (EGP-6, KLT-40S, RITM-200); large LWRs	Mature global supply chain; regulatory familiarity; proven waste management pathways	Near-term deployment ready; dominant global fuel
HALEU (UO_2 / advanced forms)	5–20% U-235[51]	Advanced SMRs (Natrium, Xe-100, some HTGRs, micro-reactors)	Higher energy density; longer refuelling intervals; enables compact and high-temperature designs	Critical enabling fuel for advanced SMRs (2030–40)
TRISO fuel	Typically 8–15% U-235 (HALEU-based)	High-temperature gas-cooled reactors (HTR-PM, HTTR, Xe-100)	Excellent fission-product retention; high temperature tolerance; enhanced passive safety	Demonstration-stage; selective policy support
Metallic fuel (U-Pu-Zr, U-Zr)	Variable	Fast-spectrum SMRs (BREST-OD-300)	High neutron efficiency; supports closed fuel cycles and recycling	Limited deployment; primarily in Russia and R&D programmes
Molten salt fuel	LEU / HALEU / U-233(design dependent)[52]	Molten salt reactors (MSRs)	Flexible fuel management; potential for online refuelling; reduced waste inventories	Early R&D and pilot phase globally

Fuel Type	Typical Enrichment	Reactor Types Using the Fuel	Key Advantages	Current Policy and Deployment Status
Thorium-based fuel (Th-U-233)	U-233 (bred in-reactor)[53]	AHWR concepts; MSRs (India-focused)	Abundant resource; improved fuel utilization; lower long-lived actinides	Long-term strategic option; India-specific focus

3.4.1

Refuelling Intervals

Refuelling practices across SMRs vary significantly depending on reactor design and fuel type. Table 3.2 represents different refuelling approaches based on the technological classification of SMR designs. It is a critical design parameter for SMRs as it directly affects plant availability, operating costs, and suitability for different end uses. Longer refuelling intervals lower fuel-handling requirements, and improve capacity factors, which is particularly important for remote locations and industrial applications requiring continuous operation. On the other hand, shorter fuelling cycles generally found in conventional reactors allow SMRs to align with existing grid operations and regulatory frameworks, supporting near-term deployment. As a result, refuelling strategies play a key role in determining the economic viability and deployment context of different SMR technologies.

Table 3.2: Refuelling approaches and operational cycles across SMR designs

SMR Category	Representative Designs	Refuelling Approach	Typical Refuelling Interval	Primary Applications / Rationale
Water-cooled SMRs	EGP-6, KLT-40S, RITM-200	Periodic offline refuelling	24–30 months[54]	Grid-connected electricity generation; alignment with conventional nuclear operating practices
High-temperature reactors (HTRs)	HTR-PM	Online / continuous refuelling	Continuous (no fixed outage cycle)	Industrial heat supply and hydrogen production requiring uninterrupted operation
Microreactors	eVinci	Sealed core (no on-site refuelling)	8–10 years[54]	Remote locations, defence facilities, and sites with limited logistics
Fast-spectrum SMRs	BREST-OD-300	Infrequent offline refuelling	~4–10 years[54]	High fuel efficiency and closed fuel-cycle concepts
Molten salt reactors (MSRs)	Concept-dependent	Continuous fuel addition and fission-product removal	Continuous	Flexible operation, enhanced fuel utilization, and reduced excess reactivity

Water-cooled SMRs, such as EGP-6, KLT-40S, and RITM-200, generally follow refuelling cycles comparable to large nuclear power plants, typically in the range of 24 to 30 months. This model aligns well with grid-connected electricity generation and established operational practices.

Advanced SMR designs adopt alternative approaches. High-temperature reactors, including HTR-PM and HTTR, support online refuelling, enabling continuous operation and making them suitable for industrial applications where uninterrupted heat supply is required. Microreactors, such as eVinci, are designed with sealed cores that can operate for 8 to 10 years without refuelling, making them suitable for remote locations, defence facilities, and sites with limited logistical access.

Fast-spectrum reactors, including BREST-OD-300, typically achieve longer refuelling intervals, often ranging from four to ten years, reflecting their higher fuel efficiency. Molten salt reactors further enhance fuel flexibility through continuous chemical processing, allowing fresh fuel to be added and fission products to be removed during operation. These varied refuelling strategies demonstrate how SMRs are being tailored to different deployment environments and end-use requirements.

3.4.2

Open and Closed Fuel Cycles

SMR designs also differ in their approach to fuel cycle management. Most water-cooled SMRs operate on an open fuel cycle, where spent fuel is removed after irradiation and stored for long-term management. This approach is well understood, simpler to implement, and aligned with existing regulatory practices.

Advanced SMR technologies, including high-temperature reactors, fast-spectrum systems, and molten salt designs, are increasingly associated with closed or partially closed fuel cycles. In these systems, spent fuel is processed and reused, reducing the volume of high-level waste and improving overall resource utilization. Such fuel cycle strategies support long-term sustainability objectives and enhance energy security by making better use of available fissile material.

India's nuclear programme aligns closely with this approach through its long-term focus on closed fuel cycles and thorium utilization. By integrating advanced fuel strategies with SMR development, countries can strengthen the sustainability and scalability of nuclear energy systems.

3.5

Industrial and Non-electric Applications of SMRs

Beyond electricity generation, SMRs are increasingly being developed as multi-purpose energy systems capable of supplying heat, power, and energy services across a range of sectors. Their ability to operate at different temperature ranges allows them to address industrial, urban, and hard-to-abate sectors that are difficult to decarbonize using variable renewable energy alone. Figure 3.4 illustrates how SMR applications align with different operating temperature requirements.

One of the most significant application areas for SMRs is industrial heat and cogeneration. High-temperature SMRs can supply steam and heat to energy-intensive industries such as steel, petroleum refining, chemicals, and fertilizers, while simultaneously generating electricity. By producing both heat and power from a single source, nuclear cogeneration can significantly improve overall system efficiency compared to electricity-only generation. This capability is particularly relevant for industries that require continuous, high-quality heat. In this context, several industrial players are evaluating SMRs as on-site energy solutions to reduce emissions while maintaining operational reliability.[55]

The SMRs also offer strong potential for **district heating**, particularly in regions with concentrated urban heat demand. Low- to medium-temperature SMRs can supply hot water or steam for district heating networks, typically within a radius of 10–15 km. Their compact size and enhanced safety features make them better suited than large reactors for deployment closer to demand centres. District heating applications are already well established in some nuclear-using countries and are increasingly being considered as part of integrated urban energy planning.[55]

Another important application area is **desalination**, where SMRs can provide both electricity and low-carbon heat for water production. This is especially relevant for regions facing water stress, where energy-intensive desalination processes must operate continuously. SMRs offer the advantage of stable operation and flexible output, making them suitable for integrated power–water systems that combine electricity generation with freshwater supply.[56]

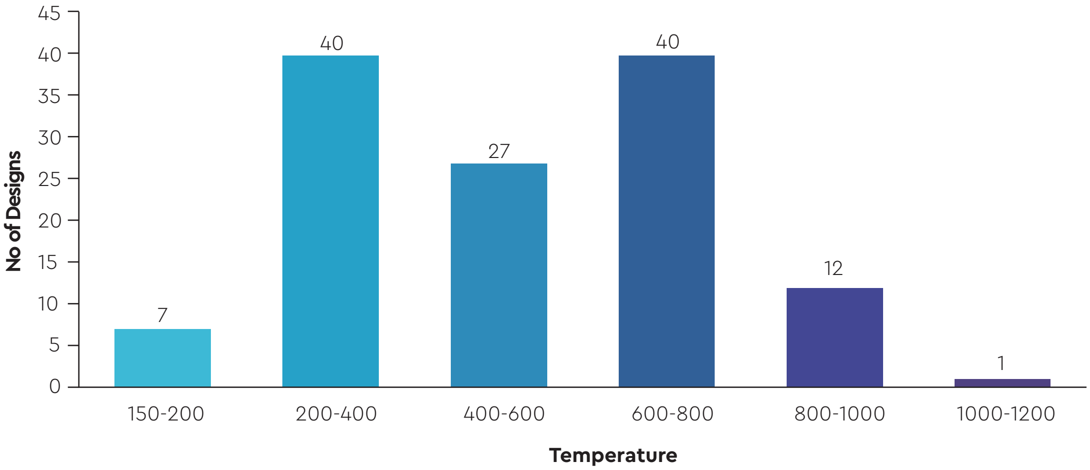
Hydrogen production is emerging as a key application that links SMRs directly to broader clean energy transitions. SMRs can support hydrogen production through conventional low-temperature electrolysis as well as high-temperature steam electrolysis, which requires process heat in the range of 700–800°C. High-temperature SMRs can improve the efficiency of hydrogen production by reducing the electricity required per unit of hydrogen. Several countries are actively exploring this integration. In the United States, pilot projects are examining hydrogen production using electricity from SMRs, while Canada and the United Kingdom are assessing the role of SMRs in large-scale electrolysis. Japan has demonstrated hydrogen production using high-temperature nuclear heat, and similar integration is being studied in China and South Korea. These efforts reflect growing international interest in nuclear-enabled hydrogen as a low-carbon fuel for industry and transport.[56]

SMRs are also being developed as part of **hybrid energy systems**, where nuclear power is combined with renewable energy and storage technologies. In such systems, SMRs provide stable baseload power while accommodating variability from wind and solar generation. This integration can enhance grid resilience, optimize energy use across sectors, and support deeper decarbonization of power systems.[57]

In addition to these civilian applications, SMRs are being explored for **strategic and remote uses**. Compact reactor designs are under consideration for naval propulsion, including submarines and aircraft carriers, where long-operating life and high-energy density are critical. SMRs are also being evaluated for remote and off-grid locations such as Arctic communities, islands, and mining operations, where reliable energy supply is essential, and grid connectivity is limited. These applications highlight the versatility of SMRs in addressing diverse energy needs under varying geographic and operational conditions.

Overall, the range of applications discussed in this section demonstrates that SMRs are not limited to power generation alone. Their ability to deliver electricity, heat, and energy services across industrial, urban, and remote contexts reinforces their role as flexible and application-driven nuclear

technologies. This application of diversity builds directly on the technological, fuel, and design characteristics discussed earlier in the chapter and provides a practical lens for assessing the future role of SMRs in national energy systems. Several countries are exploring SMRs for clean hydrogen production using nuclear heat and electricity. In the US, NuScale Power and the Idaho National Laboratory are piloting hydrogen generation through electrolysis using NuScale's 77 MWe modules, while Holtec's SMR-160 is being studied for steam electrolysis. Canada's BWRX-300 at Darlington and the Rolls-Royce SMR in the UK are being assessed for large-scale electrolysis-based hydrogen production. Japan's HTTR has successfully demonstrated hydrogen generation using the high-temperature iodine–sulphur process, and China's HTR-PM and South Korea's SMART reactor are under study for integration with high-temperature electrolysis systems. These initiatives highlight the growing global focus on SMRs as enablers of low-carbon hydrogen.



150-200	200-400	400-600	600-800	800-1000	1000-1200
• District heating • seawater desalination • low-temperature industrial processes	• Industrial steam supply • Pulp and paper processing • Chemical processing	• Petrochemical processing • Hydrogen production (low-temperature electrolysis) • Synthetic fuel production	• Methane reforming(H Production) • Ammonia production • Process heat for cement and chemical industries	• High-temperature hydrogen production • Metallurgical processing • Steel pre-heating and thermal treatment	• Direct steelmaking processes • Advanced metallurgical applications • High-temperature industrial heat uses

Fig 3.4: Applications based on heating requirements of SMR across different temperature ranges

3.5.1

Other Applications

SMRs are also being developed for niche and strategic applications such as marine propulsion and remote power supply. **Naval forces**, notably in the United States, Russia, and India, are exploring SMR technology for next-generation nuclear-powered submarines[58] and aircraft carriers[59], where compact reactor designs can provide high-energy density, long-operational endurance, and reduced refuelling needs. Additionally, SMRs are being considered for **remote and off-grid locations**, including Arctic communities[60], islands, and mining operations, where they can deliver reliable heat and electricity independent of large transmission networks. These versatile applications underline SMRs' potential to serve both **defence and decentralized energy needs** while supporting clean and secure power generation.

Global SMR developments demonstrate a shift from conceptual research to early commercialization, driven by diverse technological approaches and regional strategies. Evolutionary designs enable near-term deployment, while Generation IV concepts expand applications to industrial heat, hydrogen, and hybrid energy systems. The international experience highlights the importance of regulatory readiness, coordinated industrial ecosystems, and technological adaptability.

3.6

Policy Directions and Way Forward

a. **Adopt a diversified and resilient energy mix:** India should pursue a diversified portfolio of energy sources to meet its growing electricity and energy demand while ensuring reliability, energy security, and decarbonization. In this context, nuclear energy including SMRs should be positioned as a complementary low-carbon source alongside renewables, storage, and other clean technologies.

b. **Pursue parallel development of multiple advanced nuclear technology pathways:** India should evaluate and engage with multiple SMR technology pathways like evolutionary for near-term deployment and advanced Generation IV concepts (including high-temperature and molten salt designs) for future industrial and hybrid energy applications. A multi-technology strategy reduces risk and increases flexibility.

c. **Leverage India's abundant thorium reserves to strengthen long-term fuel security:** India holds vast thorium resources with in-situ monazite sands containing over 1 million tonnes of thorium, representing a significant share of global reserves and a long-term strategic asset for nuclear fuel cycles. Leveraging these reserves through advanced fuel-cycle strategies (for example, breeding U-233 and thorium-based fuels) can enhance fuel self-reliance, reduce dependence on imported uranium, and support sustainable long-term nuclear growth.

d. **Align SMR deployment with national development and decarbonization priorities:** SMR planning should be linked explicitly to national priorities such as industrial decarbonization, hydrogen production, energy access for remote regions, and grid stability. Deployment decisions should be application-driven, rather than solely focused on electricity generation.

3.7

Summing Up

This chapter highlighted how SMR development globally is progressing across different technologies, maturity levels, fuel strategies, and applications. The analysis shows that SMRs are being positioned as flexible nuclear systems, with near-term designs supporting electricity generation and advanced concepts enabling industrial heat, hydrogen production, and integrated energy systems.[61] International experience underscores the importance of aligning technology choices with regulatory readiness and application needs, offering relevant context for India as it evaluates the role of SMRs in its future energy strategy.

4

Chapter

India’s Challenges in Moving Forward

"A much more vigorous and sustained public outreach programme is necessary to dispel fears and highlight nuclear power as a safe and clean energy source."

-Dr Jitendra Singh, Union Minister of State, Department of Atomic Energy

4.1

Introduction

The trajectory of expanded nuclear deployment is determined by both technology availability and the institutional, regulatory, financial, and implementation conditions governing project planning and execution. While India's recent policy reforms have addressed several long-standing constraints, the transition from a state-led nuclear programme to a more diversified deployment model remains complex.[62] This is particularly relevant for small and advanced modular reactors (SMRs/AMRs), whose deployment depends on coordination across multiple institutional, regulatory, financial, and industrial dimensions.

The challenges that India is facing at this stage are therefore multifaceted. They span across policy implementation, regulatory adaptation, siting practices, financing mechanisms, supply-chain preparedness, fuel-cycle planning, and safety oversight. Many of these systems were designed for large, centrally executed projects and continue to influence how new reactor technologies are assessed and deployed. This chapter examines these cross-cutting challenges and their implications for India's ability to translate nuclear ambitions into timely and scalable outcomes.

4.2

Policy and Legislative Framework

Until recently, India's civil nuclear sector was governed by a legal framework designed for a fully state-led programme. Restrictions under the Atomic Energy Act limited ownership and operation of nuclear power plants to public sector entities, while the liability framework created high and uncertain risks for suppliers.[63] This structure ensured strong state control and safety oversight but constrained private investment, limited technology partnerships, and restricted the pace and scale of nuclear capacity addition.[64] It became imperative to address these limitations as India began exploring modular and advanced reactor technologies that rely on standardization, repeat deployment, and diversified applications.

The passing of the Sustainable Harnessing and Advancement of Nuclear Energy for Transforming India Act, 2025 (SHANTI) Act by the Parliament, provides a major attempt to address these structural limitations. The Act seeks to open non-strategic segments of the nuclear value chain to private participation, reform the liability regime to reduce supplier-side risk and create a unified legal framework governing the civil nuclear lifecycle. By enabling private firms to participate in reactor manufacturing, construction, financing, and selected operational roles, the Act aims to mobilize capital, strengthen domestic manufacturing, and support the deployment of SMRs and AMRs at scale.[65] In this sense, the SHANTI Act marks a clear shift from a purely state-executed model towards a more collaborative public–private approach to nuclear development.

Together, these changes mark a significant shift in India's nuclear policy framework, redefining the roles of the state and private actors in future nuclear development.

