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Environmental Technology & International Affairs

Importance of National Level Policies to Support Thorium-Based Advanced Nuclear Reactor Technologies: India as a case study

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Affidavit

I, **ANANTHA PADMANABHAN PRABHAKARAN NAIR SINDHU, MSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "IMPORTANCE OF NATIONAL LEVEL POLICIES TO SUPPORT THORIUM-BASED ADVANCED NUCLEAR REACTOR TECHNOLOGIES: INDIA AS A CASE STUDY", 82 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

Energy security and energy independence while keeping the environmental impact to a minimum is one of India's top priorities. India is expanding its energy production capacity to meet the increasing energy demand due to rapid economic development and population growth, with nuclear energy playing a significant role alongside renewables like solar and wind. The capability to produce reliable power while keeping the emissions to a minimum motivates India to develop its nuclear technology further. However, India faces many challenges, including unreliable power supply in its energy sector, even when focusing on renewables and other green technologies. Issues of traditional uranium-based nuclear reactors are also prominent. This study explores the potential advantages of thorium-based advanced nuclear reactors, with capacities of up to 300 MWe, as a solution to these challenges and the adequacy of existing nuclear energy policies to support this technology adoption. India's existing nuclear programme and the abundance of thorium resources give the country a strategic advantage in supporting the decision to adopt this technology to fulfil the ambition of energy security and independence. The study examines the current status of thorium-based advanced nuclear reactor technology and the status of nuclear energy in India. Through a comprehensive literature review, the study examines the existing challenges faced by the Indian power sector. Challenges across the technical, socio-political, economic and environmental sectors have been identified. The advantages such systems could bring to India's energy environment are assessed and categorised to evaluate the merits of advanced thorium-based nuclear technologies. To support the adoption of this technology, national-level policies are a must. The study also examined India's existing policies on nuclear energy, their stakeholder impact, and policy gaps in adopting thorium-based advanced nuclear energy technology. The study concluded with a policy recommendation to adopt advanced nuclear technology and a potential phase-by-phase implementation map for India to achieve energy security.

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List of Abbreviations

ADS	Accelerator-Driven Systems
AEC	Atomic Energy Commission
AERB	Atomic Energy Regulatory Board
AHWR	Advanced Heavy Water Reactor
BARC	Bhabha Atomic Research Centre
BWR	Boiling Water Reactor
DISCOM	Distribution Company
DoAE	Department of Atomic Energy
FBR	Fast Breeder Reactor
IAEA	International Atomic Energy Agency
IAEA	International Atomic Energy Agency
IGCAR	Indira Gandhi Centre for Atomic Research
IHTR	Innovative High Temperature Reactor
IMSBR	Indian molten salt breeder reactor
LFTR	Liquid Fluoride Thorium Reactor
LWR	Light Water Reactor
LWR	Light Water Reactor
MSR	Molten Salt Reactor
NPCIL	Nuclear Power Corporation of India Limited
PHWR	Pressurised Heavy Water Reactor
SMR	Small Modular Reactors
TIFR	Tata Institute of Fundamental Research
TRU	Trans Uranic Elements
WNA	World Nuclear Association

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1. Introduction

Given the rapid economic growth and rising population, India is grappling with a pressing issue of increased energy demand. To maintain its commitment to sustainable development goals and achieve net zero emissions by 2070, India can no longer rely on fossil fuel-based energy production. The urgency of the situation necessitates immediate action to adopt technologies with the least environmental impact on energy production and eventually phase out fossil fuels from the system. India has already taken bold steps to expand the capacity of renewable power plants to accelerate power production. However, for a country like India, with its exponentially increasing energy demand and demographic and geographical challenges, dependence on only renewable sources is inadequate. India should diversify its energy portfolio, and that's where nuclear energy is becoming crucial.

It is not a new field for India. India already has a robust nuclear programme predating its independence, based on uranium as a fuel. Nuclear energy has its own downsides, ranging from safety issues to waste management challenges. Of all the other energy sources with the most negligible emissions, nuclear is one of the few, if not the only, technologies that can generate high electricity with maximum efficiency at scale. Against this backdrop, if new and better technologies can make nuclear energy more promising, that should be studied and evaluated. This is why the search for new technologies like thorium-based advanced nuclear reactors up to 300 MWe capacities is paramount. If such new initiatives can eliminate or reduce the challenges posed by traditional nuclear reactors, then they should be adopted and implemented.

India is an optimal case study for this topic due to multiple reasons. It doesn't have to start from scratch as the country has an active nuclear energy programme. The country has the capacity to provide the required resources for the adoption of technology and is willing to explore further. Additionally, if India can integrate this new technology more efficiently and safely into the system, it will be a considerable advantage for achieving its energy goals. The capacity of the nuclear reactors is important because India already has reactors with capacities above 700 MWe. However, the specific challenges India is facing in technical and/or economic aspects cannot be eliminated with traditional reactors. So, implementing smaller advanced reactors based on thorium could bring a mixture of advantages to the country. But before leaping into it, a thorough analysis of the challenges, benefits and existing policies is highly necessary. It will help to understand how such technologies will affect India's energy scenario and how much has to be changed in the administrative system for the adoption process.

The second chapter of this study will analyse the current status of this technology and India's energy scenario. The third chapter will look into the current challenges in India's path to green energy transition and how advanced reactors of up to 300 MWe can make a difference in it. The fourth chapter will analyse the advantages of thorium as a nuclear fuel to India. The existing policies governing nuclear energy in India will be analysed in the fifth chapter, and based on that, a policy roadmap will be designed in the sixth chapter. The seventh and final chapter will conclude the study.

1.1. Research Question

"What will be the potential impacts of thorium-based advanced nuclear reactor technology on India's energy mix, and how can national level policies be formulated and implemented to facilitate its effective integration?"

1.2. Objectives

- Analyse the current status of advanced nuclear reactors with up to 300 MWe capacity and thorium as an alternate nuclear fuel.
- Understand the advantages and benefits of adopting thorium-based advanced nuclear reactor technology in India.
- Evaluate India's existing nuclear energy policies, identifying gaps and opportunities for thorium-based reactors.
- Identify and assess the impact of existing nuclear policies on key stakeholders in India.
- Formulate actionable policy recommendations to bolster support for thorium-based reactor development.

2. State of the art

2.1. Current status of reactors up to 300MW

The pressing issue of climate change motivates us to switch to technologies with the least carbon footprint and minimal environmental impact. The energy sector plays a vital role in decarbonising our environment, as it is one of the primary reasons for our emission statistics. While the use of renewable energy sources is growing, nuclear energy continues to contribute to energy production with minimal carbon emissions. Nuclear power's ability to contribute to all three major energy carriers, heat, electricity, and hydrogen, keeps it relevant in the energy sector. Nuclear technology is continuously evolving and exploring new and efficient methods for energy production. The latest development in the field of nuclear technology is the development of advanced nuclear reactors up to 300 MWe capacity. These reactor designs are attractive mainly due to their lesser physical profile and modularity. The major categories in this technology include Small Modular Reactors (SMR) and microreactors. The major difference between the two is their power generation capacities. SMRs have a capacity of up to 300 MWe per unit, and microreactors typically have a capacity of up to 10 MWe ("Advances in Small Modular Reactor Technology Developments" 2022). Figure 2.1 shows a comparison between traditional reactors, SMRs and microreactors.

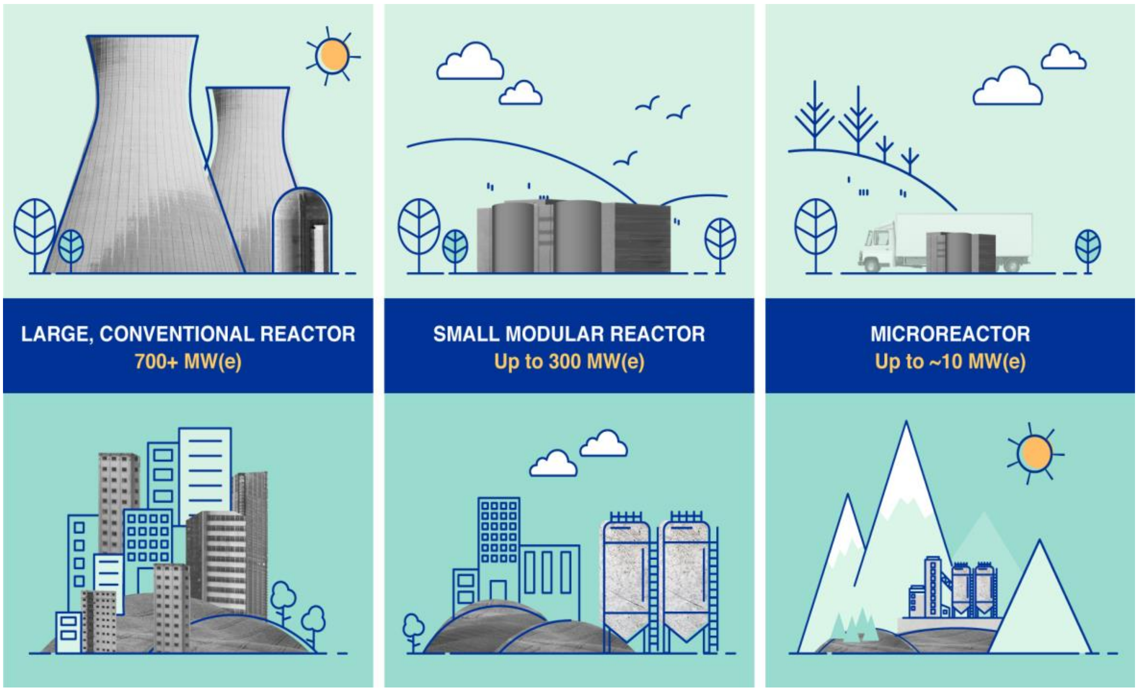

Figure 2.1Comparison between different reactor designs ("What Are Small Modular Reactors (SMRs)?" 2023)

According to “What Are Small Modular Reactors (SMRs)?” 2023, SMRs being only one-third of the size of a traditional nuclear reactor, offer advantages of being flexible with the location characteristics. It could be easily installed in places where a traditional nuclear plant is not suited. They offer reduced construction time and scalability to meet the rising energy demand. A major area where such reactors are helpful is the issue of rural electrification. Locations without sufficient grid connectivity and transmission systems could benefit from installing such advanced nuclear reactors. They consume less space and produce reliable electricity. The possibility of operating on and off the grid makes them highly flexible for remote deployment. They have smaller environmental footprint and carbon emissions. Technically, SMRs have an advantage over traditional reactors. They include simpler reactor designs and passive safety systems. Passive safety systems mainly rely on physical phenomena like force of gravity, natural circulation, convection and self-pressurisation. The natural circulation flow helps to reduce the use of pumps and reduce mechanical errors to a minimum. The simpler designs help in reducing the number of components used and the possibility of operational errors in the system. They also offer the advantages of underground deployment and modular construction, unlike traditional reactors. Such characteristics increase the safety of reactors and, in the worst cases of accidents, reduce or eliminate the unexpected release of radioactive materials into the open air. Regarding the fuel requirements, SMRs require less frequent fuel replacements of 3 to 7 years, while the traditional reactors need refuelling every 1 to 2 years. Some SMRs can even go up to 30 years without refuelling. Across the world, various countries and private institutions are involved in the development of SMRs. The world’s first commercialised reactor is in Russia, which has a capacity of 70 MWe from two reactors. It was commissioned in May 2020. Aside from Russia, the major countries involved in the development include the USA, China, Canada, Argentina and South Korea. Currently, there are more than eighty reactors are being built (under construction or in the design stage) across the globe on a commercial level. They are targeted at varied output and multiple applications. They include electricity production, heating, hydrogen production, hybrid energy systems, etc. Table 2.1 shows some examples of the development of SMR reactors.