4.3

The SHANTI Act: Scope and Key Provisions

The following figure, showcases the legislative architecture of the SHANTI Act, 2025:

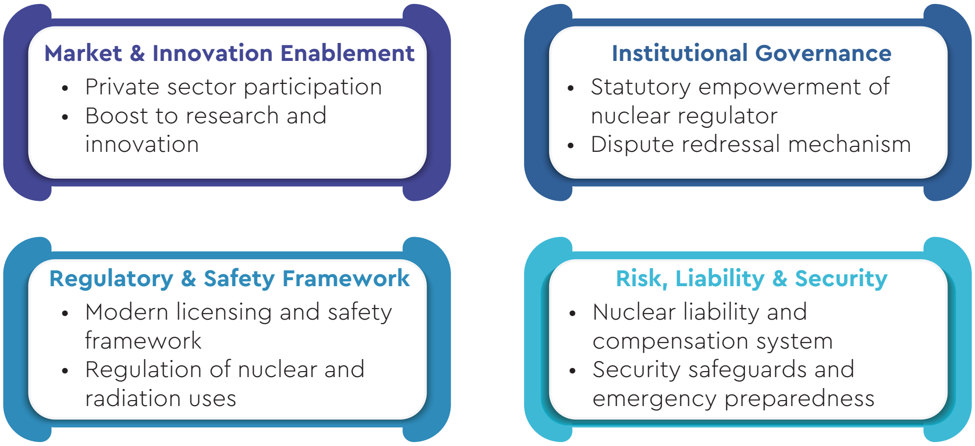


Fig 4.1: The SHANTI Act

The SHANTI Act, enacted in 2025, introduces a consolidated legal framework for India's civil nuclear sector at a stage when the country is seeking both capacity expansion and diversification of deployment models.[66] By replacing earlier legislation with a single statute, the Bill brings together provisions related to ownership, liability, regulation, safety, and lifecycle responsibilities under one framework. This consolidation reduces fragmentation across laws and formally links nuclear activities from project approval to decommissioning.[67] Figure 4.1 groups the major provisions of the SHANTI Act into four functional reform domains.

A central element of the Act is the expansion of private sector participation in India's nuclear power programme. While public and private companies such as BHEL and L&T and others have historically been involved in manufacturing, supply chain, and construction activities under the the Atomic Energy Act, 1962. The new framework marks a significant shift by enabling licensed private entities to participate more directly in the development, including build-own-operate and decommissioning of nuclear power plants, subject to regulatory oversight. The provision is particularly relevant for SMRs and AMRs, which broadly rely on standardized designs and modular manufacturing.

At the same time, the Act adopts a selective approach to liberalization. Activities considered strategically sensitive such as uranium enrichment (beyond the threshold notified by the Government), spent fuel reprocessing, and the management and accounting of nuclear materials remain under government control. Even where facilities are privately operated, material accounting, safeguards, and inspections continue to be exercised by the state. This separation ensures that private participation does not dilute India's non-proliferation commitments or strategic oversight.

The SHANTI Act also restructures the nuclear liability framework. Liability for nuclear damage is primarily assigned to the operator, with graded liability caps linked to reactor size and risk profile. Supplier liability will be governed by the contract as entered between operator and supplier. The government assumes responsibility for compensation beyond statutory limits. In parallel, the Act requires licensed operators to make financial provisions for decommissioning and site restoration, ensuring that end-of-life obligations are accounted for at the project approval stage rather than deferred to the future. Together, these provisions clarify risk allocation across the project's lifecycle.

Another important feature of the Act is the statutory recognition of the nuclear safety regulator. Legal backing clarifies the regulator's authority over licensing, inspections, enforcement, and emergency preparedness across a broader set of operators and reactor technologies. The Act also reinforces coordination requirements between operators, local authorities, and central agencies for emergency response, regardless of whether the operator is public or private.

It further provides a specialized adjudicatory mechanism to address disputes related to nuclear liability, compensation, licensing conditions, and contractual matters. By separating nuclear disputes from general courts, the framework recognizes the technical and safety-sensitive nature of nuclear activities and aims to provide faster and more specialized resolutions.

Table 4.1: Summary of of key policy shifts introduced by the SHANTI Act and their implications for nuclear deployment

Policy Area	Pre-SHANTI Framework	SHANTI Act Provision
Ownership and participation	State-only ownership	Private participation in non-strategic activities
Liability regime	Supplier liability, high uncertainty	Operator-led liability with graded caps
Regulatory authority	Non-statutory regulator	Statutory safety regulator
Legal structure	Multiple overlapping laws	Unified nuclear statute
Strategic control	State control	State control retained with some relaxation

Taken together, these provisions indicate that the SHANTI Act functions as an umbrella of legislation. It enables private participation and new deployment models while retaining strong state control over safety, safeguards, and strategic functions. The framework does not prescribe specific reactor technologies or project structures, but it establishes the legal conditions under which diversified nuclear deployment including SMRs can proceed.

While the SHANTI Act addresses several long-standing legal constraints, the effectiveness of this framework will depend on how its provisions are implemented through subordinate rules, regulatory practice, and supporting policy measures. The following section examines the challenges associated with translating this legal framework into operational nuclear projects.

Key Takeaways from the SHANTI Act

- Consolidates civil nuclear governance under a single statute
- Enables private participation in non-strategic nuclear activities
- Retains state control over fuel-cycle and nuclear material management
- Clarifies liability allocation and introduces graded liability caps
- Mandates financial provision for decommissioning and site restoration
- Grants statutory authority to the nuclear safety regulator
- Establishes a specialized mechanism for nuclear dispute resolution

4.4

Gaps and Outstanding Issues in the SHANTI Act

The SHANTI Act removes several long-standing legal constraints on nuclear deployment and provides a clearer statutory basis for private participation. However, the transition from legal reform to on-ground deployment continues to depend on a range of institutional, regulatory, financial, and social factors that are not fully addressed within the Act itself.[68] The legislation establishes eligibility and broad conditions for participation, while operational aspects such as licensing procedures, compliance requirements, ownership structures, and project responsibilities are to be specified through subordinate rules and administrative instruments. As a result, early-stage projects remain dependent on the timing and clarity of follow-on regulations.[69]

At the same time, the revised liability framework alters risk allocation without resolving all aspects of project bankability. While operator liability caps and the removal of supplier liability improve predictability for investors, responsibility for damages beyond statutory limits rests with the state. This approach is consistent with international nuclear practice, but it places long-term fiscal exposure outside the scope of the Act. In the absence of complementary insurance mechanisms, risk-pooling arrangements, or dedicated public support instruments, legal clarity alone may not be sufficient to enable financial closure for early projects, particularly for first-of-a-kind reactors.[70]

Institutional capacity also becomes a determining factor as participation broadens. The statutory recognition of the nuclear safety regulator strengthens its legal authority, but the expansion of deployment models, reactor designs, and operators increases the scale and complexity of regulatory oversight. Existing approval and inspection systems were developed for a limited number of large, centrally executed reactors and have not yet been adapted to address modular construction, factory fabrication, or repeat deployment. Without parallel adjustments in regulatory processes and staffing, approval timelines may remain long even where legal permission exists.[71]

It further does not directly address siting and land-use practices, which continue to be governed by existing environmental and safety frameworks. Existing siting and clearance frameworks were developed for large nuclear reactors located in remote or coastal areas. These frameworks remain in place for new reactor types, including SMRs, and have implications for land acquisition, local consultation, and approval timelines. As nuclear deployment expands beyond traditional sites and potentially into industrial or brownfield locations, the absence of adapted siting approaches and structured local engagement mechanisms may continue to affect project timelines.

Fuel-cycle coordination and backend planning also remain outside the scope of the Act. While the Act retains state control over enrichment (beyond the threshold notified), reprocessing, and nuclear material accounting, it does not specify how fuel supply, transport, and waste management will be coordinated for a wider range of reactor technologies. Differences in fuel requirements and waste profiles across SMRs and advanced reactors introduce additional coordination requirements that will need to be addressed through institutional arrangements rather than legislation alone.[72]

Finally, the pace of deployment will be shaped by technology readiness and global experience. Most SMR designs remain at early stages of commercial operation worldwide, with limited operating data. While the SHANTI Act provides legal coverage for advanced and modular reactors, deployment outcomes will depend on demonstration projects, supply-chain development, and regulatory learning over time. In this context, the Act establishes necessary legal conditions, but it does not by itself determine the speed or scale of nuclear expansion.

Taken together, these issues indicate that the SHANTI Act addresses questions of legal permissibility and institutional authority, while leaving key aspects of execution to subsequent policy, regulatory, and programmatic action. Closing these gaps will be central to translating legislative reform into sustained and scalable nuclear deployment.

Key Challenges Not Addressed Under the SHANTI Act

- Does not specify standard ownership or operating models for projects involving private participation
- Leaves licensing procedures, compliance requirements, and project structuring to subordinate rules
- Does not reform existing siting, land acquisition, or environmental clearance frameworks
- Does not address financing instruments such as long-term offtake mechanisms or credit support for early projects
- Does not outline mechanisms for scaling regulatory capacity alongside expanded private participation
- Does not provide guidance on fuel supply coordination and backend management for diverse reactor technologies
- Does not specify approaches for public engagement, transparency, or local benefit-sharing as deployment expands
- Does not address technology demonstration or risk-sharing mechanisms for first-of-a-kind SMR projects

4.5

Recommendation

4.5.1

Clarify Ownership and Operating Models for Private Participation

The Act should be supplemented with clearly defined ownership and operating frameworks for projects involving private entities. Standardized models such as public–private partnerships (PPP), government-owned–contractor-operated (GOCO), or joint venture structures may be notified upfront. Clear delineation of roles between NPCIL, private developers, and equipment suppliers will reduce contractual ambiguity and improve investor confidence.

4.5.2

Develop a National Framework for Fuel Supply and Backend Management

The Act should be complemented by a national framework that clearly assigns responsibility for fuel supply coordination, spent fuel management, and waste disposal. Given the diversity of reactor

designs anticipated under SMR deployment, centrally backed management under public oversight would ensure safety, consistency, and long-term accountability.

4.5.3

Adapt the regulatory framework to SMR-specific deployment models

India should develop SMR-specific licensing pathways that recognize modular construction, factory fabrication, standardized designs, and repeat deployment. Introducing staged approvals (design certification, site approval, and module deployment) can significantly shorten approval timelines while maintaining safety oversight.

4.5.4

Develop SMR-appropriate siting and land-use guidelines

As SMRs are expected to be deployed in industrial zones, brownfield sites, or captive-use locations, siting guidelines should be updated to reflect their smaller footprint and enhanced safety features.

4.5.5

Define standard project structures within the SHANTI framework

Although SHANTI permits private participation, it does not define how projects should be structured. The government should notify standard project archetypes (for example, NPCIL-led with private EPC, joint ventures, captive industrial SMRs under public oversight). This would reduce transaction costs and avoid ad-hoc project structuring.

4.6

Summing Up

India's recent legislative reforms have altered the legal conditions under which nuclear power projects can be developed, particularly by enabling private participation and diversified deployment models. At the same time, the analysis in this chapter shows that legal change alone does not resolve the operational challenges associated with nuclear deployment. Issues related to regulatory adaptation, siting practices, financing structures, supply-chain readiness, fuel-cycle coordination, and safety oversight continue to shape the pace and feasibility of new projects, including SMRs and AMRs. Addressing these challenges requires alignment between legislation, regulatory practice, institutional capacity, and project execution frameworks. The chapter therefore examined how other nuclear programmes have approached similar challenges, providing international reference points relevant to India's next phase of nuclear development.

5

Chapter

International Experience in Addressing Nuclear Deployment Challenges

5.1

Introduction

The challenges identified in India's nuclear programme are not unique. Countries with established nuclear sectors are facing similar issues as they prepare for small modular reactor and other advanced reactor (SMR/AMR) technologies. While large-scale commercial deployment of SMRs remains limited, many governments and regulators have begun adjusting policy frameworks, regulatory systems, and institutional arrangements in anticipation of future deployment. These adjustments are taking place alongside broader goals related to energy security, decarbonization, and industrial competitiveness.

International experience shows that enabling modular nuclear technologies requires changes beyond reactor design. Regulatory institutions are being strengthened to assess new technologies, licensing processes are being adapted for standardized designs, and financing and siting frameworks are being revised to manage early-stage risks. At the same time, countries are maintaining strong safety oversight and state control over sensitive aspects of the nuclear fuel cycle.

This chapter reviews how other major countries planning to deploy SMR respond to these challenges. It focuses on regulatory adaptation, licensing approaches, public–private roles, safety and waste governance, and the integration of SMRs into national energy strategies. These experiences provide reference points for understanding how nuclear systems are being prepared for modular and advanced reactors, without assuming large-scale deployment at this stage.

5.2

Reforming Regulatory Institutions

As countries prepare modular and advanced reactors, regulatory institutions are being reformed to handle a wider range of designs, deployment models, and operating contexts. As new reactor designs are being considered, regulatory institutions in several countries have focused on strengthening internal capacity and engaging earlier with developers.

In the United States, the **Nuclear Regulatory Commission** has retained institutional independence while expanding tools for early engagement with new reactor designs. Pre-application discussions and design certification pathways allow technical issues to be addressed before formal licensing begins. This approach reflects a shift towards front-loading regulatory scrutiny rather than concentrating it at the construction stage.[73]

Canada has adopted a similar preparation-focused approach through the **Canadian Nuclear Safety Commission**. Its vendor design review process allows reactor developers to engage with the regulator well before a site or project proponent is identified. While this review does not constitute approval, it helps identify safety and licensing issues early, reducing uncertainty for future projects.[74]

France has pursued institutional consolidation by bringing nuclear safety and radiation protection functions under a single authority, the **Autorité de sûreté nucléaire et de radioprotection**. This restructuring is intended to streamline oversight across the reactor lifecycle and improve coordination as new reactor types are introduced, while maintaining continuity with established safety practices.[75]

China and Russia operate within more centralized nuclear systems, where regulatory bodies are closely aligned with state-led deployment strategies. China's **National Nuclear Safety Administration**

has expanded its capacity to review multiple reactor designs in parallel, reflecting the country's focus on standardized designs and reference units. Regulatory approval is closely linked to state planning and industrial policy, allowing faster progression once a design is validated.[76,77]

Across these jurisdictions, a common pattern is visible. Regulatory reform has focused less on relaxing safety requirements and more on improving readiness for new technologies. This includes earlier engagement with designers, clearer separation of regulatory and promotional roles, and institutional strengthening to manage a broader and more complex project pipeline. These changes provide important context for understanding how nuclear governance systems are being prepared for modular reactors, even where large-scale deployment has yet to occur.

5.3

Licensing Approaches for Modular Technologies

Several nuclear jurisdictions have adjusted licensing processes to allow design-level review and project approval to proceed in defined stages. These approaches differ in how design assessment, site authorization, and repeat deployment are handled within existing regulatory systems. Table 5.1 summarizes key features of licensing practices across selected countries.

Table 5.1: Licensing approaches for modular and advanced reactors

Jurisdiction	Licensing Entry Point	Design-level Review	Site-level Approval	Treatment of Repeat Units
United States	Pre-application stage	Formal design certification	Separate site licence	Reduced review scope
Canada	Vendor-led pre-project review	Vendor design review (non-binding)	Project-specific license	Design familiarity reduces review burden
France	Project licensing stage	Integrated within project review	Combined process	Case-by-case assessment
Russia	State programme approval	Centralized design validation	State-coordinated siting	Streamlined approval
China	Reference project approval	Full design approval upfront	Linked to national planning	Accelerated licensing

5.4

Public–Private Participation in Nuclear Deployment

As countries prepare for modular and advanced reactors, public–private participation in nuclear deployment is being shaped by existing governance structures rather than by a single preferred model. Approaches differ across jurisdictions depending on electricity market design, state capacity, and the degree of strategic control retained over nuclear activities. Table 5.2 summarizes how selected country's structure public and private roles across the nuclear value chain.

Table 5.2: Public–private participation models in nuclear deployment

Country	Ownership and Control	Role of Private Sector	State Role
United States	Predominantly private	Design, construction, financing, operation	Regulation, safety oversight, limited risk backstop
Canada	Mixed (provincial utilities and private firms)	Design development, EPC, project financing	Regulation, waste management, early-stage support
France	Predominantly state-owned	Manufacturing, engineering, construction	Ownership, operation, planning, regulation
Russia	Fully state-led	Suppliers and subcontractors	Ownership, operation, fuel services, exports
China	State ownership with commercial operation	Manufacturing, construction at scale	Strategic planning, siting, fuel-cycle control

5.5

Safety, Waste Management, and Long-term Risk Governance

Across all nuclear jurisdictions, safety and long-term risk management continue to be treated as core public responsibilities, independent of reactor size, ownership structure, or deployment model. As countries prepare for modular and advanced reactors, existing safety principles are largely being extended to new technologies rather than redesigned. This reflects a broad consensus that changes in reactor scale or configuration do not reduce the need for rigorous oversight across the full nuclear lifecycle.

Independent regulatory authorities remain central to this framework. Even in systems that allow significant private participation, safety regulation, licensing, inspections, and enforcement functions remain institutionally separated from operators and vendors. This separation ensures that commercial considerations do not influence safety decisions and that regulatory authority remains consistent across different reactor types and operators.

Waste management and backend responsibilities are similarly anchored in long-term public institutions. In most countries, spent fuel storage, waste disposal, and long-term stewardship are handled through national arrangements rather than project-specific solutions. Operators are typically required to contribute financially through levies, dedicated funds, or escrow mechanisms, but responsibility for long-term custody rests with the state. This approach reflects the extended time horizons involved and the need for continuity beyond the operating life of individual facilities.

As advanced and modular reactor designs are considered, backend planning is increasingly treated as an integral part of national nuclear strategy rather than an isolated technical issue. Countries pursuing closed or partially closed fuel cycles link reactor development with parallel investments in reprocessing, storage, and waste infrastructure. This alignment helps prevent downstream bottlenecks and ensures that fuel-cycle decisions evolve alongside reactor deployment.

A further common feature across jurisdictions is the requirement for early financial provisioning for decommissioning and site restoration. By requiring operators to account for end-of-life obligations at the licensing stage, regulators reduce uncertainty around future liabilities and prevent the deferral of long-term responsibilities. This becomes particularly important in modular deployment contexts, where multiple units may be introduced over time and across different locations.

Overall, international experience shows that preparation for SMRs and advanced reactors has reinforced the role of safety, waste management, and long-term risk governance institutions rather than weakening them. While ownership models and deployment strategies vary, the underlying approach to risk remains conservative, lifecycle-based, and firmly embedded within public oversight frameworks.