Table 2.1 Examples of SMRs ("Advances in Small Modular Reactor Technology Developments" 2022)

Name	Country	Type of Fuel	Capacity (MWe)	Technology
NuScale Power	USA	Uranium	60	Light Water Reactor (LWR)
SMART	South Korea	Uranium	100	Integral Pressurized Water Reactor (iPWR)
CAREM	Argentin a	Uranium	25	Integral Pressurized Water Reactor (iPWR)
HTR-PM	China	Uranium	210	High-temperature gas-cooled Reactor (HTGR)
BWRX-300	USA	Uranium	300	Boiling Water Reactor (BWR)
ACP100	China	Uranium	125	Integral Pressurized Water Reactor (iPWR)
KLT-40S	Russia	Uranium	35	Pressurized Water Reactor (PWR)
IMSR	Canada	Uranium	195	Molten Salt Reactor (MSR)
ELENA	Russia	Uranium	30	Fast Neutron Reactor
RUTA-70	Russia	Uranium	70	Pressurised Water Reactor (PWR)

There is no standardised design for SMRs. Every reactor uses different technologies. Some of the major reactor designs recognised by the IAEA are land and marine-based water-cooled SMRs, high-temperature gas-cooled reactors, liquid metal-cooled fast neutron spectrum SMRs and molten salt SMRs ("Advances in Small Modular Reactor Technology Developments" 2022).

Developing SMRs could potentially benefit the goal of universal electrification and thereby aid sustainable development initiatives. The unique attributes of SMRs, like efficiency, reliability, and the ability to be paired up with other renewable energy plants like solar or wind to balance the intermittency issues, make them an attractive solution to achieve sustainable development goals. IAEA has taken several steps to accelerate the development of SMRs, such as creating an exclusive platform for information exchange, revising safety standards, creating technical working groups, etc. Along with SMRs, microreactors have also seen a sudden increase in their development. The advantage of being even smaller in size makes them a perfect solution for extreme use case scenarios like remote electrification, as a backup energy source, faster power restoration in emergency situations, etc. Microreactors, upon development, are predicted to have a niche electricity and heat market in the future. Across the globe, more than twelve microreactor designs are under development. The involved technologies include heat-pipe-cooled reactors, high-temperature gas-cooled reactors and liquid metal-cooled fast reactors. Countries like Canada, the Czech Republic, Japan, the United Kingdom and the United States are the forerunners in this field ("Effective Microreactor Development, Deployment" 2021).

This study, however, considers all types of advanced reactors, whether SMR or microreactor, as one category and refers to them as advanced nuclear reactors with up to 300 MWe capacity.

2.2. Current status of Thorium reactor research

Along with advanced reactor technologies, another area of nuclear energy that has received significant attention in recent years is the potential use of Thorium as a fuel instead of Uranium. However, unlike reactor technologies, the use of thorium is not a new concept. Countries have been researching thorium-based fuels for over fifty years, but uranium and uranium-plutonium-based fuels caught all the attention in the earlier years, and thorium-based research has stalled. Countries like Germany, India, Canada, Japan, China, Netherlands, Belgium, Norway, Russia, Brazil, the UK & the USA have conducted preliminary research on thorium ("Thorium - World Nuclear Association" 2024). In recent years the research has gained more traction due to the fact that thorium is more abundant and efficient compared to uranium as a fuel for nuclear reactors. The latest developments in the field include China's announcement of the completion of a thorium-based experimental reactor ("Thorium's Long-Term Potential" 2023). As of now, there are seven types of reactors which can use thorium as a potential fuel. The advantages and characteristics of each reactor type are unique to each other, but this is a significant development in thorium research. Two of the seven different types are still in the concept stage. For an overall understanding, these types and the basic details have been outlined in Table 2.2.

Table 2.2 Types of thorium-based reactor designs ("Thorium - World Nuclear Association" 2024)

Reactor Type	Potential Fuel Options	Reasons for Suitability	Examples	country	Status
Heavy Water Reactors (PHWRs)	Pu (5%) - Th LEU & Th Recycled Uranium and Th	Excellent neutron-economy Faster avg. neutron- energy Flexible refuelling	Enhanced Candu 6 (EC6), ACR-1000	Canada	Operational
High-temperature gas-cooled Reactors (HTRs)	Th-Pu mix Th - Enriched-Uranium mix	High Temperature-Stability Long Irradiation-Periods	Pebble bed, prismatic HTRs	China Germany USA	Operational
Boiling (Light) Water Reactors (BWRs)	Th-Pu mix Th - Enriched-Uranium mix	Established-Technology Design flexibility	Fukushima, Oskarshamn	Japan USA Sweden	Operational

Pressurised (Light) Water Reactors (PWRs)	Th-Pu mix Th - Enriched-Uranium mix	Less flexibility than BWRs.	Most common-reactor type	USA France Russia	Operational
Fast Neutron Reactors (FNRs)	Thorium-Depleted Uranium Mix	Thorium can serve as a fuel component; however, depleted uranium is generally more advantageous.	Various FNR designs	Russia France China	Operational, but thorium use is limited
Molten Salt Reactors (MSRs)	Th-U mix Th-Pu mix	Fluid Fuel High Temperature-Operation	MSRE (USA) TMSR-LF (China)	USA China India	Conceptual, at the design stage
Accelerator-Driven Reactors (ADS)	Th-Pu mix	Sub-Critical-Operation Thorium Capability	ADS programmes by India and CHina	Belgium India China	Conceptual, under research

As mentioned above, the research on thorium has gained traction in recent years due to resource abundance and increased efficiency. Figure 2.2 shows the efficiency of thorium over uranium as a fuel.

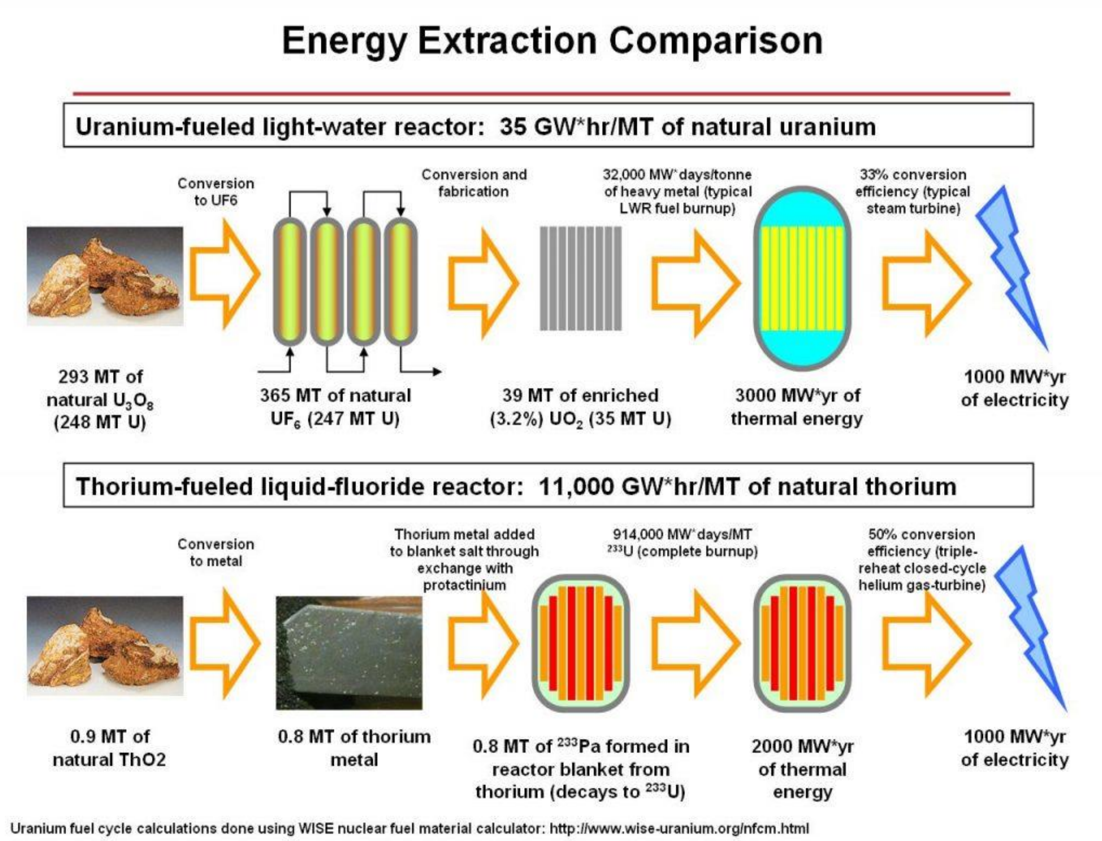

Figure 2.2 Efficiency of thorium over uranium ("NextBigFuture.Com" 2006)

However, there are more advantages to using thorium in nuclear power production. Thorium reactors have enhanced safety features. One major feature is that thorium reactors operate at atmospheric pressure, while most other uranium-based reactors are designed to operate at higher pressures. Lower pressure is ideal to avoid accidents related to pressure differences. This choice of design itself enhances the inherent safety of thorium reactors. Additionally, such reactors have other features like a negative temperature coefficient to reduce the risk of accidental failures. Waste reduction is another potential advantage of thorium reactors. The thorium fuel cycle produces fewer long-lived waste materials from a nuclear reactor. Less waste means cost reduction in waste management and storage systems. Another significant advantage is the proliferation resistance. Thorium fuel cycles are unsuitable for producing weapon-grade nuclear materials compared to traditional uranium reactors. This fact significantly reduces global security concerns. Even though thorium offers quite a number of advantages over uranium reactors, it is not without challenges. Although thorium research started over fifty years ago, it is still in its infancy stage. Developing thorium-based reactors still requires extensive research and competent reactor designs. Innovative designs and advanced materials pose hurdles along the way to the successful adoption of this technology. Such extensive R&D is expensive, too. A significant amount of investment has to be made in this sector for the timely adoption of thorium as an alternate fuel. Infrastructure is another hurdle along the way. The industry has already evolved based on uranium as a fuel. So, utilising thorium in reactors requires an entirely different infrastructure. Retrofitting or building new infrastructure will consume time and money. In addition to the difficulty of infrastructure, the complex fuel fabrication process also adds to the disadvantages of thorium-based reactors ("Thorium's Long-Term Potential" 2023).

The thorium fuel cycle differs from the uranium fuel cycle due to the differences in chemical characteristics of thorium and uranium. Unlike Uranium, thorium is not a fissile material. The fertile thorium must be converted into fissionable uranium before being used as fuel in a reactor. Figure 2.3 shows a basic representation of the thorium fuel cycle.