Key International Takeaways Relevant for India

- Countries preparing for modular and advanced reactors have prioritized regulatory readiness before deployment (for example, early SMR licensing pathways in the United States and Canada).
- Safety oversight and long-term risk governance remain public responsibilities across systems with varying ownership models (including state-led programmes such as France and Russia).
- Licensing frameworks are increasingly structured around early design review and staged approvals rather than project-by-project negotiation (as seen in Canada and China).
- Public–private participation reflects national market structures rather than a uniform global model, ranging from market-oriented systems (United States) to state-coordinated industrial approaches (China).
- Backend planning, including waste management and decommissioning, is treated as a national responsibility independent of reactor type or ownership (for example, national disposal programmes in France and Finland).

5.6

Recommendations

5.6.1

Strengthen regulatory preparedness before deployment

India should focus on putting regulatory systems in place well before the large-scale deployment of SMRs and other advanced reactors begins. This includes early dialogue between developers and regulators, advance design reviews, and clear technology-specific guidance. International experience from countries such as the United States and Canada shows that early preparedness helps avoid delays and confusion at later stages.

5.6.2

Keep safety and long-term risk governance firmly under public control

Regardless of how much private participation is allowed, responsibility for nuclear safety and long-term risk management must remain with public institutions. Experiences from both market-based and state-led systems, including France and Russia, show that strong public oversight is essential for maintaining safety, accountability, and public confidence.

5.6.3

Adopt staged and design-focused licensing approaches

India would benefit from moving away from project-by-project licensing towards a phased approval process based on early design assessment. Such an approach allows regulators to build familiarity with reactor technologies, improves consistency in decision-making, and supports smoother replication once a design is approved, as seen in countries like Canada and China.

5.6.4

Design public–private participation in line with India's market structure

There is no single global model for private participation in nuclear power. India should adopt an approach that reflects its own institutional strengths and industrial priorities. A balanced model, where the public sector retains ownership and oversight while the private sector contributes to manufacturing, construction, and project execution, would align well with India's policy and market realities.

5.6.5

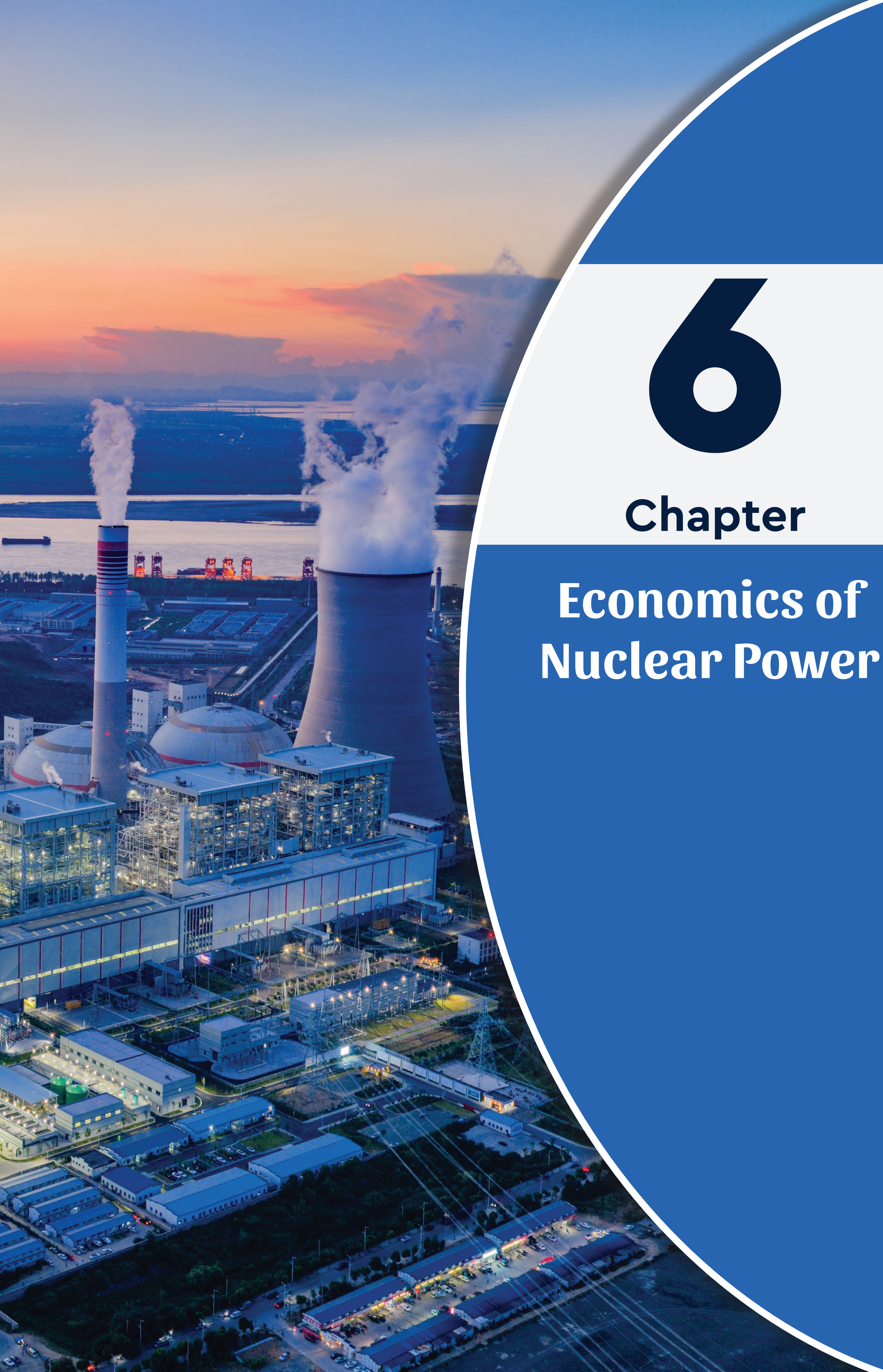
Treat backend management as a national responsibility

Issues such as spent fuel management, radioactive waste disposal, and decommissioning should be handled through a centralized national framework, independent of reactor size or ownership. International practices in countries such as France and Finland demonstrate that treating backend management as a public responsibility helps ensure long-term safety and builds public trust.

5.7

Conclusion

For India, these experiences provide useful reference points at a time when recent legal reforms have created space for more diversified nuclear deployment. The challenge now lies in translating enabling legislation into effective regulatory practice, financing structures, siting approaches, and implementation frameworks suited to modular technologies. The next chapter builds on these international lessons to evaluate how India can operationalize its nuclear reforms and chart a coherent pathway for SMR deployment within its domestic institutional context.



6

Chapter

Economics of Nuclear Power

The economics of nuclear power are fundamentally shaped by a structural characteristic that distinguishes it from most other electricity generation technologies: a high upfront capital requirement combined with relatively low and stable operating costs. This structure implies that the overall cost of nuclear power is less dependent on fuel price dynamics and more sensitive to financing conditions, construction timelines, and capital intensity. Consequently, understanding nuclear economics requires a shift from conventional cost comparisons to an analysis of cost drivers and their interactions over time.

In the Indian context, the overnight capital cost of a typical PHWR is estimated at approximately ₹12–14 crore per MW.[79] Given construction timelines of approximately five years and financing structures characterized by a 70:30 debt-equity ratio with a cost of debt of around 12%, interest during construction (IDC) significantly increases the effective capital cost.[79] When IDC, escalation, and contingency provisions are incorporated, the total cost rises to approximately ₹20–25 crore per MW, implying an increase of nearly 60–70% over the base cost.

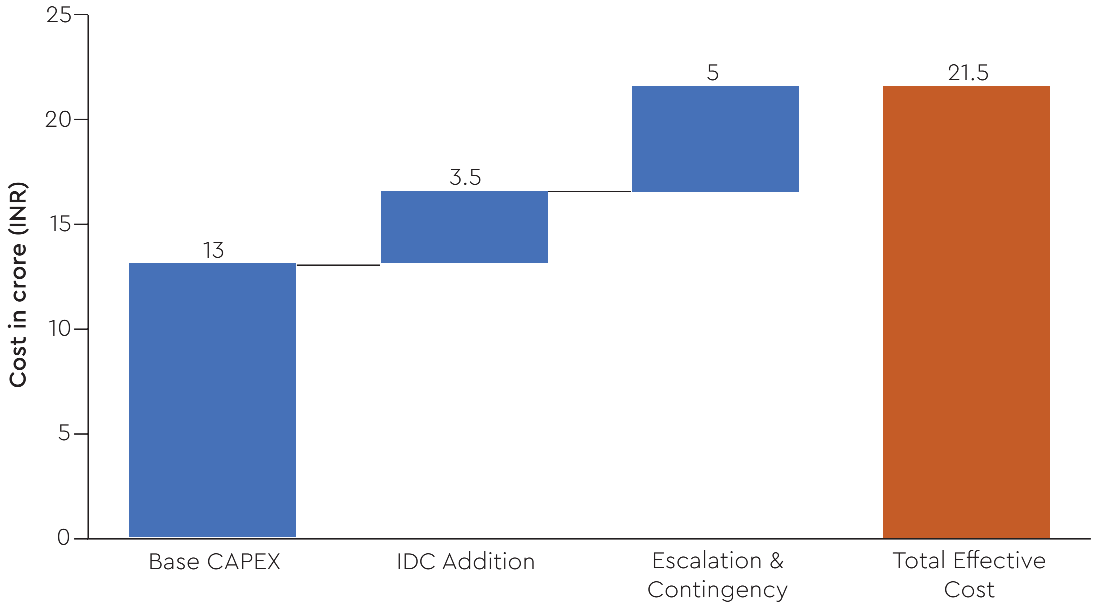


Fig 6.1: Cost per MW capital cost of Nuclear in India.

While capital costs dominate the initial investment phase, the cost dynamics shift once the plant becomes operational. Operation and maintenance (O&M) costs, though subject to inflation, remain relatively predictable. In India, O&M costs have increased from approximately ₹47.47 lakh per MW per year in 2017–18 to around ₹80.2 lakh per MW per year by 2026–27, reflecting an annual escalation rate of about 6%. Over the lifecycle of a nuclear plant, typically spanning 40 years with possible expendable up to 60 years, such increases remain manageable and do not introduce the level of volatility observed in fuel-dependent generation systems.

The combined effect of capital, O&M, and fuel costs is captured through the Levelized Cost of Electricity (LCOE), which provides a comprehensive measure of lifetime generation cost. However, nuclear LCOE exhibits substantial variation across countries and project types. Rather than being random, this variation reflects underlying differences in capital costs, project execution, and financing conditions.[79]

This relationship is illustrated in Figure 6.2, which plots capital cost against LCOE for a range of nuclear projects across countries. It highlights that India's nuclear power has one of the lowest generation costs globally at around $47.64/MWh, second only to Russia. In comparison, nuclear power costs in countries such as China, France, and the USA range between $66–71/MWh. This demonstrates the cost competitiveness of India's indigenous nuclear program, driven by standardized reactor designs, domestic manufacturing capabilities, and accumulated operational experience.

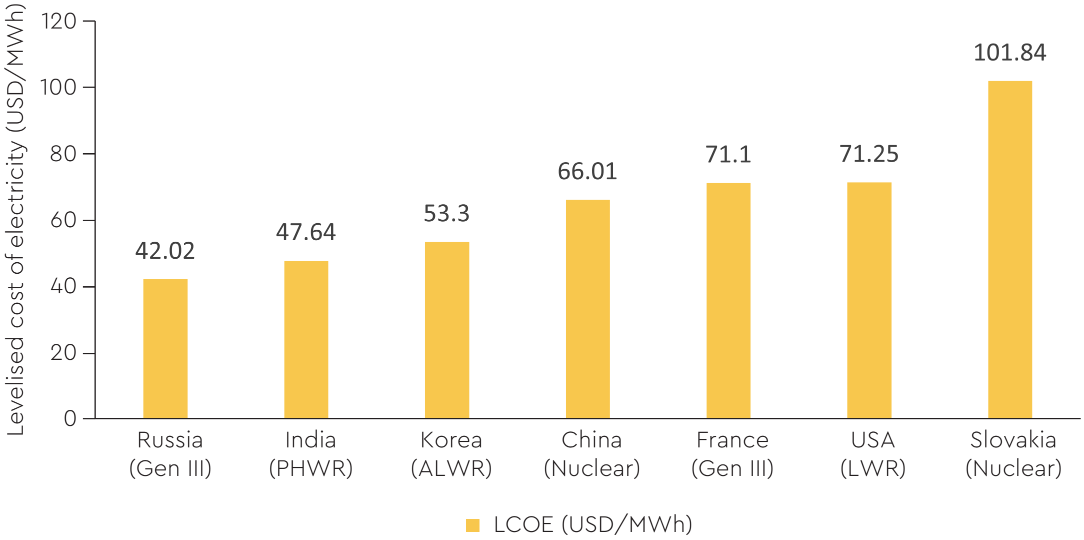


Fig 6.2: Indicative cost comparison of nuclear generation

(Source: NEA,PRIS)

The broader economic implications of nuclear power become more evident when considered in the context of India's long-term energy strategy. As India plans to achieve 100 GW of nuclear by 2047, the total investment required for this expansion is estimated at approximately ₹ 22–25 lakh crore, corresponding to a capital intensity of around ₹22–25 crore per MW.

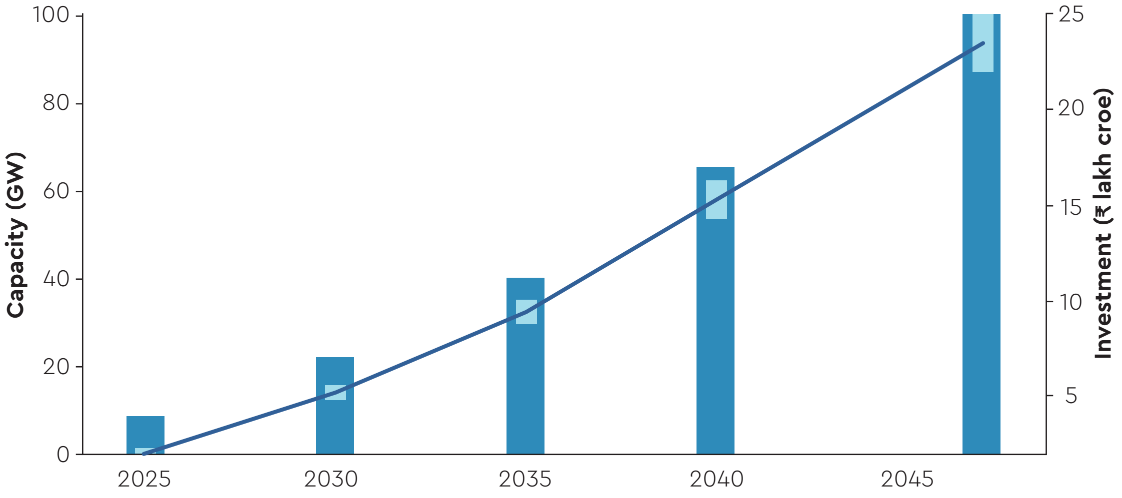


Fig 6.3: Nuclear capacity planed & investment required over the years (TERI Compilation and analysis)

As illustrated in Figure 6.3, achieving 100 GW of nuclear capacity by 2047 requires a significant acceleration in capacity addition where the scale and pace of expansion required become critical. From the current installed base of approximately 8.8 GW, and with projects under construction expected to raise capacity to around 22 GW by 2030–32, the remaining expansion implies an average annual addition of about 4.5 GW thereafter. The intermediate capacity levels for 2035 and 2040, as reflected in the analysis, represent indicative milestones necessary to maintain a consistent growth trajectory aligned with the 2047 target.

This expansion is expected to be driven largely by India's established reactor technologies, with nearly 80% of capacity coming from conventional systems such as 700 MW PHWRs and 500 MW FBRs. The remaining 20% may be met through emerging technologies such as SMRs, including BSRs, which offer greater flexibility in deployment and potential for cost optimization over time.

From an investment perspective, the required capital outlay scales proportionally with capacity addition. Based on an assumed capital intensity of ₹22–25 crore per MW and typical capacity utilization factors, the total investment requirement to reach 100 GW is estimated at approximately ₹23–25 lakh crore. The projected investment trajectory reflects a gradual but significant increase over time, with cumulative investment rising in line with capacity additions. This translates into an average annual investment requirement of approximately ₹1.0–1.2 lakh crore over the expansion horizon. Taken together, the analysis highlights that while the technical pathway to scale nuclear capacity is well-defined, the economic feasibility will depend critically on sustaining high levels of capital deployment, ensuring cost discipline, and maintaining a steady project execution pipeline.

The preceding analysis establishes that nuclear power economics are shaped primarily by capital intensity, financing conditions, and project execution timelines. While India's indigenous nuclear programme has demonstrated strong cost competitiveness, scaling installed capacity to 100 GW by 2047 requires sustained capital mobilisation on the order of ₹23–25 lakh crore. At this level of deployment, the binding constraint shifts from engineering feasibility to how nuclear projects are institutionally structured, financed, owned, and operated. Unlike most other power-generation technologies, nuclear power embeds safety accountability, regulatory compliance, fuel-cycle responsibility, and long-term stewardship within the owner–operator entity.

Business models determine how risks are allocated among stakeholders, how capital is raised, and how returns are realized. In the context of nuclear power, where upfront costs are high, gestation periods are long, and regulatory oversight is stringent, the design of these models plays a decisive role in enabling or constraining capacity addition.