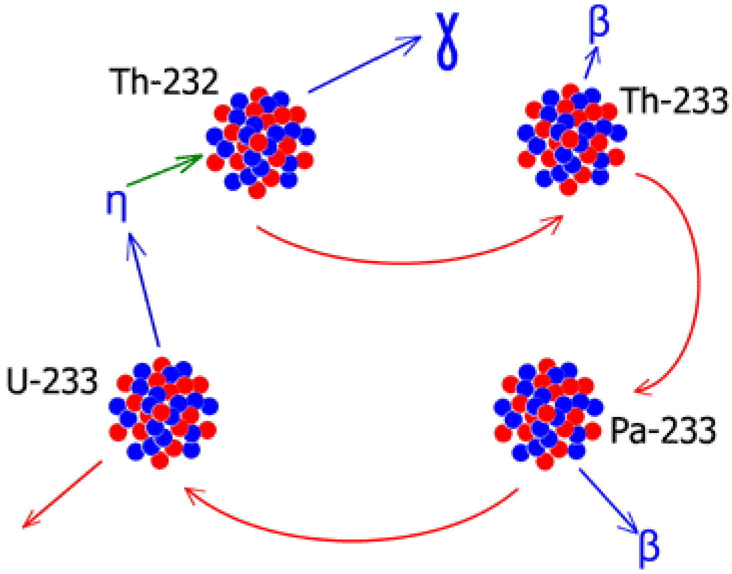

Figure 2.3 Thorium fuel cycle ("Thorium Fuel Cycle - Energy Education" 2024)

The initial fuel material is thorium oxide, ThO_2 obtained from purifying and processing the ore. After bombarding with a neutron, 232Th becomes 233Th. The fissile 233U is formed when the 233Th undergoes two subsequent beta decays. First beta decay produces 233Pa and another beta decay produces 233U. Through chemical processing methods, the irradiated thorium fuel mix and 233U can be separated. The purified 233U is then mixed with suitable fertile material to form fuel assemblies. This is the final form of fuel used in the reactor core. The fuel can be configured in different ways depending on the type of reactor, such as fuel roads, pebbles, etc.

2.3. Current status of Nuclear energy in India

2.3.1. Energy Demand/Energy status

India is at a critical stage in its energy sector. Finding a balance between the growing energy demand and reliable, affordable, and environmentally friendly energy production is paramount for India at the moment. The country's highest concern is its dependence on fossil fuel-based energy production. Almost 74 per cent of the country's energy consumption depends on fossil fuels ("Fossil Fuel Energy Consumption" 2014). However, India's strong commitment towards environmentally friendly power production and energy security is evident from its ongoing plans and future project proposals. The country's commitment to achieving the net zero emission target is marked in 2070("India's Statement at Brussels" 2024), and to achieve this goal, the country is focused on expanding its power production, emphasising green technologies like renewables, including solar, wind, hydro and nuclear energy. A quick analysis of ("Ministry of Power" 2024) data reveals that as of 2023, the installed electricity power capacity of the country stands at 417.668 GW, of which 237.269 GW depends on fossil fuel-based generation. This accounts for more than 56 per cent of the total installed capacity in the country. The most significant contributor among fossil fuels is coal, which covers around 50 per cent of the installed capacity. The highest contributor in the renewable sector is the hydro projects, which stand at 11 per cent, and solar projects come in second, with 16 per cent out of the total installed capacity. The nuclear capacity accounts for 1.6 per cent of the total installed capacity, which is 6780 MW. These numbers represent the current situation of India's electricity production, and it is important to note that half of the country's power is coming from coal alone. Due to different circumstances like a rising population and a rapidly growing economy, India cannot afford a sudden switch from fossil fuels to green technologies. India has adopted a slow yet steady path to eliminate fossil fuels and switch to green energy by 2070.

The country also faces certain challenges in its power sector, especially the issue of universal electrification and the urban-rural gap in electricity access. Universal electrification is an important goal for the government as it is vital for the holistic development of the community. In 2015, only around 83 per cent of India's rural population had access to electricity ("Access to Electricity, Rural" 2024). This was a significant challenge for India, and the government launched specific initiatives to reduce this gap. One of the major initiatives that was launched towards this goal is the 'Saubhagya' scheme in 2017. The scheme's goal was to achieve 100 per cent village electrification and the electrification of un-electrified households. This programme is considered one of the most significant initiatives of such sort, with joint efforts from national and state governments ("Saubhagya" 2024). The efforts actually gave results, and according to the World Bank data ("Access to Electricity, Rural" 2024), by 2021, 99.3 per cent of India's rural population had access to electricity. An additional 26.3 million households got access to electricity from the central grid at a subsidised rate or free of cost. This is a considerable achievement, and the programme is still in effect to complete the mission objectives.

The numbers were at an all-time high, but the quality of electricity was still questionable. Unreliability and interrupted power supply are still issues for households in rural India. Persistent daily power cuts, unanticipated power outages, and issues with the DISCOMs regarding metering, billing, and service have been observed in the country (Agarwal 2022). The average hours of electricity supply in an Indian household is estimated to be 16 hours. Rural households had fewer hours compared to urban households. Figure 2.4 shows the visual representation of daily power cuts and interruptions faced by different states in India.

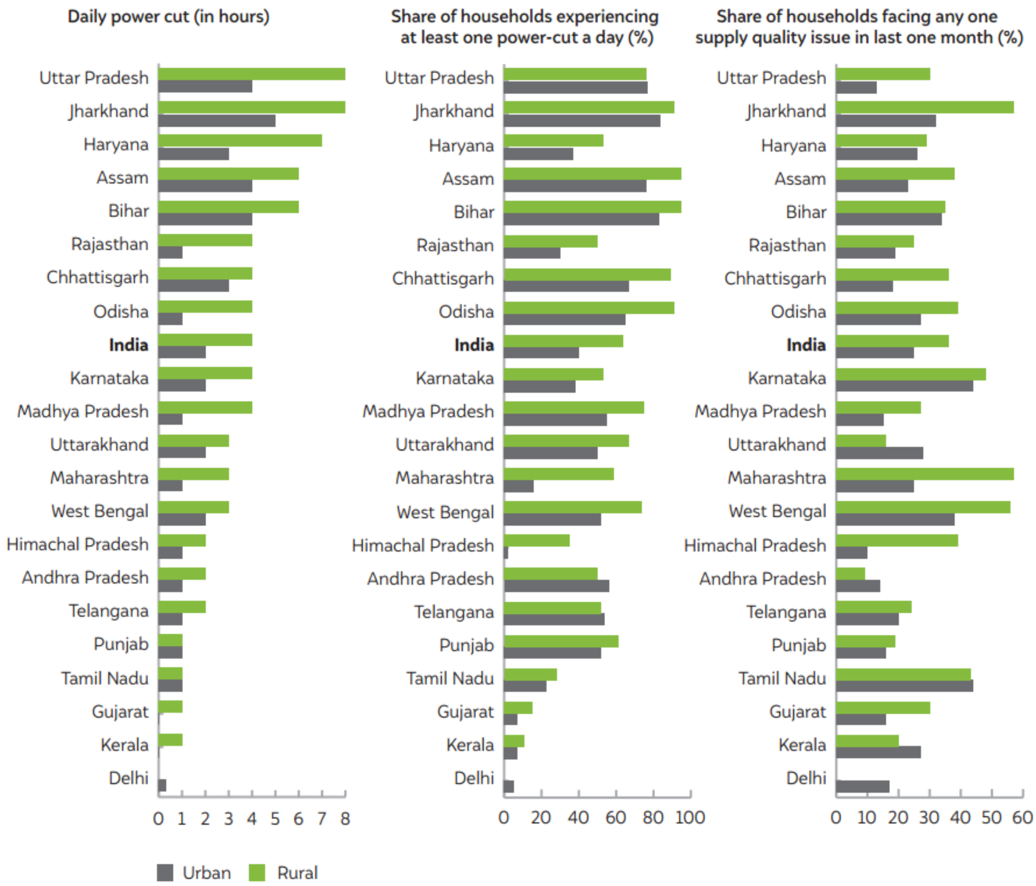

Figure 2.4 Indian states and interruptions in power supply (Agarwal 2022)

The power cuts vary with respect to seasons. It is maximum in the summer and a minimum in the monsoon time. The issues with the DISCOMs led to trust issues between the authorities and service providers. Metering and billing were not properly conducted, and people, especially in the rural region, lost their trust in the system. This further added to the financial stress DISCOMs are already suffering from. DISCOMs face serious financial issues in the country, and some of the major reasons include grid extension in rural regions and subsidised electricity supply. The distrust of people with the system and their unwillingness to pay for electricity adds extra weight to the already stressed financial state of the distributors (Tripathi 2019). Figure 2.5 shows the percentage of households facing metering and billing issues in India.

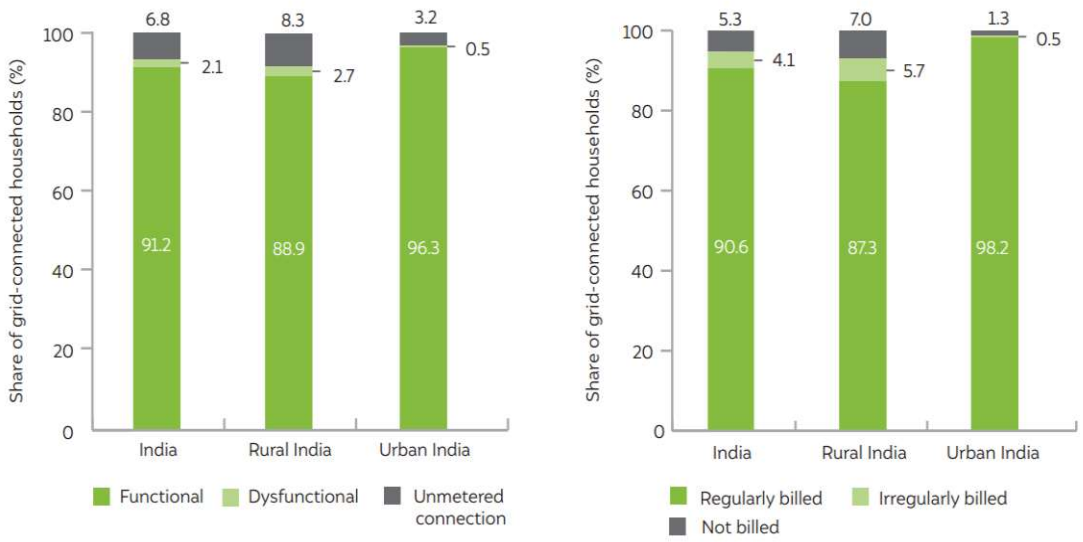

Figure 2.5 Metering and billing issues in India (Agarwal 2022)

Even though the numbers regarding universal electrification went up, the challenges still exist. Reliable supply and financial health of the DISCOMs are some of the crucial challenges the country needs to address soon. The resilience of the grid is also at stake. As part of the government initiatives to increase the share of renewables in the country, a massive rise in solar PV installation has been observed in a few years. The extreme weather dependency of solar and wind power plants causes intermittency issues. Storage systems have been adopted to protect the grind and avoid intermittency issues (ICRA 2024). A sudden addition in load and intermittency significantly affects grid resilience. Regarding the rise in solar PV installation, there have been studies regarding the massive land acquisitions and relocation of communities. Larger solar power plants require massive amounts of land area to be acquired, and it will not always be unused deserted land. Often, local ecosystems and Indigenous communities are affected, leading to socio-political issues and societal unrest in the country (Yenneti, Day, and Golubchikov 2016). It is evident that while trying to improve the country's overall energy portfolio, some challenges have emerged, and these challenges need to be addressed for a smooth transition towards a reliable, affordable, and green energy system. India has to explore multiple options to overcome these issues and bring a reliable power supply to its citizens.

2.3.2. Status of Nuclear Energy

The nuclear energy programme has always been integral to India's energy portfolio. India currently depends on fossil fuels, but in the future, India aims to increase the diverse nature of its energy mix and become energy independent. Nuclear energy is one of the vital areas that India focuses on to achieve its goal of energy security and emission-less energy production, and India has plans to expand its nuclear capacity. Recently, at the nuclear energy summit that took place in Brussels, India officially announced its goal of nuclear energy expansion and recognised nuclear energy as a "clean and environment friendly source of electricity" ("India's Statement at Brussels" 2024). It has been stated as part of the country's commitment to achieving a net zero emission goal by 2070 and accomplishing energy security and sustainable development. The long-term goal has been set for 2047 as it marks 100 years of independence, and as a medium-term target, India announced expanding the capacity from around 7.5GW at present to almost threefold by 2030. India is sticking to its three-stage nuclear programme, and with the successful development of a 700 MW indigenous PHWR in its arsenal, India is focusing on the second stage to install fast breeder reactors successfully ("India's Statement at Brussels" 2024). India currently has 23 active reactors, seven under construction, and the operable nuclear reactor power capacity is 6920 MWe ("Nuclear Power in India - World Nuclear Association" 2024). Figure 2.6 shows the map of India's nuclear power plants, operating and planned sites.

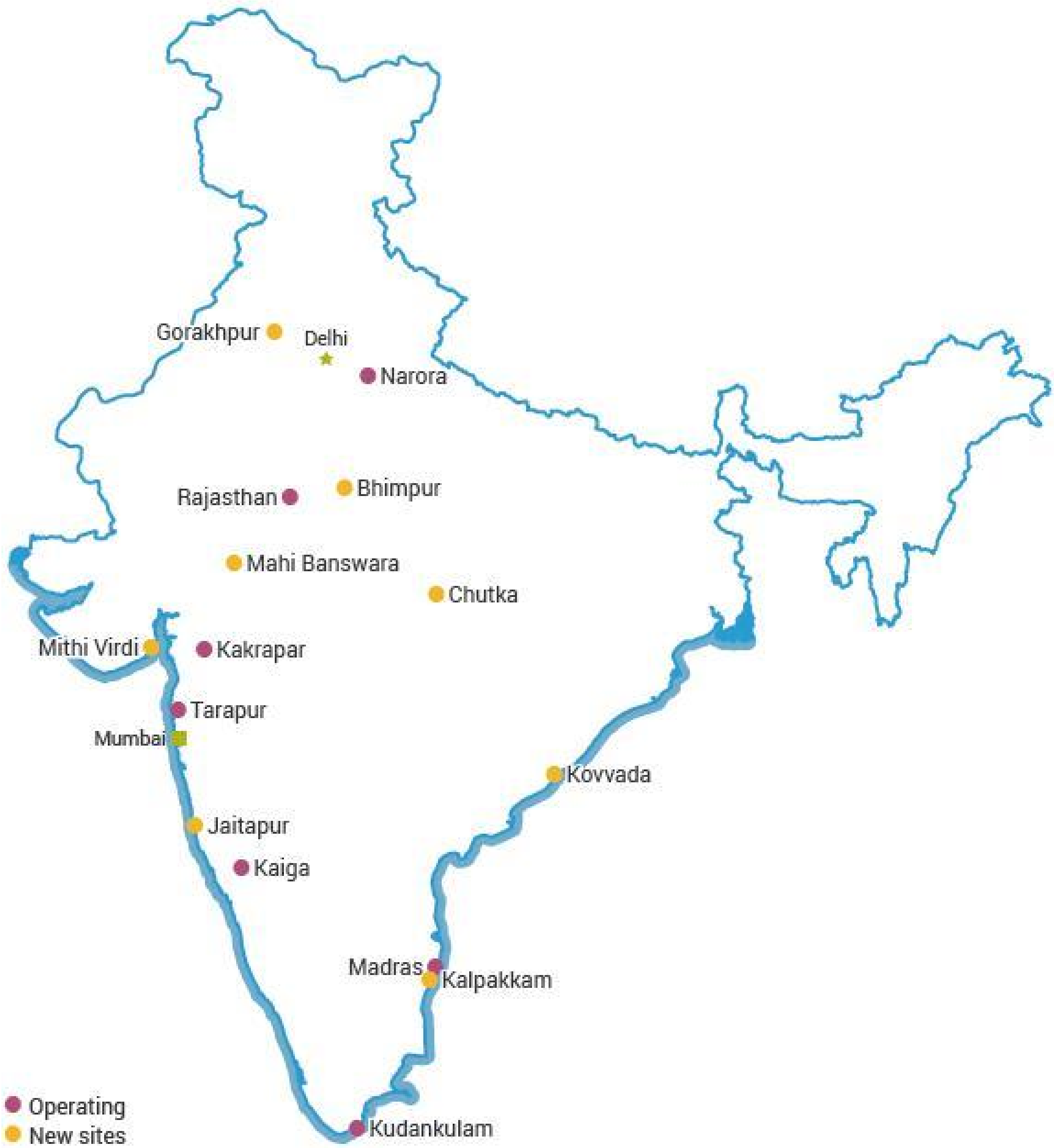

Figure 2.6 Locations of India's nuclear power plants ("Nuclear Power in India - World Nuclear Association" 2024)

The major share of the active nuclear power plants in India are based on PHWR technology and utilise indigenous and imported uranium.

The journey of the Indian nuclear power programme started with the installation of the very first BWR reactor in the 1960s. India focused on developing its own nuclear energy strategy without much foreign help as the country faced restrictions from the international community due to not becoming a party to the Non-proliferation Treaty. For the same reason, India was not part of the Nuclear Suppliers Group's cooperation. This led India to adopt the PHWR technology as it consumed less uranium. India had to depend on its limited amount of uranium resources for its research and development. During these times, India became self-reliant in uranium mining, fuel fabrication and nuclear waste management. India works with its three-stage nuclear energy programme and is currently developing fast breeder reactors as part of the second-stage goals. For uranium, India has 292,867 tonnes as identified resources in situ. Domestic mining is spread across seven different locations in India. The mines are managed by a public sector company, and private access is restricted as of now. However, India is now back on with international collaborations after the restrictions were lifted around 2008 and expects to import uranium for its increasing requirements. As the expansion plans are considered, nuclear energy gained much importance in the national energy portfolio as it was recognised as a key player in meeting India's long-term energy goals in the integrated energy policy published in 2006. The main aim of the policy was to build a comprehensive approach to meet India's growing energy demands. Nuclear energy was recognised and encouraged to pursue advanced reactor technologies for the better. Other key points included support for Indigenous mining of uranium and international collaborations. With support from the central government, India is pursuing a goal of 22,480 MW generation capacity by 2031 ("Integrated Energy Policy Report of the Expert Committee" 2006).

2.3.3. Existing Nuclear Policies in India

India has grander ambitions in the energy sector and considers nuclear energy to be one of its crucial elements in achieving them. Indian nuclear energy programme has a long history, starting even before the independence of 1947. The formation of the Tata Institute of Fundamental Research (TIFR) in 1945 laid the foundation of nuclear research in India (Ramakrishnan 2022). Soon after its independence, India entered nuclear space, among other countries, in 1948 by establishing the Atomic Energy Commission (AEC), and soon after that, the Department of Atomic Energy was under the office of the Prime Minister (Chaturvedi 2000). In less than twenty years, by 1963, India had completed the construction of two research reactors and four commercial nuclear power reactors (Chaturvedi 2000). So, India was always aware of the importance of nuclear energy and commenced the necessary efforts to explore its potential from a very early stage. The prominent cornerstone of India's nuclear policy is adopting the Atomic Energy Act of 1962. The act deals with almost every aspect of the development and governance of India's nuclear energy sector. Outside the The Atomic Energy Act, ("The Atomic Energy

Act” 1962), India has devised a nuclear energy program of its own. The three-stage nuclear energy program is the master plan of India’s efforts to develop nuclear energy in the country (Sekhar 2022). The activities related to the generation of nuclear power are carried out by various Public Sector Undertaking (PSU) companies, international collaborations, incentives and subsidies from the central government and future research initiatives.

According to the “The Atomic Energy Act” (1962), the document provides the provisions and definitions related to the use of atomic energy for the people of India. The acts clearly state that in India, nuclear energy should only be used for the welfare of the people and for other peaceful purposes. Additionally, it gives clear definitions to 'atomic energy', 'fissile material', 'prescribed substance', 'prescribed equipment', 'Government Company', and 'radiation' along with their interpretation. The act defines the power vested in the central government regarding nuclear matters in the country and empowers the government to oversee mining, construction, production and disposal operations. The government can allow or prohibit the production or use of atomic energy in the country. The decisions regarding the equipment used for production or use are also vested under the central government. When necessary, the government has the power to acquire minerals, land, mines, plants, and related equipment for the sole purpose of ‘atomic energy purposes’. The central government can also transfer the rights and liabilities of a contract with the third party to itself if need be. The act has clear sections on the discovery and safe disposal of uranium. Additionally, the act gives control to the central government for uranium mining or substances containing uranium. Any activities related to uranium mining, including the use of equipment, are prohibited without a license from the government. Regarding thorium, the act has a session explaining the procedure of thorium if discovered by any individual. It has to be reported to the government without fail. Along with the Atomic Energy Act, there are some more significant acts under the Atomic Energy Act supervising matters regarding atomic energy and radiation protection. The document “Atomic Energy (Working of the Mines, Minerals and Handling of Prescribed Substances) Rules” (1984), deals with the rules and procedures regarding the handling of radioactive substances. It defines the terms competent and licensing authorities. According to the rules, any party with licenses issued from the central government can get involved in mining and related activities. A particular set of criteria must be fulfilled to get the licence from the authorities. The act also mentions stabilisation and decontamination work that needed to be carried out upon closure of a mine. The act also mandates that the operation is allowed only if it benefits the general public, operates with the latest technology and with due sensitivity towards the environment. Additionally, the act outlines the disposal of mining waste to avoid any environmental impacts. The "Atomic Energy (Safe Disposal of Radioactive Wastes) Rules" (1987) deals with the regulations regarding the disposal and handling of radioactive waste. The competent authority mentioned in the act is the Atomic Energy Regulatory Board (AERB), and only the AERB can give the clearance to carry out any disposal activities regarding radioactive materials. According to the AERB, the country has adopted a closed fuel cycle system. This method majorly reprocesses and reuses the fuel spent in a reactor. Only about two to three per cent of the fuel spent becomes waste, and the rest is reused. These waste materials are currently stored in geological disposal facilities ("Radioactive Waste Management | AERB - Atomic Energy Regulatory Board" 2024). Outside these acts, there are also "Atomic Energy Factory Rules" (1996) "Atomic Energy (Control of Irradtion of Food) Rules" (1996) and "Radiation Protection Rules" (2004).