Existing Nuclear Business Model in India

India followed a state-owned and state-operated nuclear power model, anchored in the Atomic Energy Act, 1962, which restricted nuclear power generation to government-owned entities, with the NPCIL acting as the principal developer, owner, and operator of commercial nuclear power plants under the administrative control of the DAE, with major project risks including financing and construction largely absorbed by the government.

Recognising the balance-sheet limitations of a single utility, India has begun adopting public-sector joint venture (JV) models. A notable example is ASHVINI, a joint venture between NPCIL (51%) and NTPC Ltd. (49%), authorised by the Government of India to build, own, and operate nuclear power plants under the Atomic Energy Act. The transfer of the 4 × 700 MW Mahi Banswara Rajasthan Atomic Power Project to ASHVINI reflects an intentional move toward pooling financial strength and

project-execution capability across public-sector entities while retaining full government ownership and operational control. Going forward, the SHANTI Act, which opens the door for private sector participation, will necessitate the development of new financing and deployment models for nuclear power in India.

Relevant Global Nuclear Business Model: Ownership and Control Perspective

International experience shows that nuclear capacity has been scaled successfully under a limited set of ownership- and operator-centric models. The United States represents a contrasting model in which commercial nuclear plants are predominantly owned and operated by private utilities, subject to rigorous licensing and safety regulation by the Nuclear Regulatory Commission (NRC). Most U.S. nuclear reactors are owned by private or investor-owned utilities, although the federal government exercises extensive oversight over plant licensing, safety standards, and decommissioning obligations. This model demonstrates the feasibility of private ownership in nuclear power but also highlights the high institutional and regulatory maturity required to sustain such an approach.

Implications for India's Nuclear Expansion Strategy

1. Private Sector's Role as a Capital Provider: The core opportunity for private sector participation lies in decoupling capital provision from operational control. Private involvement may, in the initial business model, be structured primarily as a financial role, focused on long-term investment rather than plant ownership in the operational sense, while retaining flexibility for future participation in ownership and operations.

2. Use of Project Specific SPVs for Capital Pooling: Project specific special purpose vehicles (SPVs) offer a practical mechanism to induct private capital while preserving operator accountability. Under this structure, NPCIL or a public sector joint venture would remain the licensed owner and operator, with private investors participating as minority equity holders or long term debt providers. SPVs allow ringfencing of project risks, improve transparency in financial structuring, and facilitate capital allocation across multiple projects. However, their effectiveness depends critically on revenue certainty and a stable, predictable regulatory framework.

7

Chapter

Human Resource Development and Public Outreach

7.1
Introduction

The recent legislative reforms in December 2025 signal a major transformation: for the first time, the Indian civil nuclear sector is opening to private participation under the Sustainable Harnessing and Advancement of Nuclear Energy for Transforming India (SHANTI) Bill, 2025. This pivotal shift, set to accelerate capacity growth towards the 100-GW target by 2047, also places new emphasis on workforce expansion, multi-stakeholder engagement, and a more intensive strategic public outreach.

The nuclear power sector requires a wide spectrum of skilled and semi-skilled human resources across the entire project lifecycle. This includes manpower for plant design and engineering, procurement and supply-chain management, civil and electrical construction, commissioning, operations and maintenance, radiological surveillance, decommissioning, and radioactive waste management. In addition, specialized expertise is required in nuclear regulation, safety oversight, quality assurance, inspections, specialized logistics, heavy transportation, and precision erection activities.

Equally important is the need for professionals skilled in public communication, stakeholder engagement, and risk communication to address public perception, enhance transparency, and build social acceptance of nuclear projects. With the entry of the private sector, additional demand will arise for project managers, commercial and contract management professionals, financial and risk analysts, supply-chain managers, and corporate leadership roles to ensure efficient delivery, regulatory compliance, and long-term operational sustainability.

This chapter reviews the current human resource landscape of India's nuclear sector, identifies workforce requirements projected up to 2047, and assesses training and capacity-building needs, including the role of the Homi Bhabha National Institute (HBNI) and related initiatives. It also examines the status of public outreach in India's nuclear programme, highlighting recent efforts and emerging approaches aimed at strengthening public awareness, trust, and stakeholder engagement as the sector expands. It also reports some of the public outreach in few other countries.

7.2
Human Resource Development

7.2.1
Historical evolution of nuclear human resources in India

The establishment of the BARC Training School in 1957 became the foundation of a model, functioning as an intensive "finishing school" for engineering and science graduates entering the nuclear stream. Over the decades, this system produced a cohesive cadre of more than 11,000 specialists who now form the leadership backbone across BARC, NPCIL, IGCAR, and other DAE institutions.

7.2.2
Current employment statistics and demographics

The Indian nuclear workforce is primarily concentrated within the public sector. The workforce can be broadly categorized into three segments:

1. Research and development (R&D) and scientific core: Personnel engaged in research, reactor design, and fuel cycle development [BARC, IGCAR, Raja Ramanna Centre for Advanced Technology (RRCAT)].
2. Industrial and operational workforce: Personnel involved in power plant operation, mining, and heavy water production (NPCIL, Uranium Corporation of India Limited (UCIL), Heavy Water Board (HWB), Indian Rare Earths Limited (IREL), Electronics Corporation of India Limited (ECIL), Nuclear Fuel Complex (NFC).
3. Construction and project management: A largely deployment-phase specific workforce managed by contractors but overseen by NPCIL/DAE. Table 7.1 gives the distribution of workforce in public sector units.

Table 7. 1: Nuclear workforce in key public sector units (as of 2025)

Organization	Primary Function	Employee Strength (Approx.)
BARC[80]	R&D, reactor design	15,000
NPCIL[81]	Nuclear power generation	10,576
UCIL[82]	Uranium mining	4,500
HWB[83]	Heavy water production	3,200
IREL[84]	Rare earths/thorium mining	2,800
Total	-	36,076

7.2.3

Workforce projections

The Central Electricity Authority (CEA) and the DAE have outlined a roadmap to reach 100 GW by 2047. This target is driven by the "Viksit Bharat" vision and requires adding over 91 GW of capacity in roughly 22 years. Such a rapid expansion fundamentally alters the scale and composition of human resource requirements across the nuclear value chain. While the existing manpower training ecosystem has successfully supported the current fleet, the projected build-out necessitates a forward-looking assessment of workforce needs, skills mix, and institutional capacity.

Estimates of workforce requirements for India's planned expansion to 100 GW of nuclear capacity by 2047 vary across studies due to differences in scope, methodology, and treatment of peak versus average demand.

When these perspectives are considered together, a consistent range of workforce requirements emerges. During the design and engineering phase, peak manpower needs are relatively modest, in the range of 4,000–6,000 personnel, reflecting the specialized but limited scale of upstream activities. The construction phase is the most labour intensive, with peak workforce requirements ranging from 120,000 to 200,000 workers,[85] depending on the degree of project concurrency, EPC contracting models, and localization of manufacturing and construction activities. In the operation phase, staffing requirements stabilize but remain substantial, with an estimated range of 38,000–60,000 personnel, encompassing not only core plant operators but also maintenance, radiation protection, quality assurance, safety oversight, and auxiliary support functions.

These ranges reconcile both programme-level and phase-wise assessments and provide a pragmatic planning envelope for India's nuclear expansion. They underscore the need for early and sustained scaling of training capacity, contractor mobilization, and institutional strengthening to ensure that workforce availability does not become a binding constraint on the timely deployment of nuclear capacity.

7.2.4

Evolving competencies: defining the next-generation nuclear workforce

Skills for Advanced Technologies: Future roles will demand digital and AI proficiency, supply chain for reactor components, and SMR-specific manufacturing skills—areas currently underrepresented in traditional nuclear training. Further, it should be realized that the expansion into SMRs and will demand a new type of professional:

- Private sector readiness: Unlike DAE scientists protected by sovereign immunity and government service rules, private sector nuclear engineers will face commercial pressures. Training must imbue them with a safety culture that can withstand commercial incentives to cut corners.
- Digital and AI literacy: Future reactors will be digitally controlled and may need predictive maintenance. The current curriculum, heavy on reactor physics, needs to integrate data science and cybersecurity.
- Supply chain expertise: As India localizes the manufacturing of pressure vessels and steam generators for the 100 GW fleet, the supply chain (L&T, Godrej, BHEL, Walchand Nagar Industries Limited etc.) will need thousands of nuclear-qualified welders and non-destructive testing (NDT) inspectors. Training arrangements for the external industrial workforce are currently not institutionalized within a single, formal mechanism.

Beyond technical and industrial manpower, the success of India's nuclear expansion to 100 GW will also depend on the availability of human resources capable of engaging effectively with society at large. As the programme scales and private sector participation increases, the workforce must extend beyond engineers, technicians, and operators to include professionals skilled in public communication, risk communication, stakeholder engagement, and community relations. Building and sustaining public trust—particularly in regions hosting nuclear facilities—will require dedicated capacities to communicate safety, environmental performance, and local benefits in a transparent and credible manner. The recommendations for quickly increase the capacity building in the nuclear given in the subsequent section.

7.2.5

Recommendations

a) Transition from a centralized to a networked training architecture

With the entry of private players and the scale-up to a 100 GW nuclear programme, India's workforce development system must transition from a predominantly centralized, DAE-anchored model to a networked, multi-institution training ecosystem. In this structure, DAE institutions would continue to play a critical role in setting technical standards, embedding nuclear safety culture, and overseeing accreditation, while training capacity is expanded through parallel nodes in public sector utilities,

joint-venture partners, and industry-linked institutions. Leveraging the existing training infrastructure of large power and infrastructure organizations can rapidly scale volumes without compromising quality, provided these institutions operate under structured mentorship and curriculum oversight from DAE. Such a federated approach enables faster capacity creation, reduces pressure on a single training pipeline, and mirrors successful skilling models adopted in other strategic energy sectors. This shift is essential to scale training volumes rapidly without diluting quality and mirrors the institutional transition successfully undertaken in the renewable energy sector.

b) Embed nuclear orientation across career stages

Future nuclear workforce requirements will span multiple entry points, not only fresh graduates, but also mid-career professionals transitioning from thermal power, infrastructure, heavy engineering, and manufacturing sectors. Training systems must therefore shift from a one-time induction model to a career-stage-based framework, offering modular orientation, certification, and re-skilling programmes tailored to entry-level, mid-career, and senior management roles, with a strong emphasis on nuclear safety culture and regulatory compliance.

c) Establish a unified accreditation and quality assurance backbone

As training delivery diversifies, maintaining uniform standards becomes critical. A national accreditation framework, jointly stewarded by sectoral authorities, should define minimum requirements for curricula, faculty qualifications, infrastructure, and assessment methods across all nuclear training providers. Such a framework would enable planned expansion of training capacity while ensuring that personnel entering nuclear projects, whether from public or private entities, meet consistent safety, quality, and competency benchmarks.

d) Mass skilling for technicians through a "Nuclear Mitra" model

The most significant manpower gap will arise in construction, fabrication, welding, NDT, and quality inspection. Here, India can directly replicate the solar sector's success by launching a "Nuclear Mitra"–type programme, focused on:

- Training-of-trainers (ToT) models
- Specialized ITIs and polytechnics for high-precision trades
- On-the-job training linked to live nuclear projects
- Standardized certification for welders, fitters, electricians, and inspectors
- One or two specialized nuclear ITIs could act as national centres of excellence, supplying skilled manpower.

e) Strengthening inspection and quality assurance capacity

As localization of nuclear manufacturing expands, the availability of qualified inspectors will be a critical bottleneck. Capacity can be rapidly scaled by expanding domestic certification programmes through AERB, NPTI, and specialized organizations (for example, NDT and QA bodies), complemented by international collaboration and professional societies [Indian Nuclear Society (INS), Indian Association for Radiation Protection (IARP)]. This mirrors global best practice and ensures quality assurance keeps pace with manufacturing growth.

f) Talent attraction through scholarships and structured career pathways

Finally, attracting top-tier talent will require targeted interventions, including early identification of high-performing engineering students, structured internships, and scholarship-cum-bond programmes that combine financial support, advanced education, and assured employment. Similar mechanisms have proven effective in other strategic sectors and will be essential to position nuclear energy as a competitive and prestigious career option.

Workforce planning for the nuclear sector must be viewed not only as a technical and industrial challenge but also as a social one, directly linking human-resource development with structured public outreach and engagement mechanisms, which are discussed in the following subsection.

7.3

Public Outreach

The expansion of nuclear power in India is inextricably linked to public perception. The post-Fukushima era saw significant protests in locations like Kudankulam (Tamil Nadu) and Jaitapur (Maharashtra), driven by safety fears and land acquisition grievances.In response, the DAE and NPCIL have overhauled their public outreach strategy, moving from a "decide and announce", model to one of "engage and explain".

7.3.1

India's initiatives over the years

In 2025, India's nuclear public outreach is characterized by a "hyper-local" strategy that blends large-scale digital campaigns with deep community involvement. Key successful programmes include:

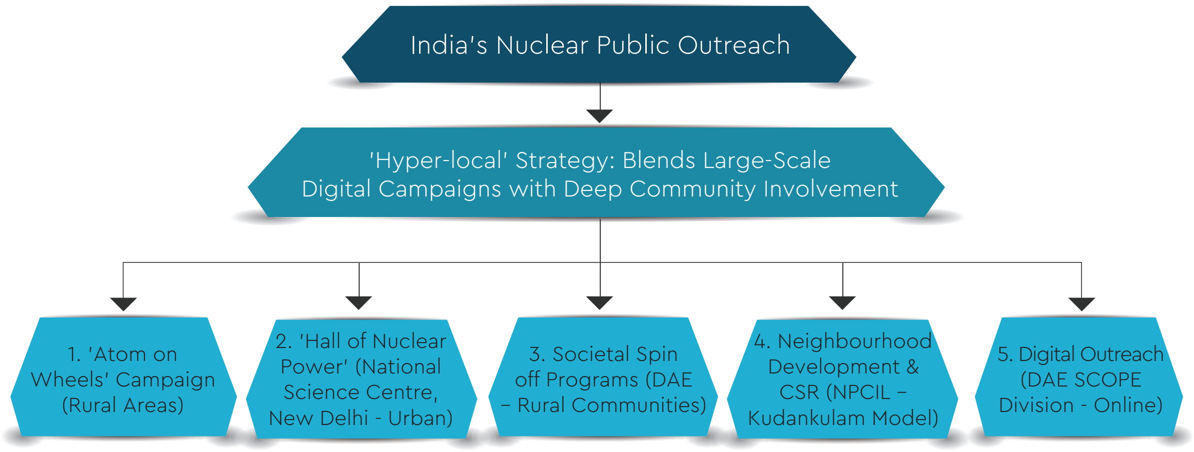


Fig 7. 1: India's nuclear public outreach

1. The "Atom on Wheels" Campaign

This award-winning mobile exhibition is one of India's most successful outreach tools for rural areas.

- **Method:** Specially designed buses travel through thousands of villages, using multi-lingual multimedia presentations, models, and interactive panels to demystify nuclear technology.
- **Impact:** The first phase successfully reached over 6 lakh (600,000) people across six states (Haryana, Rajasthan, Madhya Pradesh, Gujarat, Maharashtra, and Andhra Pradesh). In 2024–25, it expanded to cover 250 additional villages surrounding the upcoming Mahi Banswara project in Rajasthan.

2. The "Hall of Nuclear Power" (National Science Centre)

A flagship urban outreach project, this modernized gallery in New Delhi reopened in 2025 with advanced features:

- **Technology**: It utilizes 3D walkthroughs, augmented reality, and 56 interactive exhibits to explain nuclear reactor safety and power generation to the youth and urban public.
- **Success metric:** It serves as a central hub for educational trips, directly engaging thousands of students annually to build long-term public trust.

3. Societal spinoff programmes (AKRUTI and DTRI)

The Department of Atomic Energy (DAE) uses non-power applications to demonstrate the tangible benefits of nuclear science to rural communities.

- **DTRI (DAE Technologies for Rural India):** This programme provides forums at the grassroots level to showcase nuclear "spinoffs", such as radiation-mutated high-yield seeds and water purification systems.
- **AKRUTI:** Empowers rural entrepreneurs by transferring BARC-developed technologies (like Nisargruna biogas plants) to villages, showing that "nuclear" also means improved agriculture and waste management.

4. Neighbourhood development and CSR (Kudankulam Model)

After facing intense protests in 2011, the Nuclear Power Corporation of India Limited (NPCIL) implemented a massive "neighbourhood development" strategy that has since become a blueprint for new sites.

- **Infrastructure:** NPCIL invested over ₹131 crore in 2023–24 alone for local development, including building schools, handing over ambulances to primary health centres and organizing free medical camps.
- **Direct engagement:** Regular "Site Visits" for local leaders *(Sarpanches)* and teachers allow them to see safety measures firsthand, significantly reducing local opposition at brownfield sites.

5. Digital outreach (SCOPE Division)

The DAE's Science Communication, Outreach, and Public Engagement (SCOPE) Division has successfully modernized India's nuclear narrative online.

- **Engagement:** Using social media (X, Instagram), they run campaigns like #NuclearEnergyFacts to counter misinformation in real-time.
- **Visual Storytelling:** The publication of high-quality "coffee table books" (for example, Our Flying Guests) documents the thriving biodiversity around nuclear plants, proving they are environmentally benign.

7.3.2

Global Practices: Some Highlights

Globally, different nations have adopted diverse strategies to bridge the gap between technical complexity and public perception, ranging from consent-based siting models to dedicated educational outreach for youth. Table 7.2 provides a comparative overview of international best practices in public outreach and stakeholder engagement, highlighting how countries like the USA, UK, France, Finland, China, and Russia navigate the social and regulatory challenges of the nuclear sector.