2.3.4. Nuclear Energy Initiatives by India

The basic structure of India's nuclear energy program is the three-stage programme formulated by Dr Bhabha in 1954 (Sekhar 2022). The aim is based on the idea of making India at the end of achieving this sequential program's goals. The programme envisaged using India's existing uranium and thorium sources and a closed fuel system for the reactors. The waste from one stage is expected to be reprocessed and used as fuel in the next stage. The program's first stage contains the use of PHWR based on uranium. The spent fuel is cooled and reprocessed to recover uranium and plutonium and remove other fission products. The uranium and plutonium recovered from the first stage are then used as fuel for the Fast Breeder Reactors (FBR) in the second stage. Due to the working principle of breeder reactors, they produce energy and fuel which can be used again. The third stage of the nuclear program uses breeder reactors based on thorium for power production. As part of the second stage of development, India successfully commenced the 'core loading' process of its first-ever fast breeder reactor with a capacity of 500 MWe ("Commencement of Core Loading at Fast Breeder Reactor" 2024). Figure 2.4 shows the basic structure of India's three-stage nuclear program.

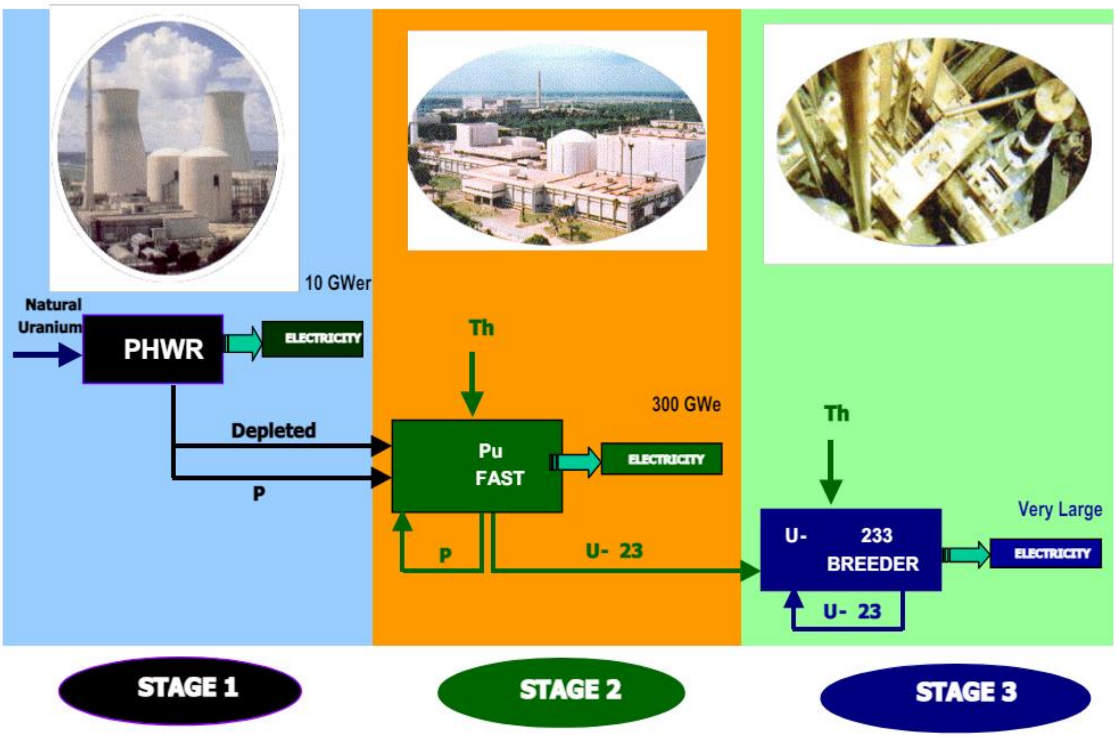

Figure 2.7India's three-stage nuclear programme (Jain, n.d.)

As part of the third stage of the nuclear program, India is conducting research and development to utilise its thorium resources as fuel for the future. The research initiatives include the development of a 300 MWe Advanced Heavy Water Reactor (AHWR) by BARC ("Annual Report" 2023). The idea of HWR gained attention in India due to its passive safety features and the possibility of using thorium as fuel instead of uranium. The passive safety features of AHWR make it possible to be constructed near populated regions ("BARC Activities for Indian Nuclear Power Program" 2024). AHWR is considered an initial step towards a large-scale utilisation of thorium for India's future nuclear power plants. India is operating a special-purpose research reactor named KAMINI with a capacity of 30 KW. It has the speciality of being one of a kind in the world to use Uranium-233 as fuel ("Annual Report" 2023). Outside these reactors, India is developing its own reactor technology to utilise the thorium resource as part of the 3rd stage in its nuclear program. The Indian molten salt breeder reactor (IMSBR) is the country's solution for the future. IMSBR, with a capacity of 850 MWe, was conceptualised by BARC, and as a pilot project, BARC initiated the development of an IMSBR with a capacity of 5 MWTh (Maheshwari et al. 2021). In addition, another reactor technology, Innovative High-Temperature Reactor (IHTR), is also under development by BARC. The main aim behind the development of IHTR is to provide high-temperature process heat for hydrogen production through thermochemical water splitting ("BARC Activities for Indian Nuclear Power Program" 2024).

It is important to note that, in India, Only the central government has the power to coordinate every activity related to nuclear energy, and the government do it through several Public Sector Undertaking (PSU) companies. However, India has recently initiated talks to invite private investments into the sector, which is a first in India's history (Singh 2024). The PSUs include research institutes like BARC, IGCAR, etc., which coordinate every research and development-related task in India and companies like Nuclear Power Corporation of India Limited (NPCIL), which is involved in constructing power plants. The mining of resources is carried out by the PSU Indian Rare Earth Limited. One outreach activity India has recently adopted to raise awareness of nuclear energy is the memorandum of understanding signed by NPCIL and NCC ("NCC & NPCIL" 2024). Outside these domestic policies, India has made commitments to several international agreements, adherence to the safeguards published by the IAEA and several civil nuclear cooperation agreements. Some of these include the agreements India signed with foreign countries like the United States of America, Japan, Russia, France, etc., with an aim of nuclear technology exchange and fuel supply.

3. Advanced Nuclear Reactors up to 300MW: Current and Future Prospects for India

A detailed analysis of the energy sector in India shows that the country's energy sector is undergoing a rapid evolution. Ever growing urbanisation and economic development demand intense energy consumption more than ever. To cope with the rising energy demand, the national government has designed and launched a myriad of projects for the future. These projects include a considerable investment in renewable energy-based power production such as solar PV, Wind, Bio-mass, hybrid systems and Nuclear energy. The primary aim is to diversify the energy mix and reduce the dependency on fossil fuels to achieve the national goals towards fulfilling the country's commitments under the SDGs. A successful transition to green energy is more crucial than ever. However, at this critical juncture for the country, accomplishing these goals comes with its fair share of challenges and complications. Significant issues of many statuses linger over the nation's attempts to transform these plans into reality. Some crucial hurdles along the way include the issue of last-mile connectivity, geographical difficulties in implementing renewable energy-related projects, high primary investment and operational cost of such massive projects, Weather conditions, grid stability and scalability, at the least. This chapter attempts to look further into these challenges and evaluates how advanced nuclear reactors with capacities up to 300 MWe could potentially avoid some of these issues entirely or partially to aid India's ambitious future energy projects.

3.1. India's path to energy transition: Current Challenges and concerns

Out of the multiple significant challenges India faces regarding the electrification of the country, last-mile connectivity is the most important. The vast diversity in geography, demography and economic status prevents the country from achieving universal electrification. Even the consumption pattern of the country varies depending on the region. There is an increasing gap in electricity consumption when it comes to rural and urban India (Nathan, Das, and Ps 2022). Due to the increased urban population and industrialisation, India has seen rapid growth in its electricity consumption in cities, which results in the consumption of low-grade energy, leading to a gap between demand and supply in the rural parts of the country (Kumar et al. 2020). Initiatives like Saubhagya in 2017 from the national government helped to level up the gap in numbers. As mentioned in previous sessions, through the aggressive implementation of national initiatives across the country, there is free or subsidised grid electricity for rural areas (Agarwal 2022). Even though the initiative made a massive impact in numbers, the reliability and uninterrupted supply of electricity is still in question. Despite the emphasised success of schemes like Saubhagya, a large number of families in rural Indian areas lack access to a reliable and uninterrupted supply of electricity. Even though the grid could reach far-fetched lands of rural areas, the quality remains problematic. The goals have always been hindered by issues like difficult terrain, maintenance issues, inadequate infrastructure, and villagers being unable or unwilling to pay. Extending the national grid to such difficult and far away terrain comes with a huge investment. The people cannot afford this electricity without subsidies. Even with the subsidies, the power is unreliable. Such frequent power outages and voltage fluctuations affect their daily life and limit the usage of their daily appliances. Lack of electricity is a major indicator of a country's holistic development. It negatively affects basic services people need, like access to decent health care, agriculture, and quality education, hindering all lives and livelihoods (Agrawal, Kumar, and Joji Rao 2020). Schools in such villages face a tough time due to the unstable supply of electricity. With times changing, students are struggling to keep up with modern tools and technology to aid their education, like computers and the internet, which is extremely important at this time. Lack of power also affects the study hours of these institutions. Without a continuous supply, poor lighting situations affect the student's learning outcomes and future possibilities. Healthcare and agriculture are as important as education in India. Complication in reliable power supply is a severe issue in the health care system, especially in rural India. The rural population does not have the luxury of hospitals on every corner or rushing to a private hospital whenever there is an emergency. Indian rural areas already suffer from a lack of access to quality health care. The government and private sector majorly invest in health care in urban settings("Healthcare Access in Rural Communities in India" 2019). In the severely underperforming rural healthcare sector, a lack of reliable electricity can only worsen things. Essential medical equipment, temperature-sensitive medicines, treatment procedures, etc, are compromised and pose a danger to the people. In the agriculture sector, productivity is severely affected. Seventy per cent of the rural population in India still depends on agriculture as their primary mode of income, with 82 per cent of them in the small and marginal section ("India at a Glance | FAO in India | Food and Agriculture Organization of the United Nations" 2018). Clearly, agriculture is a significant part of India's rural lifestyle. Inconsistent power supply massively affects the irrigation and post-production storage part of the agriculture sector. Needless to say, these three major sectors contribute significantly to India's economic development. Any hindrance in the performance of these sectors will cause a negative shift in the country's development. Additionally, India's widespread medium- to small-scale entrepreneur sector heavily depends on reliable power supply. The problem is only growing bigger considering the future scenarios. India is facing a multitude of challenges, like population growth, rising urbanisation, and economic inequality. The demand for reliable power will only increase in the future. With the expected population growth and urbanisation, the demand for power will go up, which will directly translate to increased infrastructure and, essentially, production. The migration of people from rural to urban areas will cause an explosion in power consumption. The new suburban areas resulting from such migration will demand reliable and uninterrupted electricity. And at this point, providing electricity of that magnitude is definitely a challenge. Also, lack of access to electricity could boost the already existing economic inequality in the country by widening the gap between urban and rural areas. Following that, such economic inequality could be further widened by the lack of technology penetration rural areas will face due to the inaccessibility of reliable power. Additionally, the lack of electricity will limit households from using conventional fuels like coal, diesel, and kerosene for their daily needs. It can negatively affect their health and contribute to increased pollution of their surrounding environment. Eventually, it will hinder the country's aim to achieve environmental goals in the long run. These concerns clearly show the necessity of addressing the last-mile connectivity issue in the country.

Another major challenge the country faces in improving its electricity sector is the financial health of the distribution companies (DISCOMS). They are an integral part of a nation's energy supply chain and a very crucial one. DISCOMS interact directly with the end users, making them vulnerable to financial issues even more than the other players. The financial difficulties are mainly caused by the losses from transmission and distribution losses, illegal consumption of electricity from the power lines, unmetered or dysfunctional connections, and inefficient collection practices. Among these major issues, apart from transmission and distribution loss, everything else takes place at the end-user front. The subsidised and even no-cost electricity provided to certain categories like agriculture and extreme-backwards communities presents a mismatch between electricity procurement expense and the revenue from the collection. Such financial instability of DISCOMs in India has implications in the long run. The mismatch in revenue and expenses will lead to a complicated purchasing situation for the DISCOMs. Even though enough money was collected from the end users, the companies struggled to purchase power from the producers. When there is insufficient purchasing, it will lead to scheduled and unscheduled power outages in the country. The instability is reflected in infrastructure development, too. The inability to invest in new infrastructure and maintenance of the existing infrastructure results in further inaccessibility and breakdowns. It will add to higher technical losses. This inadequate investment in the system is affecting the service quality as well. The users facing discomfort will eventually lose trust in the DISCOMs. It will lead to even more significant complications. Financial distress also prevents them from investing in cleaner technologies and meeting regulatory compliances and safeguard measures. All of these existing issues are slowly causing the DISCOMs to accumulate debt. Debt management always prevents companies from investing in new technologies and improved operations. These concerns will become even more critical in the future as our demand is only going up. Financial stress will bring down the efficiency of them even more. Growing demand is a primary concern for

DISCOMs. As discussed in the previous sessions, the growing population, rising urbanisation, growing industrial sector, etc., will keep adding pressure on the companies to supply reliable power, and the companies must evolve. Added demand means improved and increased infrastructure from the DISCOM side. With a financial crisis on the side, investing in new infrastructure will be a complicated move. Regulatory compliance is also going to be problematic in the future. With the government strengthening their regulations and safeguards to keep the services safer and green day by day, complying with them, especially in the environmental and infrastructure efficiency regulations, will add additional pressure on the companies. The topic of rural electrification is closely associated with the financial struggle of DISCOMs. Rural electrification is a priority for the government, and expanding the network falls directly under the responsibilities of DISCOMs. Extending the grids will cause an increased tariff for the consumers. In rural areas, the consumers are mainly in the lower and/or lowest income category and cannot afford the increased tariffs unless it is heavily subsidised. This will eventually be reflected in the revenue of DISCOMs. Also, this will cause an increased illegal consumption. People tend to steal electricity for their private use when it is no longer affordable to them. Unaffordability and reliability play an essential role in keeping the relationship between people and DISCOM smooth. Also, as the regions are remote and far away from the service stations, operation and maintenance are delayed, further complicating the reliable supply to the rural population. Addressing these existing and future concerns is extremely important and time-sensitive.

Another significant concern when it comes to a highly populated country like India is regarding the land requirements. Increasing power production in any capacity requires land acquisition to a great extent. Especially with India's focus on adding renewable energy to the mix, projects based on solar and wind take up extensive tracts of land. Solar projects require vast open lands with minimal to zero shading, and wind farms are possible only if there is a consistent wind flow. Such complex requirements of these projects might take up substantial land areas that could otherwise be used for agriculture, residential buildings, or even the natural ecosystem. This is a complex situation that involves a multitude of legal, socio-political, and economic challenges. Major concerns related to such renewable projects are the proportion between generated power, the land utilised to produce that power and the existence of supporting infrastructure. Claiming such a substantial amount of land area will lead to issues like years-long legal battles that delay the project, social unrest due to possible displacement of communities, trading off fertile land instead of using it for agriculture, the economic burden for the state from paying off land owners and last but not the least, a number of environmental concerns from disrupting the local ecosystems. The future does not look promising either. The country cannot increase its dependency on fossil fuels, and the preferred solution is to turn to green technologies. However, installing more solar and wind systems comes with all these issues. With an increasing demand for reliable power, the demand for land will intensify, accelerating all the above-mentioned concerns. The issue of grid stability and weather dependency are closely associated with each other, especially when it comes to adding more generation capacity through renewables. Solar and wind are heavily dependent on weather conditions. Varying weather conditions will result in an unpredictable power output from such production projects. This is a challenge to maintain a reliable power supply. However, such unpredictable power output from renewable plants creates a massive challenge to the stability of the power grid. The traditional power grids are designed for stable power transmission. The intermittency issues from renewable sources can cause variations in the voltage and eventually lead to blackouts or power surges. This calls for investments in improved storage and extra infrastructure systems in the future. As renewable integration increases, grids need to be appropriately managed to avoid any type of power interruptions. Supplying constant power is the best available option for optimum grid performance. Last but not least, the country must also address its issues regarding regulatory hurdles and dependency on fossil fuels. Complex projects are often delayed by bureaucracy uncertainty and approvals delays. Old, inconsistent, or even non-existent policies often hinder the implementation of new technologies. As the energy sector evolves and the number of projects increases, the need for streamlined regulations and adaptive and forward-thinking policies will become much more critical. This will eventually result in efficient investments and rapid growth in the energy sector. Dependency on fossil fuels is a significant concern for India. India still depends on coal, oil and gas for most of its energy production. This makes the country vulnerable to global market fluctuations when trading these resources. Global fuel prices and geopolitical tensions can affect the country's energy security, economic development and environmental concerns. India cannot continue depending only on fossil fuels in the future as countries across the globe are battling climate change. Shifting towards renewables and finding an indigenous energy source should be India's top priority in staying independent in the energy sector. Additionally, an important aspect which can influence all of these sectors is the privatisation of India's energy market. Even though

India now projects a positive environment towards private investment in the sector, it has been mostly associated with the DISCOMs ("Bringing the Private Sector into India's Energy Sector" 2024). Letting in private investments could open a lot more opportunities for the country to deal with its increased energy demand. Table 3.1 outlines the challenges and future concerns discussed so far in a condensed form.

Table 3.1Significant challenges, impacts and future concerns of the Indian energy sector

Challenge	**Issue**	**Impact**	**Future Concerns**
Last-Mile Connectivity	Lack of reliable electricity in rural/remote areas	Hindered socio-economic development Education, healthcare, and agriculture impacted	Growing demand for reliable electricity Potential increase in regional inequalities Hindered economic growth
Land Requirements	Extensive land needed for renewable projects	Project delays and increased costs Legal battles and social unrest	Intensified land demand Displacement of communities Loss of agricultural land
Weather Dependency	Variability in solar and wind energy generation due to weather	Unpredictable energy output Grid stability challenges Need for backup	Altered weather patterns due to climate change Need for advanced Forecasting technologies

		power sources.	Need for a diversified energy mix
Grid Stability	Integrating intermittent renewable energy into existing grid	Instability, voltage fluctuations, blackouts Compromised electricity reliability	Increased complexity in managing grid stability Necessity for smart grid technologies Energy storage solutions Robust grid management strategies
Financial Health of DISCOMs	High losses, theft, inefficient billing practices	Difficulty in purchasing power Challenges in investing in infrastructure upgrades Service disruptions Declining service quality	Strained financial health with increasing energy demand Need for comprehensive reforms to enhance operational efficiency The financial burden of extending the grid to rural areas where villagers may not afford electricity
Regulatory and Policy Hurdles	Complex regulatory frameworks	Uncertainty in project approvals Increased project	The necessity for adaptive regulatory frameworks

	Bureaucratic delays	Costs Investment deterrence	Streamlined Regulations Predictable investment environment
Dependency on Fossil Fuels	Heavy reliance on imported fossil fuels for power and Transportation Vulnerability to global market fluctuations	Energy security is affected by volatile fossil fuel prices and geopolitical Tensions. Economic stability impacted	Imperative transition from fossil Fuels Acceleration towards renewable energy Development of domestic energy resources Reduced vulnerability to global market dynamics

It is abundantly clear that India faces significant challenges in its energy sector, especially considering the future scenarios. Suppose the country needs to tackle these challenges efficiently. In that case, it needs to focus on more comprehensive strategies, which include areas such as increased power production, efficient distribution, affordability, investment in green energy, and public-private partnerships. Policies and regulatory frameworks play a crucial role in this process. A careful approach is more than a necessity for India at this point to emerge independent in the energy sector.

3.2. India's Path to Energy Transition: Overcoming Challenges with Advanced Nuclear Reactors of Capacity Up to 300MWe

The challenges India is facing are spread across the spectrum of technical, socio-political, economic and environmental concerns. A single-point strategy is never the solution to the issues India is facing. However, the potential of nuclear energy, especially advanced nuclear reactors with capacities of up to 300MWe, offers a set of viable solutions for India. The lack of reliable and uninterrupted electricity access in India is a significant concern for its sustainable development. An economic development based on energy access is highly possible with a bottom-up, holistic approach in the energy sector (Ailawadi and Bhattacharyya 2006). This is where the numerous possibilities of advanced reactors with smaller capacities shine. They offer some significant potential advantages in the fields of enhanced production and distribution, investments, reliability and long-term operation. Again, such advanced reactors cannot single-handedly solve India's issues in the energy sector. Instead, the solutions they offer can efficiently bring the gaps in the current system closer than ever before. India currently has no nuclear reactors that can be categorised as advanced reactors with capacities of up to 300 MWe. So far, the country has uranium-based medium-sized Pressurised Heavy Water Reactors (PHWR) of capacities between 200 and 220 MW. These share no similarities with the new reactor technologies. They are well-established, commercially proven technologies in the nuclear industry. And they have been in operation for several decades. Even though they offer some advantages over conventional Light Water Reactors (LWR) of high capacities like 1000 MW ("Nuclear Fission and Types of Nuclear Reactor" 2015), they are not as competent as advanced reactor technologies when it comes to smaller power production capacities. Let's look at the particular advantages of advanced nuclear reactors with smaller capacities of up to 300 MWe.

One significant advantage such reactors offer is their scalability and flexibility in deployment. Depending on the variable energy requirements, advanced reactors can offer adaptable solutions, unlike traditional reactors with capacities like 1000 MW. The advanced reactors can be developed with varying capacities. Typically, the capacities range from as little as 50 MWe to 300 MWe. This allows the design of a custom plan for regions with varying energy demands. The deployment can be flexible according to the demand, and this facility prevents the under or over-capacity associated with larger pants. Also, the advanced reactors can be deployed in a phased manner, meaning the capacity could be altered depending on the growing energy demand of the communities. Such flexibility and scalability on demand make it easier to deploy in various geographical locations. Such huge advantages make them an attractive solution for some of the challenges India is facing, especially with the last-mile connectivity. Advanced reactors of smaller sizes make it easier to achieve the goal of complete rural electrification. This is not just to provide electricity connections but to enable them to have reliable and uninterrupted power. As discussed, installing reactors closer to the demand areas will decrease the transmission distance and hence contribute to minimising the transmission loss. It will improve the efficiency and affordability of reliable power to remote locations. The flexibility and modularity of these reactors directly benefit the concept of decentralised power production in India. Also, by eliminating the long transmission lines, reactors close to the demand areas can improve grid resilience, too. Unlike renewables, advanced reactors can provide constant and adjustable power when it comes to grid stability. With varying demands, the reactors can adjust their power output. In this way, the network can avoid using additional storage units to compensate for interim losses. Since these reactors are smaller in size compared to other projects, they require significantly less land area. This factor is equally important in rural electrification as well as for powering new cities. Growing power demand due to urbanisation also benefits from such modular reactors. Even in environmentally sensitive areas with power demand, such reactors could be considered as a viable option. Additionally, since the reactors follow a standardised design and are modular, they even allow the possibility of remote manufacturing. They could be manufactured in a central facility and installed elsewhere, minimising land disturbances. Lesser land footprints automatically result in fewer disputes regarding land use and faster commencement of projects.