Table 7. 2: Global public outreach/stakeholder engagement practice

S. No.	Countries	Public Outreach / Stakeholder Engagement Practice	What They Do?
1.	Finland	Leadership Commitment and "Making a Difference" Model[86]	In Finland, leadership commitment is treated as a cornerstone of the nuclear industry's success and is viewed as the foundation that supports long-term operations. The sector benefits from high public trust in technical institutions and experts, but this trust can sometimes reduce open debate and make it harder to fully understand underlying public attitudes. Dialogue and two-way communication are considered essential, with honesty, openness, and a willingness to acknowledge mistakes emphasized as core principles. Industry representatives note that transparency is already embedded in practice, and ongoing dialogue is supported through easy access to nuclear professionals. Measuring impact is also valued, with organizations using surveys and polls to assess whether engagement efforts are making a meaningful difference. A May 2025[1] survey by Energy Industry Finland reported 68% support, driven largely by perceptions of low emissions and strengthened energy security. These findings are broadly consistent with earlier surveys, including a December 2022 Kantar Public study that recorded 60% support. Nuclear power already plays a major role in Finland's energy mix, supplying around 40% of national electricity in 2024, underscoring its established presence and contribution to the country's energy system.
2.	USA	Consent-based Siting for Nuclear Waste[87]	The US Department of Energy (DOE) uses a consent-based siting process to engage communities for siting spent nuclear fuel storage facilities. It funds consortia to conduct inclusive community dialogues, hundreds of public engagements, tribal engagements, educational resources, and government interactions to gather feedback and inform communities before any siting decisions are made. Public input shapes the process and equity concerns are embedded in planning.
		Community Outreach by GAIN (Advanced Nuclear)[88]	GAIN's community outreach programme engages "nuclear-curious" communities through workshops, webinars, presentations, and pilot studies to educate and gather feedback on advanced nuclear technologies and community impacts.

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[1] Helsinki Times. 2025, May 3. Finnish public support for nuclear power reaches record high. Details available at <https://www.helsinkitimes.fi/finland/finland-news/domestic/26734-finnish-public-support-for-nuclear-power-reaches-recordhigh.html>

S. No.	Countries	Public Outreach / Stakeholder Engagement Practice	What They Do?
3.	United Kingdom (UK)	Environmental Permit Public Consultation (Sizewell C)[89]	The UK Environment Agency publishes a formal consultation and engagement plan for environmental permits related to Sizewell C. It describes how they: (a) notify public via GOV.UK, libraries, local points, and e-bulletins; (b) attend stakeholder meetings, NGO forums, online events; (c) allow online comments via Citizen Space; (d) publish responses and summaries showing how stakeholder input shapes decisions.
		Continuous Local Community Forums[90]	Sizewell C maintains community newsletters, a local Information Office, public drop-in events, and forums where people can ask questions and receive updates on ongoing construction, jobs, and mitigation efforts. These activities aim to build trust and transparency near the host community.
4.	France	Public Debate on Radioactive Waste Management (PNGMDR)[91]	France's National Commission for Public Debate (CNDP) organizes formal public debates on national nuclear plans — for example, the PNGMDR public debate held across multiple regions with in-person debates and remote participation. The debate runs for months, involves public meetings and town halls, and is mandated by law to inform all actors and the general public.
		ASN and Public Consultations on Nuclear Safety[92]	France's nuclear safety regulator ASN conducts public consultations on draft safety resolutions and manages participatory platforms where citizens submit questions, opinions and stakeholder presentations on radioactive waste and safety issues.
5.	China	International Nuclear Safety Cooperation and Transparency[93]	China's Nuclear Safety White Paper emphasizes international exchanges and cooperation on nuclear safety policy, regulatory communication and peer reviews, promoting transparency and regulatory dialogues with international partners (US, Russia, Japan, OECD/NEA). This supports China's communication of safety standards and public trust building.

S. No.	Countries	Public Outreach / Stakeholder Engagement Practice	What They Do?
6.	Russia	Rosatom Public Education and Youth Engagement[94]	Russia's Rosatom runs a network of Information Centres for Atomic Energy that host educational outreach for students and the public, including international quizzes and projects aimed at popularizing nuclear science and raising awareness of peaceful applications of nuclear technology. Large outreach events attract hundreds of thousands of participants to build long-term public understanding.

7.4

Recommendations

As India scales up nuclear deployment, public outreach must move from ad-hoc awareness drives to a structured, evidence-based strategy that builds long-term trust and social legitimacy. Experience across countries shows that public acceptance grows not merely from technical assurances of safety, but from credible institutions, continuous dialogue, and visible local benefits. Lessons synthesized from international experience offer several actionable pathways for India.

1. Anchor communication in trust, transparency, and honesty

The international review highlights that public communication around nuclear energy often over-emphasizes technology and under-addresses social concerns such as health, environment, and economic well-being. Successful outreach emphasizes integrity, competence, and benevolence as the foundation of trust, alongside open acknowledgement of uncertainties and mistakes when they occur.

For India, this implies moving beyond "assurance-based messaging" towards transparent conversations that explain both benefits and risks, describe how risks are managed, and invite scrutiny rather than resist it. Public communication should assume that nuclear technology is perceived as inherently risky and explain how that risk is mitigated in practice, rather than insisting on absolute notions of safety.

2. Shift from one-way information to structured dialogue

The report stresses that unidirectional public relations have limited impact. Smaller, discussion-based forums, where residents can ask questions freely and interact with experts, are far more effective than large lecture-style events—especially in communities that may be skeptical or anxious.

India can institutionalize local liaison groups, citizen advisory panels, and sustained town-hall style engagements around every new site. These should operate not just during project approval phases but throughout construction, operation, and decommissioning, allowing communities to see continuity and accountability in engagement.

3. Integrate schools, universities, and local institutions

International experience repeatedly emphasizes the role of education systems in normalizing nuclear literacy. In countries such as the United States, children are taught about radioactivity, emergency preparedness, and the role of nuclear power in everyday life.

A similar strategy in India could include:

- curriculum modules on radiation, energy choices, and emergency planning;
- partnerships between plant operators and nearby universities; and
- exposure visits, science clubs, and internships for local students.

Such initiatives build familiarity, demystify technology, and create future local champions, aligning closely with India's broader skill-development priorities.

4. Make-benefits visible at the local level

The international analysis shows that communities most accepting of nuclear facilities tend to experience tangible economic and social benefits—including jobs, business development, education funding, and municipal infrastructure improvements.

Indian nuclear projects already implement corporate social responsibility programmes, but these can be better aligned with local development priorities and explicitly communicated as long-term social partnerships rather than project-linked obligations. Consistent frameworks for benefit-sharing can help communities perceive nuclear plants as engines of regional prosperity, not just industrial assets.

5. Strengthen credibility of regulators and risk communication

The document notes that building confidence requires clear accountability, depoliticized messaging, and frequent, open communication between regulators, local governments, and citizens.

For India, this means expanding the public-facing role of safety authorities, publishing accessible risk assessments, and participating visibly in dialogue processes. Communicating how regulatory decisions are made, and where they err on the side of caution, can significantly reduce perceptions of secrecy and distance.

6. Institutionalize outreach through national frameworks

Several countries now rely on codified engagement charters and toolkits that set standards for openness, responsiveness, and participation. The report underscores the value of consistent, nation-wide engagement principles to avoid fragmented communication and uneven expectations across regions.

India could adapt a similar approach, for example, developing a national nuclear public engagement framework that defines roles, processes, disclosure norms, and grievance mechanisms across government, industry, and private developers.

7. Establish a dedicated nuclear public outreach fund

To support the scale-up of nuclear power to 100 GW and facilitate private sector participation, it is recommended that a dedicated nuclear public outreach fund be created as a distinct budgetary and programmatic instrument. Public outreach in the nuclear sector cannot rely solely on project-level or operator-led communication; instead, it requires systematic, continuous, and diversified engagement across regions and stakeholder groups. A ring-fenced fund would enable sustained outreach activities independent of individual project timelines and would signal long-term institutional commitment to transparency and public trust.

Drawing lessons from the renewable energy sector particularly solar India has successfully deployed multiple, decentralized outreach and capacity-building programmes through schemes such as Surya Mitra, state-level skilling missions, industry associations, academic partnerships, and civil society engagement. In the solar sector, training and public awareness are not confined to a single institution; instead, multiple accredited entities implement programmes under common guidelines, supported by public funding and monitored for outcomes. This pluralistic model has enabled rapid scale-up, geographic reach, and tailored messaging for different audiences.

A similar approach should be adopted for nuclear public outreach. Under the proposed fund, NGOs, universities, research institutes, professional societies, and specialized communication organizations should be invited to participate through transparent selection processes based on demonstrated expertise, training capability, and credibility. These entities could design and deliver region-specific outreach programmes, including community dialogues, school and college engagement, media briefings, digital communication campaigns, and independent safety awareness initiatives, all aligned with nationally defined communication standards.

Establishing a dedicated outreach fund and a multi-institution delivery model will be critical to ensuring that public engagement keeps pace with the technical and institutional expansion of India's nuclear power programme.

8. Strengthening human resources through public outreach and capacity building in the nuclear sector

To strengthen human resource development, a dedicated website should be established to support public communication and outreach by presenting evidence-based information on the myths and realities of nuclear energy, disseminated through multiple media channels. The platform should also host regular (weekly) newsletters highlighting developments in the nuclear sector.

In parallel, there is an urgent need to develop structured training and teaching materials for institutions outside DAE/NPCIL, given the limited availability of India-specific textbooks on nuclear technologies. Despite operational experience with PWRs, PHWRs, and FBRs, comprehensive open literature remains absent. Retired DAE/NPCIL professionals, in collaboration with HBNI, should be engaged to develop standardized educational resources, as no secrecy constraints apply.

7.5

Conclusion

Developing a future-ready workforce is the foundation for the next stage of India's nuclear energy growth. As the sector opens to private companies and introduces new technologies, the traditional way of training personnel must evolve. Beyond scientific roles, there is an increasing need for skilled professionals in construction, quality control, and project management. As the industry expands, maintaining a strict safety culture will remain the most important priority for all stakeholders involved.

Furthermore, the long-term success of India's nuclear plans relies as much on public trust as it does on technical expertise. Outreach efforts are now moving towards a model where local communities are more involved, and their concerns are addressed directly. By focusing on transparent communication and local benefits, the sector can gain the social support needed to expand. Together, a skilled workforce and a clear plan for public engagement are the two pillars that will ensure India's nuclear expansion is both successful and sustainable.


Policy

8

Chapter

Policy Recommendations

To achieve the national target of **100 GW by 2047**, India must transition from a project-centric nuclear model to a programmatic, ecosystem-wide approach. The following recommendations provide a roadmap for balancing technological innovation with regulatory rigour and social acceptance.

8.1

Adopt a Dual-track Technology Strategy

India's nuclear roadmap should explicitly integrate large-scale reactors and small modular reactors (SMRs) as complementary rather than competing technologies.

Large-scale units must remain the backbone of base-load power generation for grid stability.

SMRs should be strategically deployed for niche applications, including the decarbonization of hard-to-abate heavy industries (for example, steel and cement) and captive power/heat for industrial clusters.

8.2

Modernize Regulatory and Licensing Frameworks

To support the rapid deployment of modular technologies, the AERB should evolve towards a phased, design-based licensing system.

- **Shift from project-specific to design-certified approvals**, allowing for repeat licensing of identical SMR units to reduce timelines.
- **Streamline safety assessments** to reflect the inherent safety features of advanced reactors, ensuring that high safety standards do not become a bottleneck for deployment.

8.3

Operationalize the SHANTI Act Through Institutional Reform

The **SHANTI Act** represents a milestone in governance. Success now depends on the clarity of subordinate rules and inter-ministerial coordination.

- **Clarify private participation models:** Define the roles of private developers in "Build-Own-Operate" models and provide transparency on liability limits.
- **Establish a single-window interface:** Create a coordinated regulatory interface between the DAE, Ministry of Power, and Ministry of Environment, Forest and Climate Change to eliminate delays in project approval process during early project stages.

8.4

Invest in Human Resource and Skill Diversification

Scaling to 100 GW requires a workforce capable of managing next-generation digital controls and modular construction techniques.

- **Launch dedicated training programmes:** Collaborate with academic institutions to create specialized curricula for nuclear reactor operation and maintenance, advanced materials science, and digital twinning.
- **Diversify skillsets:** Focus on cross-disciplinary training that merges nuclear engineering with digital project management and international safety regulation.

8.5

Establish a National Framework for Fuel and Waste Management

As the reactor fleet becomes more diverse, a unified national framework is essential for the entire fuel cycle.

- **Centralized planning:** Ensure long-term accountability for spent fuel management and radioactive waste disposal across both conventional and modular sites.
- **Fuel security:** Strengthen domestic exploration and international fuel supply agreements to ensure uninterrupted operation of the expanding fleet.

8.6

Prioritize Demonstration Projects and "Learning-by-doing"

The government should lead the way by financing **SMR pilot projects** at brownfield or retired thermal power plant sites.

- **Validation of costs:** Use these pilots to establish realistic construction timelines and O&M costs under Indian conditions.
- **Risk mitigation:** Early deployments will serve as "regulatory sandboxes", allowing the AERB to refine safety protocols based on real-world operational data.

8.7

Institutionalize Public Engagement and Transparency

A "Social Licence to Operate" is critical as nuclear projects move closer to industrial hubs and smaller towns. To accelerate nuclear deployment a dedicated yearly budget for public outreach should be created to support:

- **Stakeholder consultation:** Develop structured mechanisms for early community engagement and transparent communication regarding safety.
- **Benefit sharing:** Link nuclear projects to local community development, ensuring that residents see direct benefits in terms of infrastructure, employment, and energy access.

9

Chapter

Conclusion and Way Forward

While the target of 500 GW of non-fossil capacity by 2030 establishes immediate momentum, the path to Net-Zero by 2070 requires a paradigm shift in how we view baseload power. As solar and wind capacity expands, the grid's need for firm, dispatchable, and clean energy becomes non-negotiable. This report establishes that nuclear energy specifically through a hybrid fleet of large reactors (PHWRs) and SMRs & FBRs is the only viable solution to anchor this future grid.

Achieving the vision of 100 GW of nuclear capacity by 2047 is not merely a technical challenge; it is a test of institutional agility. It requires moving from a government-led, closed-cycle approach to a collaborative, public-private ecosystem underpinned by robust legislative reforms.

9.1

Synthesis of Strategic Pillars

The analysis in the preceding chapters identifies four critical pillars necessary to unlock this growth:

- **Legislative Clarity (Chapter 4):** The current atomic energy laws were designed for an era of state monopoly. Enacting the **SHANTI Bill** is the prerequisite for clarifying liability, defining private sector roles, and streamlining licensing for SMRs.
- **Financial Innovation (Chapter 6):** Nuclear power is highly capital intensive, and achieving India's 100 GW target will require innovative financing structures. Nuclear must be included in India's green taxonomy to unlock global ESG capital flows. In parallel, project-specific SPV models led by NPCIL should be institutionalised to enable private sector participation as capital providers while retaining public control over operations. Additionally, risk-sharing mechanisms, including sovereign support and assured tariff frameworks, are essential to mitigate construction and financing risks and crowd in long-term private investment.
- **Technology Leadership (Chapters 2 and 3):** A dual-track strategy is essential accelerating the deployment of indigenous PHWRs while simultaneously securing technology transfers for SMRs to address hard-to-abate industrial sectors.
- **Human Capital and Public Perception (Chapter 7):** Infrastructure alone cannot generate power. A dedicated "National Nuclear Workforce Initiative" is urgently needed to train the scientists, operators, and regulators who will manage this expanded fleet. Equally critical is the "social license" to operate. To achieve this, the government must institute a dedicated multi-year public outreach fund. This scheme should operate through competitive annual disbursements to academic institutions and civil society organizations, empowering them to lead sustained, science-based dialogue and dismantle long-standing perception barriers regarding nuclear safety.

9.2

Implementation Roadmap to 2047

To operationalize these recommendations, this report proposes a phased implementation roadmap. This trajectory moves beyond simple capacity addition; it targets the structural transformation of India's nuclear ecosystem.

The roadmap envisions three distinct phases of evolution: 1) foundation and reform, 2) acceleration and deployment, and 3) diversification and leadership.

Phase I: Foundation and Reform (2025–30)

The immediate priority is to consolidate ongoing indigenous projects, such as the fast breeder reactor (PFBR), while simultaneously laying the groundwork for private sector entry through the enactment of the SHANTI Act. However, regulatory reform alone is insufficient; this phase must aggressively target the "soft infrastructure" of nuclear energy. A dedicated national nuclear workforce initiative will be launched to train the specialized cadre needed for future SMR fleets, ensuring human capital is ready before steel is poured. Concurrently, the government must institutionalize a transparent, data-driven public outreach campaign, utilizing a dedicated 10-year fund to empower academic and civil society partners in dismantling long-standing myths about nuclear safety and securing the social license to operate.

Phase II: Acceleration and Deployment (2030–40)

This phase marks a decisive shift from bespoke, project-based construction to "Fleet Mode" manufacturing, characterized by the rapid serial production of indigenous PHWRs. Parallel to this, the first commercial fleets of SMRs will become operational, specifically targeting captive power requirements for hard-to-abate sectors like steel and cement. These deployments will be facilitated through novel hybrid asset management models, allowing private players to operate plants under NPCIL supervision. Beyond electricity, the nuclear ecosystem will mature to support non-electric applications, with pilot projects for desalination and district heating reaching commercial viability. Crucially, as nuclear footprints expand closer to communities and industrial hubs, the public perception initiatives launched in Phase I must be sustained and scaled; maintaining a regular dialogue is essential to secure the social acceptance required for this widespread integration.

Phase III: Diversification and Leadership (2040–47)

By 2040, the sector's focus shifts towards achieving total energy sovereignty through the realization of closed fuel cycles and advanced technological applications. This period will witness the large-scale deployment of Generation IV reactor systems alongside the progressive utilization of India's vast thorium reserves through advanced heavy water reactors (AHWRs). Beyond traditional power generation, the ecosystem will pivot towards deep industrial decarbonization, with SMRs integrated directly with electrolyzers for dedicated, low-cost green hydrogen production. Ultimately, nuclear energy will solidify its critical role as the primary load-following partner to renewables, anchoring the national grid against intermittency.

Phase I : 2025-2030

- Completion of ongoing PHWR/FBR projects
- Accelerated public outreach engagement through a dedicated yearly fund
- Update regulatory frameworks/policy for SMRs
- Nuclear transition for private & small reactors
- Initial fuel fabrication expansion
- Site selection/evaluation for SMR
- Partnership with key SMR designs the indigenisation of technology
- Pilot projects for heating applications, such as desalination, district cooling using BSR
- Private sector participation with constraints

Phase II : 2030-2040

- Serial PHWR/FBR Deployment
- Initial SMR commercialisation and fleet development
- Pilot projects for SMR-Based Desalination
- Heating applications reaching 400 MW are hard to abate
- Development of the thorium fuel cycle
- Private Sector Participation with Operations

Phase III : 2040-2047

- Large-scale capacity addition (Generation IV)
- SMR for Green Hydrogen Production and Hard-to-Abate Sectors
- Heating applications reaching 700 MW are hard to abate
- Deployment of thorium-based Advanced Heavy Water Reactors
- Integration with National Grid for Base load flexibility

Fig 9. 1: Strategic roadmap for 100 GW nuclear capacity by 2047

9.3

Conclusion

The journey to 2047 is about more than just electricity; it is about energy security and industrial competitiveness. By adopting the recommendations laid out in this report specifically the regulatory reforms of the SHANTI Act and the phased deployment strategy India can transform its nuclear sector from a niche contributor into the backbone of a decarbonized economy. The technology is mature, the demand is clear, and the geopolitical climate is favourable. The final variable is policy will. With the execution of this roadmap, India will not only meet its climate pledges but emerge as a global leader in the peaceful and productive use of nuclear energy.

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Annexure I

Nuclear History of India

India's civil nuclear programme has evolved through several distinct phases shaped by geopolitical developments, technological constraints, and changing national priorities. From its early emphasis on scientific self-reliance and strategic autonomy, the programme has gradually expanded to support energy security and climate objectives. The evolution of India's nuclear trajectory can broadly be understood through six phases detailed here.

Phase I: The Visionary Foundations (1940s–50s)

India's nuclear programme emerged in the immediate post-independence period, driven by a strong vision of scientific development and technological self-reliance. The Tata Institute of Fundamental Research (TIFR) was established in 1945 under the leadership of Dr Homi J Bhabha, laying the scientific foundation for nuclear research. Following independence, the Atomic Energy Commission (AEC) was created in 1948 to guide India's nuclear policy and research activities.

In 1954, the Department of Atomic Energy (DAE) was established under the direct authority of the Prime Minister, consolidating nuclear research and development efforts under a central institutional framework. During the same period, Dr Bhabha articulated the Three-stage Nuclear Power Programme, a long-term strategy designed to utilize India's limited uranium reserves while leveraging its vast thorium resources. The Programme envisaged a phased transition from natural uranium-fuelled reactors to fast breeder reactors and eventually thorium-based systems.

Unlike many nuclear programmes during the early Cold War period—where nuclear development was closely tied to military objectives following the Manhattan Project—India emphasized peaceful applications of atomic energy. As a leading member of the Non-Aligned Movement, India sought to develop nuclear technology primarily for electricity generation, scientific advancement, and national development.

Phase II: Strategic Reorientation (1960s)

During the 1960s, India's nuclear programme began to evolve in response to changing regional security dynamics. In 1963, India entered into a civil nuclear cooperation agreement with the United States for the construction of the Tarapur Atomic Power Station (TAPS), which became the country's first nuclear power plant and began operations in 1969.

However, geopolitical developments significantly reshaped India's strategic outlook. The 1962 border conflict with China and China's nuclear weapons test in 1964 heightened security concerns in the region. These developments strengthened India's resolve to maintain strategic autonomy in nuclear policy.

In 1968, India declined to sign the Treaty on the Non-proliferation of Nuclear Weapons (NPT), arguing that the Treaty created a discriminatory global order by formally recognizing only a limited group of nuclear-weapon states while imposing restrictions on others. India maintained that it would pursue nuclear development while retaining the option of technological independence and strategic flexibility.

Phase III: Indigenous Development (1970s–80s)

A major turning point in India's nuclear trajectory occurred with the Pokhran-I nuclear test conducted in May 1974, which India described as a peaceful nuclear explosion. The test triggered significant international reactions and led to the formation of the Nuclear Suppliers Group (NSG), which imposed restrictions on nuclear trade with India.

As a result, India faced challenges in importing technologies and limited access to nuclear fuel and equipment from international markets. While these constraints slowed the expansion of nuclear power capacity, they also accelerated efforts towards technological self-reliance.

During this period, India developed significant indigenous capabilities across the nuclear fuel cycle, including heavy-water production, fuel fabrication, reactor design, and spent-fuel reprocessing. The pressurized heavy water reactor (PHWR) technology became the cornerstone of India's nuclear power programme, allowing reactors to operate on natural uranium and reducing dependence on imported enriched fuel.

Despite external constraints, India gradually expanded its nuclear infrastructure and strengthened domestic technological capabilities, laying the foundation for future nuclear growth.

Phase IV: Strategic Assertion and Nuclear Deterrence (1990s)

The end of the Cold War and evolving regional security dynamics shaped the next phase of India's nuclear policy. In May 1998, India conducted a series of nuclear tests at Pokhran (Pokhran-II), formally demonstrating its nuclear weapons capability.

Following these tests, India articulated a nuclear doctrine based on the principles of credible minimum deterrence and a No-first-Use (NFU) policy. This phase represented a strategic assertion of India's security interests while maintaining a clear distinction between its military nuclear posture and its civil nuclear energy programme.

Although the tests initially led to international sanctions, they also marked the consolidation of India's status as a nuclear-armed state while continuing to emphasize the peaceful development of nuclear energy.

Phase V: International Integration and Civil Nuclear Cooperation (2000s)

After decades of relative isolation from global nuclear commerce, India's nuclear programme entered a new phase of international engagement in the 2000s. The Indo-US Civil Nuclear Agreement concluded between 2005 and 2008 marked a major shift in global nuclear diplomacy.

The agreement was followed by a waiver from the Nuclear Suppliers Group in 2008, allowing India to participate in international nuclear trade despite not being a signatory to the NPT. This development enabled India to import nuclear fuel and technology and helped address long-standing fuel supply constraints that had limited the performance of several nuclear power plants.

At the same time, India preserved its strategic autonomy by keeping its indigenous three-stage nuclear programme outside international safeguards. This phase re-integrated India into global

nuclear commerce while supporting the expansion of nuclear power as part of the country's long-term energy strategy.

Phase VI: Nuclear Energy in the Era of Energy Transition (2020s–Present)

In recent years, India's nuclear policy has increasingly converged with broader goals related to climate change mitigation, energy security, and technological innovation. A major milestone was achieved in 2024 with the core loading of the prototype fast breeder reactor (PFBR) at Kalpakkam, marking a significant step toward the second stage of India's three-stage nuclear programme.

At the same time, global commitments to net-zero emissions have renewed interest in nuclear power as a reliable low-carbon energy source capable of complementing renewable energy. Recognizing this role, India has set an ambitious target of achieving 100 GW of nuclear power capacity by 2047.

Emerging technologies such as small modular reactors (SMRs) are expected to play an important role in expanding nuclear deployment by enabling flexible siting, modular construction, and applications beyond grid electricity, including industrial heat and hydrogen production.

In this phase, nuclear energy is increasingly viewed as a strategic component of India's clean energy transition, providing firm low-carbon power while strengthening long-term energy security.

Annexure II

a) Under Construction

Name	Cooling Method	Tharmal Capacity (MWth)	Electrical Capacity (MWe)	Reactor Type	Application Type	Country (Developer)	Developer(s)	Type of Developer	Cooling Capacity (Inlet Temperature °C)	Cooling Capacity (Outlet Tempreture °C)	Fuel Type
HTR-PM	Helium gas	250	210	Twin HTR	Civil	China	INET, CNEC and Huaneng, China	Public	250	750	TRISO
HTTR	Helium gas	30	0	HTGR	Civil	Japan	JAEA	Public	395	950	UO_2
EGP-6	Pressurized light water	62	11	LWGR	Remote	Russia	OKBM Afrikantov	Public	340	490	LEU
KLT-40S	Pressurized light water	150	35	PWR	Marine	Russia	OKBM Afrikantov (Rosatom)	Public	280	316	LEU
RITM-200	Pressurzed light water	198	50	Integral PWR	Marine	Russia	OKBM Afrikantov (Rosatom)	Public	284	321	LEU
CNP-300	Pressurized light water	999	325	PWR	Civil	Pakistan and China	SNERDI/ CNNC	Public	277.5	302	LEU
PHWR-220	Heavy water	755	236	PHWR	Civil	India	NPCIL	Public	249	293	Natural U

	Refuelling cycle	Deployment Mode	Grid Connection Year	Status	Operating Year (First)	Operation Year	Operation Site	Country Where Operation Started	Licensing Authority	Passive Safety Features	Load Following Capability	Target Market/Use case
	Online refueling/ 35 months	Land based	2021	Operating	2021	2021	Shidao Bay Nuclear Power Plant, Shandong	China	NNSA (China)	Yes	Yes	High temp. heat, hydrogen
	660 days	Land based		Operating	1998	2001	Oarai, Japan	Japan	Japan Automic Energy Authority	Yes	Yes	Remote areas and industrial applications
	1 year	Remote/ land	1970s	Operating	1973	1974	Bilibino Nuclear Power Plant, Chukotka	Russia	Rostechnadzor	No	No	Remote settlements (Arctic)
	30–36 months	Barge	2020	Operating	2019	2020	Akademik Lomonosov, Pevek, Chukotka	Russia	Rostechnadzor	Yes	Yes	Arctic, Remote deployment
	120 months	Ship based	2022	Operating	2021	2022	Arktika-class Icebreaker, Baltic	Russia	Rostechnadzor	Yes	Yes	Icebreakers, marine fleet
	18 months	Land based	2000s	Operating	1994	2000s	Chasma Nuclear Power Plant (Punjab)	Pakistan	NNSA (China)	Yes	Yes	Grid support, export
	24 months	Land based	1991	Operating	1985	1991	Kaiga Generating Station, Karnataka	India	AERB (India)	Yes	Partial	Base load power

b) Operational

Name	Tharmal Capacity (MWth)	Electrical Capacity (MWe)	Coolant Capacity (Inlet Temperature °C)	Coolant Capacity (Outlet Temperature °C)	Refuelling Interval	Moderature	Reactor Type	Application	Country (Developer)	Developer(s)
CAREM25	100	30	284	326	14 months	Light water	Integral PWR	Electricity generation	Argentina	CNEA and INVAP
ACP100/ Linglong One	385	125	286.5	319.5	24 months	Light water	Integral PWR	Electricity generation and process heat	China	CNNC
BREST-OD-300	700	300	420	535	36 – 78 months	Lead cooled	Liquid metal cooled fast reactor	Electricity generation and can be used for burning plutonium	Russia	RDIPE
KP-FHR	320	140	550	650	Online Refuelling	Graphite	HTGR	Electricity generation and process heat	US	Kairos
eVinci	15	5	N/A	N/A	8 months	Graphite	HTGR	electricity generation and process heat	US	Westinghouse Electric
Marvel	0.075–0.1	0.015-0.027	450	520	60 months	Hydrogen	Liquid metal cooled	Load-following electricity demand, process heat, hydrogen production, and water purificationand potentially for powering military installations	US	Idaho National Library

	Type of Developer	Coolant	Fuel Type	Deployment Mode	Status	Operating Year (Planned)	Operation Site	Country where operation will started	Licensing Authority	Passive Safety Features	Load Following Capability
	Public	Light water	UO_2	Land	Under construction	Expected 2028	Atucha Complex, Buenos Aires Province	Argentina	ARN (Argentina)	Yes	Yes
	Public	Light water	UO_2	Land	Under construction	Expected 2026–27	Changjiang NPP, Hainan Province	China	NNSA (China)	Yes	Yes
	Public	Lead	Mixed uranium plutonium nitride	Land	Under construction	Expected 2027	Siberian Chemical Combine, Seversk	Russia	Rostechnadzor	Yes	Expected
	Private	Molten fluoride salt	TRISO	Land	Under construction	Expected 2030	East Tennessee Technology Park, Oak Ridge, Tennessee	United States	NRC	Yes	Expected
	Private	Heat pipe	TRISO	Land	Under construction	Expected 2026	Idaho National Laboratory (for test reactor) and remote/ off-grid sites for deployment	United States	NRC	Yes	Yes
	Public	Sodium-potassium eutectic	HALEU	Land	Under construction	2025	Idaho	United States	NRC	Expected	Yes

C) Near-term adv deployment

Name	Thermal Capacity (MWth)	Electrical Capacity (MWe)	Cooling Capacity (Inlet Temperature °C)	Cooling Capacity (Outlet Temperature °C)	Refuelling Cycle (Months)	Reactors Type
NuScale Power Module	250	77	249	316	Nominal 18	Integral PWR
CNSP		300			12–24	PWR/HI-THERM HSP solar thermal system
BWRX-300	870	300	270	288	12–24	BWR
PRISM	840	311	360	485	18	Sodium FNR
Natrium	840	345	350	540	18–24	Sodium FNR
ARC-100	286	100	355	510	240	Sodium FNR
Hermes prototype	35	Non-electric		650	Online Refuelling	MSR-Triso
Xe-100	200	80	260	750	Online fuel loading	HTR
Xe-mobile		5	260	750	Online fuel loading	HTGR
NuScale Micro	250	77	249		21	PWR

	Application Type	Country (Developers)	Developer(s)	Type of Developer	Coolant	Moderators	Fuel Type
	Electricity generation, desalination, hydrogen, district heating	United States	NuScale Power + Fluor	Private	LW	LW	UO$_2$
	Electricity generation and Industrial heat	United States	Holtec	Private	LW+Solar thermal	LW	UO$_2$
	Electricity generation, process heat, hydrogen production, desalination, district heating	United States	GE Hitachi	Private	LW	LW	UO$_2$
	Electricity generation, plutonium disposition	United States	GE Hitachi	Private	Liquid sodium	N/A	MO$_x$ or metallic
	Electricity generation, thermal storage (flexible grid support)	United States	TerraPower + GE Hitachi	Private	Liquid sodium	N/A	HALEU
	Electricity generation, industrial heat	United States	ARC with GE Hitachi	Private	Liquid sodium	N/A	Metallic uranium alloy
	Test prototype (non-commercial) → future electricity/heat	United States	Kairos	Private	Fluoride salt	Graphite	TRISO
	Electricity generation, process heat, hydrogen	United States	X-energy	Private	Helium	Graphite	TRISO
	Electricity generation for defence & remote sites	United States	X-energy LLC	Private	Helium	Graphite	TRISO
	Microgrid electricity, remote/off-grid power	United States	NuScale Power	Public	LW	LW	Liquid uranium

d) Early stage

Name	Thermal Capacity (MWth)	Electrical Capacity (MWe)	Application Type	Coolant Capacity (Inlet Temperature °C)	Coolant Capacity (Outlet Temperature °C)	Fuel Type
EM2	500	265	Grid-capable electricity generation, industrial process heat	550	850	UC
FMR	100	44	Electricity generation	506	800	UO_2
VK-300	750	250	Cogeneration of electricity and heat for district heating and for seawater desalination		285	UO_2
AHWR-300	920	304	Electricity production	258.2	285	LEU
CAP200 or LandStar-V	660	200	Grid electricity, process heat, district heating	289	313	UO_2
SNP350	1035	350	Electricity generation, desalination, and district heating			LEU
ACPR100	450	140	Electricity generation, district heating, steam production, and seawater desalination	283	321	UO_2
IMR	1000	350	District heating, seawater desalination, process steam production, generate electricity	329	345	UO_2
Westinghouse SMR	800	225	Electricity, hydrogen production, desalination, district heating, grid stabilization	294	324	UO_2

	Refuelling Cycle (Months)	Coolant	Moderator	Reactors Type	Country	Developer	Type of Developer
	360	Helium	None	Gas-cooled fast reactor	United States	General Atomics	Private
	180	Helium	None	Gas-cooled fast reactor	United States	General Atomics + Framatome	Private
	18	Light water	Light water	BWR	Russia	NIKIET	Public
		Boiling light water	Heavy water	PHWR	India	BARC	Public
	20	Light water	Light water	PWR	China	SNERDI/SPIC	Public
	18–24	Light water		PWR	China	SNERDI	Public
	18	Light water	Light water	Integral PWR	China	CGN	Public
	26	Light water	Light water	Integral PWR	Japan	Mitsubishi Heavy Ind*	Private
	24	Light water	Light water	Integral PWR	United States	Westinghouse*	Private