Another significant advantage of such advanced reactors is the lower initial investment. Less capital investment really aids the rapid development of energy production. As discussed before, the modularity of such reactors significantly helps reduce initial investment. Such a reduction in the upfront investment makes it an attractive option for investors. The cost efficiency is closely associated with the modularity of the reactors. Besides the lower upfront cost, the production cost is also reduced to a good margin. Two major factors, eliminating on-site construction and standardised design, give them the edge in financial savings. Taking advantage of the standardised design of these reactors allows for economies of scale in manufacturing. This will further reduce the cost of production. This financial accessibility and the ease of deployment offered by such reactors will boost the economic feasibility of such projects and thus accelerate the green energy transition. The reduced upfront cost will help the country to adopt nuclear power in a broader aspect. Financial benefits coupled with flexibility will provide the economic benefits local communities seek. Additionally, these economic benefits significantly help the DISCOMs that are under severe financial stress. Reduced upfront cost, reduced transmission cost, and the possibility of phased deployment will monumentally help DISCOMs improve their financial health. Matching the demand growth with technology with lesser upfront costs will reduce the risk associated with their investments. Also, such reactors offer them more control than other technologies. However, the reduced manufacturing cost of such advanced reactors does not mean that they compromise on their safety features. As we have already seen in the previous chapter, they come with enhanced safety features and lower risk profiles. Especially when it comes to the safety of traditional reactors, the passive safety features of such reactors bring in a great sense of safety. A combination of these passive safety systems, simplified and standardised design, reduces the risk of accidents compared to traditional reactors. Such reduced risk profile of advanced reactors makes them a potential choice for deployment in various locations, even closer to populated areas. Additionally, a broader population can benefit from clean energy through public awareness about the enhanced safety measures. Overall, the enhanced safety measures of advanced nuclear reactors offer significant advantages for nuclear power. By minimising risks and improving public opinion, they provide a better chance to face the challenges in the energy sector.

The socio-political advantages of advanced reactors up to 300 MWe are also essential for India. In addition to the direct economic benefits outlined above, such reactors help mitigate issues across multiple sectors. They offer a strategic advantage by ensuring India's energy independence and long-term energy supply. Unlike colossal solar and wind farms, the weather independence of advanced reactors helps them provide a stable and reliable energy supply. This is a considerable advantage for rural and regional areas prone to extreme weather conditions. This stability will bring the energy gap between urban and rural regions of India, thereby improving the essential services like education, health care and agriculture. A reliable and uninterrupted power supply will also strengthen trust between people and energy providers. Holistically, this switch to advanced nuclear power will enable India to shift its focus from fossil fuels. That directly translates to less import of resources from the international market and greater energy independence for the country. Economic stability is also improved because the price volatility of fuels in the global market will no longer considerably impact India's energy sector. As the energy sector becomes more stable and reliable, there will be positive changes in the industrial and economic growth in India. Without power shortages and interruptions, the productivity of the country's industrial sector will see a gradual improvement. It can lead to attractive investments in the country. The current issues of unemployment and under-employment rates in the country could be reduced by a limit. Better economic development and the development of the nuclear industry in the country will open up both direct and indirect employment opportunities for skilled and unskilled labourers. As the nuclear sector develops, investment in innovation and technological development will also rise. India will attract top talents, drive up scientific research and develop new technologies. Table 3.2 sums up the major advantages of using advanced nuclear reactors to overcome the challenges. For ease of understanding, these advantages are divided into technical, socio-political, economic and environmental categories.

Table 3.2 Major advantages of using advanced nuclear reactors in India's energy sector

Categories	**Solutions**
Technical	Scalability and Flexibility
	Decentralised Power Production
	Enhanced Safety Features
	Reliable and Stable Power Supply
	Technological Advancements and Innovation
Socio-political	Energy Independence
	Improved Essential Services
Economical	Lower Initial Investment
	Economic Growth and Job Creation
Environmental	Support for Climate Goals
	Reduced land use

The investment in new reactor technologies can holistically affect the country's development. Any productive outcome from the new technology can strengthen India's economic footprint on the global level. Exporting new technologies and expertise can potentially open up new revenue streams, too. Additionally, sustainable development and environmental impact will also have positive effects. The energy sector is one of the largest contributors to GHG emissions. Nuclear energy is considered green due to its low emission characteristics. The emission profile is even better if advanced reactor technologies of lesser capacities are implemented. Development in all three pillars of sustainable development, social, economic, and environmental, will accelerate India's goals for climate action.

3.3. Nuclear energy, Hand in Hand with Renewables

One prominent aspect that needs to be addressed separately is the possibility of combining nuclear energy and renewable energy in the energy mix. Especially for a country like India, where the switch from non-renewable energy sources is a necessity in order to achieve the climate goal quicker, penetration of low-emission methods into its energy mix is more crucial than ever. India already has big plans to install ambitious power production projects using solar and wind energy. Driving up the use of renewables is essential for the country's energy profile. However, the central issue of weather dependency associated with every solar and wind power project exists in this case as well. Solar irradiation, cloud cover, geographical restraints, minimum wind velocity, etc., still play a key role in determining the power output from renewable power projects. At this crucial point, integration of nuclear power, especially advanced nuclear reactor designs with a generation capacity of up to 300 MWe, can come in as a potential way around. As mentioned multiple times before, Nuclear energy is not a single-step solution to India's energy problems, nor can it single-handedly power the entire country's demand. Instead, it provides solutions to get one step closer to a successful green energy transition for the country. To achieve that goal, every possible scenario has to be explored. Combining advanced nuclear reactors with a capacity of up to 300 MWe is one such solution to ensure the supply of green energy.

Besides the advantage of renewable energy being the best option to reduce carbon footprint in the energy sector, its weather and geographical dependency cause serious damage to the final power output. Without optimal conditions, the power output is often compromised, damaging the grid network and power reliability. The power fluctuations caused by such issues need to be eliminated by some other means to minimise the damage.

One of the most common ways is to use other sources of electricity in a load-following configuration to compensate for the variations in output. Traditionally, hydroelectric and nuclear power plants are the optimum choices due to their minimal carbon emission and ability to generate abundant power. However, large hydroelectric projects are less attractive due to their higher environmental impact. Consequently, nuclear power stands out as a viable option for this issue. To compensate for the interim power issues of renewable energy plants, the nuclear reactors should be designed in such a way that they have enhanced load-following capabilities. Many traditional nuclear reactors of larger capacities are designed as baseload-generating plants to operate continuously at full capacity. So, it is not an immediate solution. On the other hand, converting or operating some large nuclear power plants as load-following involves complex power manoeuvring procedures and components capable of handling thermal cycling (Ingersoll et al. 2015). For these types of operations, using newer technologies like advanced nuclear reactors of capacities up to 300 MWe could be highly beneficial. Such reactors offer the required flexibility and ease of operation compared to traditional reactors and help resolve the intermittency issue of renewable power generation. These advanced reactors can provide support to the grid through a variety of load-following capabilities. Some of these operational capabilities include processes like ramping, automatic responses to fluctuating frequency and managing step changes in output (Ingersoll et al. 2015). Ramping is the process where the reactor's power output is changed in response to the changing load conditions. For example, whenever there is an increased power demand, through the process of ramping up, the reactor can increase its power output and meet the demand and vice versa. The speed at which reactors can increase or decrease their ramping capabilities is called ramp rate. The advanced reactors have ramp rates up to 40%. This is a vital advantage of such reactors when they are used in load-following capacity. Combined with other technical advantages mentioned above, advanced nuclear reactors are a viable option for load-following scenarios, making integrating nuclear and renewable easier and more critical. Figure 3.1 shows the result from an experiment conducted where an advanced nuclear reactor of a capacity of 50 MWe is used in combination with a wind farm.

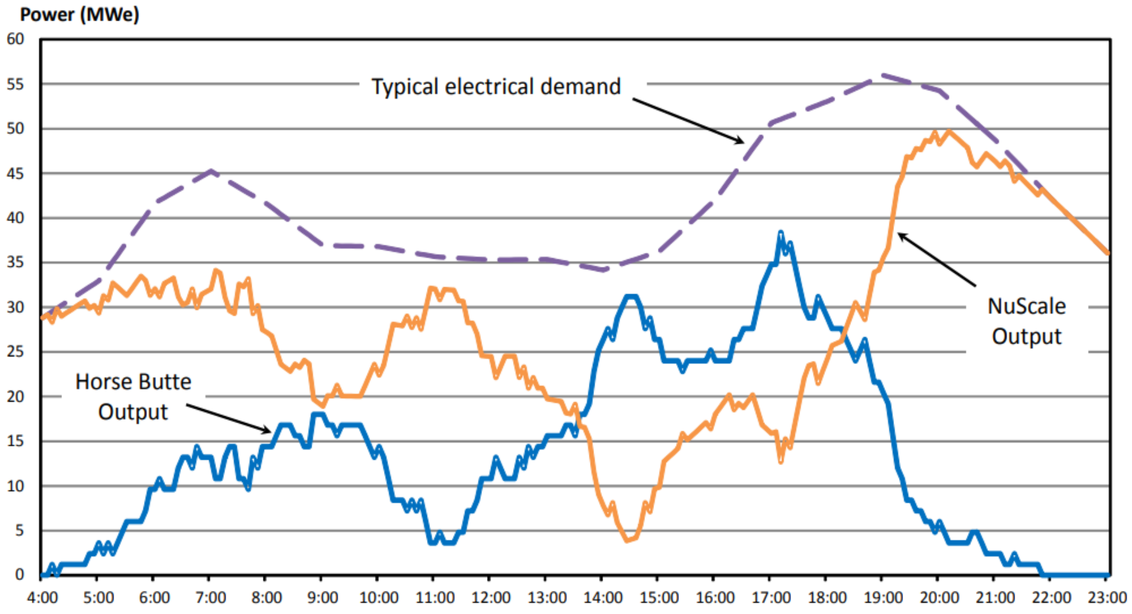

Figure 3.1A combination of wind power and nuclear energy (Ingersoll et al. 2015)

The reactor was developed by a company called NuScale, and in the experiment, they used it in a load-following configuration with the output from the Horse Butte wind farm. considering the daily power demand and the wind farm output, the reactor adjusted its power delivery to compensate for the fluctuations from the wind farm. This experiment is a perfect example showing the possibilities of the load-following capabilities of advanced nuclear reactors. This scenario could be extrapolated to fit real-life electricity demand by adding additional reactor modules. For India, this is an incredibly viable solution. A combination of renewable and nuclear energy can solve many issues the energy sector is facing at the moment and challenges in the future.

However, it is to be considered that this is a relatively new technology, and even though it is comparatively better than traditional methods, there are technical and economic challenges. Especially when integrating two different technologies, renewables and nuclear. More research and development should be dedicated to these technologies before large-scale implementation. Such solutions require skilled and qualified personnel for their successful implementation. Also, institutional partnerships can be formed from within and outside the country. Economic challenges like the cost of new designs, additional equipment, economies of scale, etc., are also crucial to realise this technology. Ultimately, in an integrated nuclear-renewable environment, materialising these new technologies to overcome the challenges faced by the country depends on the economics, policy mandates and regulatory requirements for developing the load-following capabilities of nuclear reactors.