Name	Thermal Capacity (MWth)	Electrical Capacity (MWe)	Application Type	Coolant Capacity (Inlet Temperature °C)	Coolant Capacity (Outlet Temperature °C)	Fuel Type	
mPower	500	195	Electricity production, retrofitted to support heat-requiring OR cogeneration	290.5	318.9	UO$_2$	
Rolls-Royce UK SMR	1358	470	Electricity generation, rapid deployment, potential industrial uses	295	322	UO	
PBMR	400	165	Electricity generation and cogeneration, industrial process	500	900	TRISO	
HTMR-100	100	35	Industrial process, heat or desalination, supplying electric power	250	750	TRISO	
MCFR		Large					
SVBR-100	280	100	Electricity generation	340	485	UO, MO$_x$	
Westinghouse LFR	950	450	Grid power, process heat	420	600	Oxide and nitride ceramic	
TMSR-SF	100	N/A	Generating grid electricity and enabling high-temp heat applications			TRISO With LEU	
PB-FHR	236	100	Electricity generation and high-grade industrial heat			TRISO	
Moltex SSR-U	40	150	Electricity and direct industrial heat		700	LEU	

	Refuelling Cycle (Months)	Coolant	Moderator	Reactors Type	Country	Developer	Type of Developer
	48	Light water	Light water	Integral PWR	United States	BWXT*	Public
	18	Light water		PWR	United Kingdom	Rolls-Royce SMR	Public/ private
	Online Refuelling	Helium	Graphite	HTR	South Africa	PBMR*	Private
	Continuous online	Helium	Graphite	HTR	South Africa	HTMR Limited	Private
				MSR/FNR	United States	Southern Co, TerraPower	Private
	Apr-00	Lead–bismuth		Lead-Bi FNR	Russia	AKME-Engineering*	Private
	480	Lead–bismuth		Lead FNR	United States	Westinghouse	Private
	120–240	Molten fluoride salt	Graphite	MSR	China	SINAP	Public
	Continuous	Molten fluoride salt	Prismatic beryllium	MSR	United States	UC Berkeley	Public
	Continuous	Molten fluoride salt		MSR/FNR	United Kingdom	Moltex	Private

Name	Thermal Capacity (MWth)	Electrical Capacity (MWe)	Application Type	Coolant Capacity (Inlet Temperature °C)	Coolant Capacity (Outlet Temperature °C)	Fuel Type
Thorcon TMSR	557	250	Grid electricity			Uranium tetrafluoride and thorium tetrafluoride
Leadir-PS100	300	36	Industrial heat plant and electricity			TRISO
CALOGENA	30	0	District heating	110		UO_2
i-SMR	520	170	Electricity generation	286	321	UO_2
Bandi	200	60		293	322	UO_2
HTR50S	50	17.2	Heat and power generation, desalination	325	Phase 1- 750, Phase 2- 900	UO_2 TRISO
MHR-100	215	25–87	Regional power and heat production	490	795	Hexagonal prism graphite blocks with coated particle fuel
MHR-T	4*600	4*205.5	Hydrogen production	578	950	TRISI
PeLUIT-40	30	10	Electricity, industrial steam, hydrogen	250	750	Spherical elements with coated particle fuel
Unitherm	30	6.6	Generation of electricity, district heating, seawater desalination and process steam production	249	330	UO_2
Pylon D1	1	0	Electricity and industrial heat	327	727	TRISO

	Refuelling Cycle (Months)	Coolant	Moderator	Reactors Type	Country	Developer	Type of Developer
	Continuous	Molten fluoride salt		MSR	United States	Martingale	Private
	Continuous	Liquid lead		Lead cooled	Canada	Northern Nuclear	Private
	24	Demineralized water		Pool type	France	Calogena SA	Private
	24	Light water	Light water	PWR	South Korea	KHNP and KAERI	Public
	48–60	Light water		Floating PWR	South Korea	KEPCO E&C	Public
	730 days	Helium	Graphite	HTGR	Japan	JAEA	Public
		Helium	Graphite	HTGR	Russia	JSC Afrikantov OKBM	Public
	30	Helium	Graphite	HTGR	Russia	JSC Afrikantov OKBM	Public
	On-line Refuelling	Helium	Graphite	HTGR	Indonesia	BRIN	Public
	200	High purity water		PWR	Russia	NIKIET	Public
	30	Helium (Primary) and sCO_2 (Secondary)	Zirconium hydride	HTGR	United States	Ultra Safe Nuclear Corporation	Private

Name	Thermal Capacity (MWth)	Electrical Capacity (MWe)	Application Type	Coolant Capacity (Inlet Temperature °C)	Coolant Capacity (Outlet Temperature °C)	Fuel Type
XAMR	80	40	Production of hydrogen and/or decarbonized electric fuels, with a particular focus on maritime	Undisclosed	Undisclosed	Molten salt
AMR	10	3	Electricity and heat	450	750	TRISO
ELENA	3.3	0.068	Produce heat, electricity generation, desalination	311	328	UO_2 pellet
SMR-300	1050	366	Electricity generation, process heat, industrial steam, or desalination	292	321	UO_2 pellet
Blue Capsule**	150	50	Industrial heat and power generation	400	750	Prismatic, TRISO with UO_2
LFR-AS-200	480	200	Industrial production and electricity generation	420	530	MO_x
SEALER-55	140	55	Electricity, industrial/process heat, passive safety	420	550	UN
CMSR	250	110	Electricity generation for grid, industrial production and hydrogen production	600	650	LEU
FUJI	450	200	Electricity generation, desalination and hydrogen production	565	704	Molten salt with Th and U
LFTR (lithium flouride thorium reactor)	600	250	Cogeneration, electricity generation	500	650	$LiF\text{-}BeF_2\text{-}UF_4$

	Refuelling Cycle (Months)	Coolant	Moderator	Reactors Type	Country	Developer	Type of Developer
	38	Molten Salt		MSR	France	NAAREA	Private
	96	Helium	Graphite	HTGR	South Africa	Power Cell Micro Reactor Pty	Private
	300	Light water	Light water	PWR	Russia	National Research Centre "Kurchatov Institute"	Public
	18	Light water	Light water	PWR	United States	Holtec International	Private
	Continuous	Sodium	Graphite	Sodium cooled	France	Blue capsule technology	Private
	16	Lead		Lead cooled	Italy/Frace	NewCleo	Private
	300	Lead		Lead cooled	Sweden	BlyKalla	Private
	Online refuelling with 5% LEU	Fluoride fuel salt	Graphite	MSR	Denmark	Seaborg Technology	Private
	Continuous	Molten fluoride	Graphite	MSR	Japan	International Thorium Molten-Salt Forum: ITMSF	Private
	Continuous	Molten salt $MgCl_2$	NaCl	MSR	United States	Flibe Energy	Private

Name	Thermal Capacity (MWth)	Electrical Capacity (MWe)	Application Type	Coolant Capacity (Inlet Temperature °C)	Coolant Capacity (Outlet Temperature °C)	Fuel Type	
Stable Salt Reactor – Wasteburner	700	300	Electricity and high-temperature industrial heat, hydrogen production, industrial process use	575	625	Molten salt	
Energy Well	20	8	Generation of electricity, heat, and hydrogen	660	700	TRISO	
ThorCon	557	250	Scalable, cost-competitive power, coal-replacement	560	704	UF_4	
Thorizon	250	100	Electricity generation and waste reduction	500	800	Molten salt	
Aurora	150	50	Electricity generation for grid, industrial production and hydrogen production			Metal fuel	
HolosQuad	22	10	Electricity generation, process heat, emergency or off-grid power, with passive-air cooling and high load-following flexibility	590	855	Qualified TRISO-UCO compacts	
Gen 4 module	70	25	Electricity, industrial heat, hydrogen production		500	Uranium nitride	
4S	30	10	Remote power, off-grid energy needs, or regional microgrids	355	510	Metal fuel (U-Zr alloy) enriched uranium	
ABV-6E	38	9	Generate electric power or provide heat and power cogeneration	250	325	UO_2 pellet	

	Refuelling Cycle (Months)	Coolant	Moderator	Reactors Type	Country	Developer	Type of Developer
	N/A	Molten salt $MgCl_2$	NaCl	MSR	United States/ Canada	Moltex Energy	Private
	84	Molten salt FLiBe	No	MSR	Czech Republic	Centrum výzkumu Řež	Public
	12	Molten salt	Graphite	MSR	United States	ThorCon International	Private
	5–10 years	Chloride salt	No	MSR	Netherlands/ France	Thorizon BV	Private
	120–240	Liquid metal	No	FR	United States	OKLO, Inc.	Public
	96	Helium	Graphite	HTGR	United States	HolosGen	Private
	10 Years	Lead-bismuth		Liquid metal cooled	United States	Gen4 Energy Inc.	Private
	N/A	Sodium		LMFR	Japan	Toshiba Corporation	Private
	120–144	Light water	Light water	Floating PWR	Russia	JSC Afrikantov OKBM	Public

Name	Thermal Capacity (MWth)	Electrical Capacity (MWe)	Application Type	Coolant Capacity (Inlet Temperature °C)	Coolant Capacity (Outlet Temperature °C)	Fuel Type
ACP100S	385	125	Electricity generation, heating, steam production, and seawater desalination	286.5	319.5	UO_2
CA Waste Burner	N/A	100	Electricity generation, industrial heat, and desalination, Consume waste fuel	600	650–700	7LiF-UF_4 or 7LiF-ThF_4- (TRU)F_3

	Refuelling Cycle (Months)	Coolant	Moderator	Reactors Type	Country	Developer	Type of Developer
	24	Light water	Light water	Integral PWR	China	CNNC	Public
	N/A	Fuel salt	Heavy water	Molten salt reactor	Denmark	Copenhagen Atomics	Private

Name	Thermal Capacity (MWth)	Electrical Capacity (MWe)	Application Type	Coolant Capacity (Inlet Temperature °C)	Coolant Capacity (Outlet Temperature °C)	Fuel Type
FLEX Reactor	60	24	Electricity generation and industrial process, district heating, and hydrogen production, desalination	725	795	Molten salt
GTHTR300	600	100–300	Electric power generation, thermochemical hydrogen production, desalination cogeneration using waste heat only, and steelmaking	587	850	UO$_2$ TRISO
Holos-mono	22	10	Electricity generation, process heat, desalination, and potentially other industrial uses	590	855	TRISO
HTGR-POLA	30	11.5	Electricity generation and process heat applications	325	750	UO$_2$ TRISO
Integral NSR	442	195	Electricity generation, process heat and load-following			
Jimmy	20	N/A	Industrial heat generation	300	700	UCO TRISO
PWR-20	80	20	Industrial applications and distributed baseload for grid applications	270	331	UO$_2$ pellet
MoveLuX	10	4	Power generation, process heat supply, and hydrogen production	680	885	Silicide (U$_2$Si$_2$)

	Refuelling Cycle (Months)	Coolant	Moderator	Reactors Type	Country	Developer	Type of Developer
	36–60	Molten eutectic AlF_3 /NaF coolant salt	Commercial grade graphite moderator	Molten salt reactor	United Kingdom	Moltex Energy	Private
	48	Helium	Graphite	Prismatic HTGR	Japan	JAEA Consortium	Public
	82	Helium	Graphite	High-temperature gas reactor (HTGR)	United States	HolosGen LLC	Private
	20	Helium	Graphite	High-temperature gas reactor (HTGR)	Poland	NCBJ	Public
					United States	NuScale Power	Public
	No refuelling	Helium	Graphite	High temperature gas-cooled reactor	France	JIMMY ENERGY SAS	Private
	72	Light water	Light water	PWR	United States	Last Energy	Private
	Continuous	None (sodium heat pipe cooled)	Calcium hydride (CaH_2)	Heat pipe cooled and calcium hydride moderated reactor	Japan	Toshiba Corporation	Private

Annexure III

Institutional Framework of India's Nuclear Sector

India's civilian nuclear programme operates through an integrated institutional framework led by the Department of Atomic Energy (DAE) and guided by the Atomic Energy Commission (AEC). This structure includes specialized research institutions, public sector enterprises, fuel-cycle organizations, and regulatory authorities responsible for different aspects of nuclear energy development.

Together, these institutions manage the entire nuclear value chain—from uranium exploration and fuel fabrication to reactor deployment, electricity generation, and nuclear safety regulation—while supporting India's long-standing policy objective of technological self-reliance in the nuclear sector.

1. Atomic Energy Commission (AEC)

The Atomic Energy Commission (AEC) is the apex policy-making body responsible for formulating India's nuclear policy and guiding the development of the national atomic energy programme. The Commission was first established in 1948 and was reconstituted in 1958 with full executive and financial powers.

The AEC determines long-term strategies for nuclear energy development, including research priorities, reactor deployment pathways, fuel-cycle policies, and international cooperation. The Chairman of the Atomic Energy Commission simultaneously serves as the Secretary of the Department of Atomic Energy, ensuring coordination between policy formulation and programme implementation.

2. Department of Atomic Energy (DAE)

The Department of Atomic Energy (DAE) was established in 1954 and operates directly under the Prime Minister of India. The department functions as the executive arm responsible for implementing the policies formulated by the Atomic Energy Commission.

The DAE oversees research and development activities, nuclear power generation, fuel-cycle management, radiation technologies, and international cooperation in the nuclear sector. It coordinates the activities of several research institutions, industrial organizations, and public sector enterprises involved in India's nuclear programme.

3. Nuclear Power Corporation of India Limited (NPCIL)

The Nuclear Power Corporation of India Limited (NPCIL) is a public sector enterprise under the Department of Atomic Energy responsible for the design, construction, commissioning, and operation of nuclear power plants in India. The NPCIL was established in 1987 to manage India's commercial nuclear power generation programme.

The organization is responsible for site selection, project development, reactor construction, plant operation, and maintenance of nuclear power facilities. The NPCIL also works with domestic industries and international partners in areas such as reactor technology development, equipment manufacturing, and project implementation.

4. Bharatiya Nabhikiya Vidyut Nigam Limited (BHAVINI)

Bharatiya Nabhikiya Vidyut Nigam Limited (BHAVINI) is a public sector enterprise established in 2003 under the Department of Atomic Energy to implement India's fast breeder reactor programme.

The BHAVINI is responsible for constructing and operating fast breeder reactors that form the second stage of India's three-stage nuclear power programme. Its flagship project is the prototype fast breeder reactor (PFBR) at Kalpakkam, Tamil Nadu, which represents a key step towards utilizing plutonium resources and eventually enabling large-scale deployment of thorium-based reactors.

5. Nuclear Research and Development Institutions

India's nuclear research and technology development activities are carried out through specialized institutions under the Department of Atomic Energy.

Bhabha Atomic Research Centre (BARC)

The Bhabha Atomic Research Centre (BARC) in Mumbai is India's premier nuclear research institution. The BARC conducts advanced research in nuclear science, reactor technologies, fuel-cycle processes, radiation applications, and nuclear safety. The centre plays a central role in the development of indigenous nuclear technologies and provides technical support for reactor design and fuel-cycle operations.

Indira Gandhi Centre for Atomic Research (IGCAR)

The Indira Gandhi Centre for Atomic Research (IGCAR) located in Kalpakkam focuses on research related to fast breeder reactors and advanced nuclear technologies. Its work includes reactor physics, materials research, sodium-cooled reactor technologies, and fuel-cycle systems associated with fast reactors.

Raja Ramanna Centre for Advanced Technology (RRCAT)

The Raja Ramanna Centre for Advanced Technology (RRCAT) in Indore specializes in accelerator technologies, lasers, and advanced instrumentation used in nuclear science and related research fields.

6. Nuclear Fuel-cycle Organizations

Several specialized institutions under the Department of Atomic Energy manage different stages of the nuclear fuel cycle.

Uranium Corporation of India Limited (UCIL)

The Uranium Corporation of India Limited (UCIL) is responsible for uranium exploration, mining, and processing in India. UCIL operates uranium mines and milling facilities that produce uranium ore concentrate, which serves as the primary raw material for nuclear fuel fabrication.

Nuclear Fuel Complex (NFC)

The Nuclear Fuel Complex (NFC) located in Hyderabad manufactures nuclear fuel assemblies, zirconium alloy cladding, and structural components used in Indian nuclear reactors. The NFC plays a key role in supporting indigenous reactor technologies and ensuring the availability of fuel components for nuclear power plants.

Heavy Water Board (HWB)

The Heavy Water Board (HWB) manages the production and supply of heavy water (D_2O) required for pressurized heavy water reactors (PHWRs). The Board oversees heavy water plants across India and supports technological development related to heavy water production and associated chemical processes.

7. Nuclear Safety Regulation

Atomic Energy Regulatory Board (AERB)

The Atomic Energy Regulatory Board (AERB) was constituted on 15 November 1983 by the President of India, exercising powers under the Atomic Energy Act, 1962, to oversee nuclear and radiation safety in the country.

The AERB is responsible for establishing safety standards, granting regulatory licences, and monitoring compliance across nuclear installations and radiation facilities. The Board regulates nuclear power plants, fuel-cycle facilities, radiation sources, and waste-management systems to ensure that the use of nuclear energy does not pose undue risks to public health or the environment.

8. International Engagement and Safety Cooperation

India's civilian nuclear sector engages with international organizations to strengthen safety standards and operational practices. India cooperates with the International Atomic Energy Agency (IAEA) through safeguards agreements, safety review missions, and technical cooperation programmes.

Indian nuclear operators also participate in international knowledge-sharing platforms such as the World Association of Nuclear Operators (WANO), which promotes best practices in nuclear power plant operation and safety management.

Annexure IV

Nuclear Power Plants in India

Name	Type	Status	Location	Reference Unit Power [MW]	Gross Electrical Capacity [MW]	First Grid Connection
Kaiga-1	PHWR	Operational	Kaiga	202	220	2000–10–12
Kaiga-2	PHWR	Operational	Kaiga	202	220	1999–12–02
Kaiga-3	PHWR	Operational	Kaiga	202	220	2007–04–11
Kaiga-4	PHWR	Operational	Kaiga	202	220	2011–01–19
Kaiga-5	PHWR	Under construction	Kaiga	630	700	
Kaiga-6	PHWR	Under construction	Kaiga	630	700	
Kakrapar-1	PHWR	Operational	Surat	202	220	1992–11–24
Kakrapar-2	PHWR	Operational	Surat	202	220	1995–03–04
Kakrapar-3	PHWR	Operational	Surat	630	700	2021–01–10
Kakrapar-4	PHWR	Operational	Surat	630	700	2024–02–20
Kudankulam-1	PWR	Operational	Tirunellveli-Kattabomman	932	1000	2013–10–22
Kudankulam-2	PWR	Operational	Tirunellveli-Kattabomman	932	1000	2016–08–29
Kudankulam-3	PWR	Under construction	Tirunellveli-Kattabomman	917	1000	
Kudankulam-4	PWR	Under construction	Tirunellveli-Kattabomman	917	1000	
Kudankulam-5	PWR	Under construction	Tirunellveli-Kattabomman	917	1000	

Name	**Type**	**Status**	**Location**	**Reference Unit Power [MW]**	**Gross Electrical Capacity [MW]**	**First Grid Connection**
Kudankulam-6	PWR	Under construction	Tirunellveli-Kattabomman	917	1000	
Madras-1	PHWR	Suspended operation	Madras	205	220	1983–07–23
Madras-2	PHWR	Operational	Madras	205	220	1985–09–20
Narora-1	PHWR	Operational	Narora	202	220	1989–07–29
Narora-2	PHWR	Operational	Narora	202	220	1992–01–05
Pfbr	FBR	Under construction	Madras	470	500	
Rajasthan-1	PHWR	Suspended operation	Kota	134	100	1972–11–30
Rajasthan-2	PHWR	Operational	Kota	187	200	1980–11–01
Rajasthan-3	PHWR	Operational	Kota	202	220	2000–03–10
Rajasthan-4	PHWR	Operational	Kota	202	220	2000–11–17
Rajasthan-5	PHWR	Operational	Kota	202	220	2009–12–22
Rajasthan-6	PHWR	Operational	Kota	202	220	2010–03–28
Rajasthan-7	PHWR	Operational	Kota	630	700	2025–03–17
Rajasthan-8	PHWR	Under construction	Kota	630	700	
Tarapur-1	BWR	Suspended operation	Boisar	150	160	1969–04–01
Tarapur-2	BWR	Suspended operation	Boisar	150	160	1969–05–05
Tarapur-3	PHWR	Operational	Boisar	482	540	2006–06–15
Tarapur-4	PHWR	Operational	Boisar	378	540	2005–06–04

Annexure V

Innovative Models Adopted by Various Countries to Attract Investment in Nuclear Power

Several countries have adopted innovative policy and financing mechanisms to address the high capital costs and long construction timelines associated with nuclear power projects. These models aim to reduce financial risks, improve investment certainty, and attract private sector participation.

United Arab Emirates (UAE)

The UAE adopted a model that relies on strong government support combined with foreign technology partnerships. The Barakah Nuclear Power Plant project was implemented through a partnership with the Korea Electric Power Corporation (KEPCO).

Under this model, the UAE government provided long-term contractual arrangements and power purchase guarantees that ensured predictable revenue streams for investors and operators. The project was structured through government-backed financing and long-term electricity supply agreements, which significantly reduced project risk.

In the Indian context, foreign investment in the nuclear sector remains restricted under the current Foreign Direct Investment (FDI) Policy. While the Policy prohibits foreign investment in "atomic energy", it permits 100% FDI in nuclear equipment manufacturing under the automatic route, creating opportunities for technology collaboration in the supply chain.

United Kingdom

The United Kingdom has developed innovative financial models aimed at improving the bankability of nuclear power projects.

Contract for Difference (CfD)

Under the Contract for Difference (CfD) mechanism, the government guarantees a pre-agreed "strike price" for electricity generated by nuclear plants. If the market electricity price falls below the strike price, the government compensates the generator for the difference. Conversely, if the market price exceeds the strike price, the generator returns the excess revenue.

This mechanism reduces revenue volatility and provides long-term price certainty for investors. As a result, financing costs can be lowered, although any resulting costs are ultimately reflected in consumer electricity tariffs.

Regulated Asset Base (RAB) Model

The UK is also exploring the Regulated Asset Base (RAB) model for nuclear projects. Under this approach, developers can begin recovering project costs from consumers during the construction phase rather than only after the plant becomes operational.

By providing earlier revenue streams, the RAB model lowers financing risk and reduces overall capital costs. This model may also be suitable for projects supplying electricity to large industrial consumers.

China

China has adopted a strategy combining technology acquisition, domestic manufacturing, and state-backed financing to expand its nuclear programme.

The country imported reactor technologies from several international partners, including Russia, France, the United States, and Canada, to build technological capabilities while maintaining geopolitical balance. In 2008, China acquired the Westinghouse AP1000 Generation III reactor technology, including technology transfer arrangements that facilitated the development of indigenous designs such as the CAP1400 and ACP100 reactors.

In addition, the Chinese government supported nuclear expansion through favourable electricity pricing. In 2013, China set a benchmark wholesale tariff of approximately CNY 0.43 per kWh (about 7 US cents per kWh) for new nuclear power projects, compared to around CNY 0.30 per kWh for coal-based generation. This policy created stronger incentives for nuclear investment and helped accelerate deployment.

France

France's nuclear sector has historically relied on strong state involvement and public financing mechanisms. The French government has supported nuclear expansion through state-backed loans and financing arrangements for Électricité de France (EDF), the country us state-owned utility.

These mechanisms reduce financing costs and mitigate the financial risks associated with large nuclear projects, particularly given the significant upfront capital requirements and long construction timelines.

United States

In the United States, both federal and state governments have played a significant role in supporting nuclear power development through a range of financial and policy instruments.

One key mechanism is the provision of federal loan guarantees, which reduce financing risk by assuring lenders that their investments will be repaid even in the event of project delays or cost overruns. For example, the U.S. Department of Energy (DOE) provided approximately $12 billion in loan guarantees to support the construction of Vogtle Units 3 and 4 in Georgia, which entered commercial operation in 2023 and 2024.

In addition, the Inflation Reduction Act (IRA) of 2022 introduced production tax credits to support the continued operation of existing nuclear power plants. Under this framework, eligible nuclear facilities can receive tax credits of up to $15 per MWh for electricity generation between 2024 and 2032. These credits are designed to ensure the economic viability of existing reactors while preventing excessive profit margins, as the credit value declines when market revenues exceed specified thresholds.

Annexure VI Global Policy Scenario

Parameter	United States	Canada	China	Russia	South Korea
Regulatory framework	NRC approved NuScale's 77 MWe SMR design (2022) with a defined licensing process. Non-light-water SMRs (for example, molten salt) face complex, lengthy approvals. Grid integration policies are evolving for distributed energy.	CNSC's 27-point SMR Action Plan (2020) streamlines licensing. Pre-licensing vendor design reviews completed for GE-Hitachi BWRX-300 and others. Grid integration tailored for small reactors, especially in remote areas.	CNNC oversees robust regulations for ACP-100 and HTR-PM, with clear safety and licensing protocols. Operational SMRs demonstrate regulatory maturity. Grid integration supports small-scale reactors.	Rosatom regulates RITM-200 and floating SMRs (for example, Akademik Lomonosov). Domestic licensing is streamlined, but international deployment faces regulatory alignment challenges.	KINS licensed SMART SMR (100 MWe). 2022 policy updates support nuclear expansion. Grid integration policies are developing but not fully optimized for smaller SMR outputs.
Government funding	DOE invested $600M in NuScale via ARDP (2019–present). Additional funding for X-energy and TerraPower designs. Supports demonstration and commercialization.	CAD $20M allocated for SMRs, with federal and provincial funding for demonstration projects for example, OPG's Darlington site). Additional R&D grants via NRCan.	State-driven funding under Five-Year Plans supports HTR-PM and ACP-100. Exact amounts undisclosed but estimated in billions USD for nuclear expansion.	Rosatom funds RITM-200 and Akademik Lomonosov. Budgets are substantial but constrained by sanctions and geopolitical tensions since 2022.	Government funds SMART SMR via KAERI and MOTIE. Post-2022 policy shift increased R&D and demonstration funding, though less than US or China
Policy incentives	Inflation Reduction Act (2022) offers tax credits (for example, 30% for clean energy). Loan guarantees via DOE for SMR projects. State-level incentives vary.	Federal tax credits and grants for clean energy under SMR Action Plan. Provincial incentives in Ontario and Saskatchewan for nuclear projects.	State subsidies reduce SMR capital costs. Tax exemptions and land grants for nuclear projects align with carbon goals. Details often opaque.	Subsidies for remote energy projects. Tax breaks for Rosatom-led initiatives, but international sanctions limit broader incentives.	Tax incentives and export credits for nuclear projects post-2022. Focus on desalination and small grid applications. Limited compared to US

Parameter	United States	Canada	China	Russia	South Korea
Public acceptance	Mixed due to Three Mile Island (1979) and Fukushima (2011) concerns. DOE's public outreach emphasizes SMR safety. Regional opposition (NIMBY) persists.	Growing acceptance via clean energy narrative and SMR Action Plan consultations. Indigenous and regional concerns addressed through engagement.	Limited public engagement due to centralized governance. No major opposition reported, but transparency on safety is low, affecting trust.	Low due to Chernobyl (1986) legacy and geopolitical distrust. Minimal public engagement; state-driven projects face skepticism.	Moderate, improving with 2022 pro-nuclear shift. Fukushima concerns linger, but education campaigns boost support for energy security.
Economic viability	High first-of-a-kind costs ($3–$5M/MW). Factory-built SMRs aim for $2–$3M/MW with series production. Market for coal plant replacement and data centres.	Competitive for remote grids ($3–$4M/MW). Economies of series production and federal/provincial incentives enhance viability.	Cost-competitive (~$2M/MW for HTR-PM) due to subsidies and operational SMRs. Large domestic market for grid and industrial applications.	Competitive for remote regions (~$2.5M/MW for RITM-200). Floating SMRs reduce land costs. Sanctions limit export markets.	Competitive for niche markets like desalination (~$3M/MW for SMART). Factory fabrication and export focus improve economics.
Technological readiness	NuScale's 77 MWe SMR NRC-approved, with UAMPS deployment planned for late 2020s. Non-light-water designs (for example, X-energy) in R&D phase.	GE-Hitachi BWRX-300 in pre-licensing. Demonstration projects planned for early 2030s at Darlington. No operational SMRs yet.	HTR-PM (200 MWth) operational since 2021. ACP-100 under construction. Multiple designs in advanced R&D.	Akademik Lomonosov (70 MWe) operational since 2020. RITM-200 powers icebreakers, with land-based versions in development.	SMART SMR (100 MWe) licensed, with potential deployment by 2030s. R&D for advanced designs focuses on export markets.
Infrastructure availability	92 operating reactors provide robust nuclear infrastructure. Grid upgrades needed for distributed SMR integration in some regions.	19 reactors in Ontario support nuclear infrastructure. Grid adaptable for SMRs, especially in remote and industrial areas.	50+ reactors with expanding infrastructure. Grid supports SMR integration in coastal and industrial zones.	37 reactors and floating SMR infrastructure. Land-based grid integration requires upgrades for broader deployment.	26 reactors with centralized grid. SMR integration requires adaptations for smaller outputs.

Parameter	United States	Canada	China	Russia	South Korea
Environmental policy alignment	SMRs align with net-zero 2050 goals and coal phase-out. DOE targets SMRs for grid decarbonization and industrial heat (for example, data centres).	Central to net-zero 2050 and fossil fuel replacement in remote areas. Ontario's clean energy strategy prioritizes nuclear.	Supports 2030 carbon peak and 2060 neutrality. SMRs replace coal and power industrial zones.	Contributes to low-carbon mix but overshadowed by fossil fuel reliance. Focus on remote energy supply.	Aligns with 2050 carbon neutrality. 2022 policy targets coal replacement and energy security via SMRs.
International collaboration	Active in IAEA SMR working groups and G7 harmonization initiatives. Collaborates with Canada and UK on regulatory alignment. Limited export focus.	Leads IAEA SMR initiatives. Partners with U.S. and UK on standards. Emerging export potential via GE-Hitachi and others.	Limited collaboration due to state-driven model. Partners with IAEA and developing nations for SMR exports.	Rosatom pursues SMR exports (for example, Arctic markets). IAEA collaboration active, but sanctions limit partnerships.	SMART SMR targets exports (for example, Saudi Arabia desalination). Active in IAEA and bilateral nuclear agreements.
Workforce expertise	~100,000 nuclear workers, but aging workforce prompts DOE and university training for SMRs. Focus on next-generation reactor skills.	~20,000 nuclear workers. OPG and universities train for SMR-specific skills under SMR Action Plan.	Growing workforce with state-backed training. Expertise supports operational SMRs and nuclear expansion.	~50,000 workers via Rosatom. Training programs support domestic and export-focused SMR projects.	~15,000 nuclear workers. KAERI and universities train for SMR development and export projects.
Safety standards	NRC enforces stringent safety protocols for SMRs, emphasizing passive safety systems. NuScale design meets high standards.	CNSC's rigorous safety protocols tailored for SMRs. Pre-licensing reviews ensure compliance with international standards.	CNNC enforces high safety standards for operational SMRs (for example, HTR-PM). Aligned with IAEA guidelines.	Rosatom's safety standards for RITM-200 and floating SMRs meet domestic and IAEA requirements.	KINS enforces stringent safety for SMART SMR, with passive safety features aligned with global standards.
Waste management	Plans leverage existing repositories (for example, Yucca Mountain, under debate). SMRs produce less waste, easing management.	Deep geological repository planned, adaptable for SMRs. CNSC ensures waste strategies align with safety goals.	Centralized waste management with plans for geological disposal. SMRs integrated into existing frameworks.	Established waste management via Rosatom, but public scrutiny persists. SMRs reduce waste volume.	Waste management for SMART SMR aligns with existing repository plans. Focus on minimizing waste.

Parameter	United States	Canada	China	Russia	South Korea
Market applications	Coal plant replacement, data centres, military bases, and industrial heat. Suited for distributed grids.	Remote communities, mining, and industrial heat. Targets off-grid and grid-connected applications in Ontario.	Grid power, industrial heat, and coastal desalination. Supports urban and industrial energy demands.	Remote Arctic regions, industrial heat, and export markets. Floating SMRs serve isolated areas.	Desalination, small grids, and export markets (for example, Middle East). SMART targets niche applications.
Supply chain development	Strong domestic supply chain for light-water SMRs (for example, NuScale). Non-light-water designs rely on international partners.	Developing supply chain via GE-Hitachi and local firms. International partnerships for advanced components.	Robust domestic supply chain for HTR-PM and ACP-100. Limited reliance on international suppliers.	Rosatom controls domestic supply chain for RITM-200. Sanctions disrupt international supply chains.	Domestic supply chain for SMART SMR via KEPCO and Doosan. Export focus requires international partnerships.
Research and development	DOE funds R&D for NuScale, X-energy, and TerraPower. Universities and national labs drive innovation in advanced SMRs.	NRCan and universities fund R&D for BWRX-300 and others. Focus on demonstration and commercialization.	State-funded R&D via CNNC for HTR-PM and ACP-100. Universities support advanced reactor designs.	Rosatom invests in RITM-200 and next-generation SMRs. Focus on practical deployment and exports.	KAERI leads R&D for SMART and advanced designs. Government funds export-oriented innovation.
Private sector involvement	NuScale, X-energy, and TerraPower lead development with DOE support. Private investment growing but risk-averse.	GE-Hitachi, Terrestrial Energy, and X-energy Canada drive projects. Private-public partnerships via OPG.	Limited private involvement; CNNC and state firms dominate. Some private investment in R&D.	Rosatom dominates, with limited private involvement. Export projects attract some private interest.	KEPCO and Doosan lead SMART development. Private sector active in export-oriented projects.
Energy security goals	SMRs reduce reliance on fossil fuel imports. DOE emphasizes grid resilience and domestic energy supply.	SMRs enhance energy access in remote areas and reduce fossil fuel use. Ontario prioritizes nuclear for security.	SMRs support energy independence by replacing coal and expanding nuclear capacity.	SMRs ensure energy for remote and Arctic regions, reducing reliance on diesel. Export focus enhances influence.	SMRs bolster energy security post-2022 policy shift. Export markets reduce dependence on fossil fuels.

Parameter	United States	Canada	China	Russia	South Korea
Grid flexibility	SMRs suit distributed grids but require upgrades in some regions. Load-following capability being developed.	Flexible for remote and grid-connected systems. Ontario's grid adapts to smaller SMR outputs.	Grid supports SMR integration, especially in industrial zones. Load-following aligns with renewable integration.	Floating SMRs bypass grid limitations. Land-based SMRs require grid upgrades for flexibility.	Centralized grid requires adaptations for SMRs. SMART designed for small-scale flexibility.
Public engagement	DOE and NuScale conduct outreach via webinars and community forums. Focus on safety and economic benefits.	SMR Action Plan includes stakeholder consultations, especially with indigenous groups. Transparent engagement.	Minimal engagement due to centralized governance. State media promotes nuclear benefits.	Limited engagement; Rosatom focuses on project execution over public dialogue.	Post-2022 campaigns educate public on nuclear safety and energy security. Community forums increasing.
Export potential	Limited focus on exports; NuScale targets domestic market. Some interest in Canada and Eastern Europe.	Emerging export potential via GE-Hitachi BWRX-300. Targets US and UK markets	ACP-100 and HTR-PM aimed at developing nations. Belt and Road Initiative supports export growth.	RITM-200 and floating SMRs target Arctic and developing markets. Sanctions limit broader reach.	SMART SMR designed for export, with Saudi Arabia desalination project as key example.

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