4. Analysis of thorium-based advanced nuclear reactors up to 300MWe in India

Energy security and sustainability are among India's top priorities, and the country is really focused on its goal of universal electrification with sustainable development goals in mind. Reducing the carbon footprint is a top criterion when implementing new energy projects. In the previous chapter, the advantages of investing in nuclear energy, especially in advanced nuclear reactor technologies of generation capacity up to 300 MWe, have been explored. Such advanced nuclear reactors in combination with other renewable projects and as stand-alone plants, bring in a significant number of advantages to the energy sector of India. Along with these benefits, India has an almost exclusive opportunity to further develop the technology and benefit even more. Whether it is technical, socio-political or environmental advantages, India has the chance to go the extra mile. And that depends on the abundant reserves of thorium India has at its borders. Thorium is a potential fuel for nuclear reactors and has several advantages over uranium. Using thorium in advanced nuclear reactors with a capacity of up to 300 MWe opens up a new world of opportunities for India. This chapter aims to analyse such critical benefits of adopting thorium for the nuclear energy needs of a country like India further, underscoring its potential not just to meet energy demands but to revolutionise the energy sector.

4.1. Advantages of thorium: An Indian point of view

Based on the previous sections, it is evident that advanced nuclear technologies appear to be a significant promise in shaping the future of energy production. The increasing planet's temperature and the rising need of the nations for energy independence push the planet towards methodologically new and innovative approaches to mitigate the problem. Among the nations that go this way, there is India. Geographically, India, within its borders, holds only a limited amount of uranium for conventional reactors (Vijayan et al. 2017). On the other hand, the country has a remarkable amount of thorium resources under its soil, and it could propel India's nuclear energy doctrine towards utilising thorium as an alternate fuel instead of uranium (Ünak 2000). As a matter of fact, India anticipates a large-scale utilisation of thorium for its future reactors (Anantharaman, Shivakumar, and Saha 2008). For India, thorium offers not just resource abundance but also a potential solution to several critical challenges. Reactors based on thorium can address these challenges in ways that traditional uranium-based reactors cannot. This is the major driving force for India to take up R&D in this sector. From table 2.2 before, it is clear that, even though India doesn't have any reactors that could poterntially be converted to utilise thorium, the country has started its research on future technologies focusing on thorium consumption. Waste reduction and management are other key highlights of thorium-based reactors. This advantage considerably affects the environmental impact of nuclear reactors, making long-term waste management more efficient. Additionally, uranium reactors inherently possess several safety concerns, one of them being the significant proliferation risk of nuclear materials. Thorium reactors offer enhanced safety features and considerably less proliferation possibility. Last but not least, as discussed in the state-of-the-art chapter, India's already existing three-stage nuclear policy considers the availability of thorium in the country and sees it as a potential fuel for long-term energy sustainability. Developing and implementing thorium-based reactors will strategically align with this existing policy and support India's growing energy demands. It will indeed aid the efforts to reduce carbon emissions from the energy sector as well.

4.2. India's Thorium Resource Abundance

According to officials from India's Department of Atomic Energy (DoAE), as of 2014, the country holds about twelve million tonnes of monazite, a thorium-bearing mineral, in its in-situ resources. This number is almost equivalent to a total of 1.07 million tonnes of usable thorium. The significant reserves are spread around six different Indian states, predominantly concentrated along the coast of Kerala, Karnataka and Odisha. The adjacent states of Kerala and Karnataka alone contribute to more than seventy per cent of the total reserves ("Thorium Reserves in Country" 2014). India tops the list of countries in the world with thorium resource, according to the "Thorium - World Nuclear Association" (2024), and Table 4.1 shows the distribution of thorium sources in India.

Table 4.1Thorium deposits in India ("Thorium Reserves in Country" 2014)

State	**Monazite (Million tonnes)**
Odisha	2.41
Andhra Pradesh	3.72
Tamil Nadu	2.46
Kerala	1.9
West Bengal	1.22
Jharkhand	0.22
Total	11.93

Such a large concentration of domestically available thorium could ultimately ensure India's energy security. The current dependency on uranium imports could be reduced to a great extent once the thorium reactors become operational. The stable and abundant amount of thorium ensures an uninterrupted supply of nuclear fuel for the country, significantly improving the life span of the nuclear program. Additionally, the aspect of implementing fuel breeding technology highly benefits the utilisation of thorium as a fuel. Thorium cannot continue a nuclear chain reaction on its own, meaning it is not a fissile material. In reactors, the thorium-232 is first converted into uranium-233 to make it into a fissile material and then used for chain reaction. This conversion of fertile material into fissile nuclear fuel is called fuel breeding (Internationale Atomenergie-Organisation 2005). The fuel breeding technology offers several advantages including

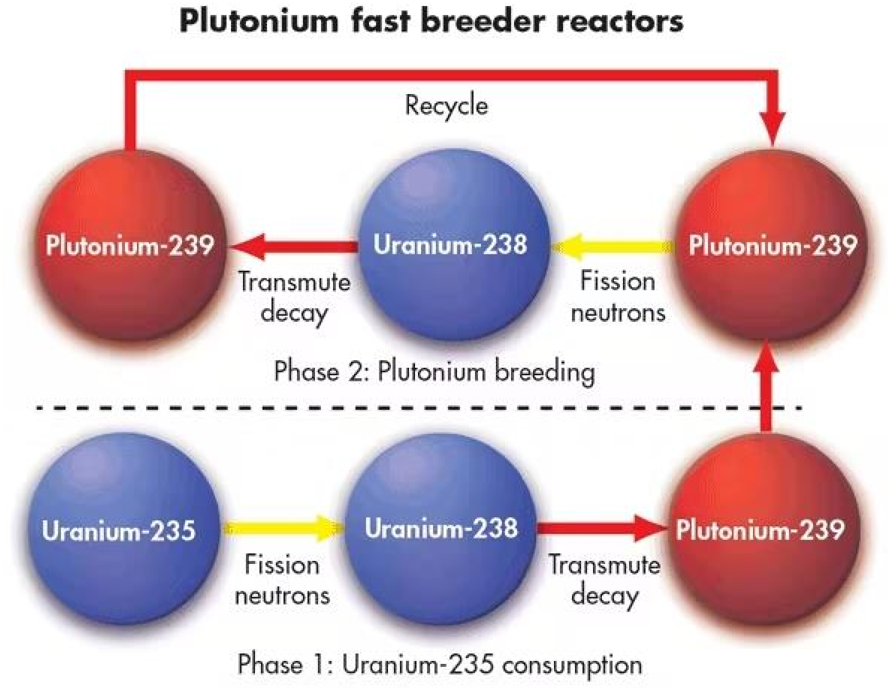

Figure 4.1Increased fuel consumption through breeding (Sorensen 2016)

the maximised utilisation of thorium fuel (Sehgal 2019). Figure 4.1 shows the breeding cycle of plutonium involved in the thorium fuel cycle Where the plutonium provided the necessary neutrons to continue the thorium cycle (Sorensen 2016).

In this way, the efficiency and sustainability of the fuel cycle is significantly increased. A maximum amount of thorium can be converted into fissile uranium, and an efficient energy output can be achieved. In effect, this method will ensure the maximum utilisation of indigenously available thorium. Being independent regarding nuclear fuel is strategically crucial for India, considering its future predictions on energy usage and government plans to expand its nuclear energy capacity. By 2032, the government is envisaging a GDP growth rate of 7-9%, and to facilitate this growth, the country is planning to increase the installed capacity to a whopping 700 GWe. Out of this capacity, 63 GWe is going to be ("Nuclear Power in India - World Nuclear Association" 2024). Even though the number was later revised to 22.5 GWe by 2031, the plan is still in effect. Research and development in the nuclear energy field, especially in thorium, is already crucial for the country because of its earlier trade bans and India's non-participation in the Nuclear Non-Proliferation Treaty. It drastically affected the trade in nuclear plants and materials for almost thirty-four years and hampered the development of civil nuclear energy ("Nuclear Power in India - World Nuclear Association" 2024). Considering the projection in energy demand and lack of indigenous uranium, India is forced to diversify its nuclear fuel sources and explore its thorium potential, which is a potential solution. It can reduce the country's imported uranium dependency, enhance energy security and aid in fulfilling sustainable development goals. Hence, developing nuclear reactors using thorium as a nuclear fuel clearly gives India a strategic edge and the potential to lead the industry in the future outside its technical and environmental benefits.

4.3. Waste management and safety

Dependence on nuclear energy, in general, comes with the crucial disadvantage of managing nuclear waste. Waste management is complex, mainly considering nuclear waste materials' radioactivity and long half-lives. The long-lived actinides like neptunium, americium, and curium produced from nuclear reactors using uranium remain hazardous for a very long period, and their number is growing, reaching about 200 tonnes in 2020 (Korobeinikov et al. 2020). Their proliferation potential is also considered a significant threat (Todosow et al. 2005). At present, the only available mitigation measure for the issue of nuclear waste is to build stable storage for extremely long durations. Such storage facilities require vigorous containment strategies and comprehensive monitoring to prevent the waste materials from causing any harm to human health or the environment. The heat generated from the uranium-based reactor waste is another issue that needs to be addressed when building such storage. Dissipating this heat is extremely crucial to prevent any type of unexpected accidents (Bayliss and Langley 2003). The socio-political issues associated with waste management add an extra level of complexity to this issue on top of the technical challenges (Vander Beken, Dorn, and Van Daele 2010). Resistance by the general public towards nuclear waste and nuclear reactors, as well as the expense of constructing long-term storage facilities, further makes the process challenging to succeed. Especially for a country with a population of 1.2 billion[1], socio-political issues carry almost the same weightage as the technical challenges. Lessening of any kind when it comes to nuclear waste is extremely important for India. Here, thorium reactors offer a potential alternative to the issue. Even though the issue of nuclear waste cannot be avoided entirely, there are certain advantages that give leverage over the reactors based on uranium. A key advantage of thorium reactors is that they produce substantially less hazardous waste materials. In a closed fuel cycle, they have the potential to burn

[1] As of 2011, when the last official census of India was conducted

transuranic waste and lower the build-up of harmful waste isotopes (Fiorina et al. 2013). The waste materials produced from the fission process of uranium-233, which is created when thorium-232 is used as fuel, produce waste with shorter half-lives in comparison with the fuel cycle consisting of uranium-235 and plutonium-239. Due to this advantage of the reduced half-life of the waste produced, they can significantly minimise the risk of long-lived nuclear toxicity (Rubbia 2016). Also, regarding proliferation matters, replacing the 238U fertile components of the conventional low-enriched uranium in reactors with thorium fuel (232Th) can reduce the proliferation possibilities to a great extent (Todosow et al. 2005). Studies have shown that even in conventional reactor technologies like Light Water Reactors (LWR), thorium-based fuels can reduce concerts related to waste produced and proliferation (Todosow et al. 2005). Such advantages of thorium-based reactors directly translate into a simplified waste management process compared to conventional uranium reactors. The burden of extremely long-term containment with round-the-clock monitoring is eased by the thorium-based fission products that have shorter lives. It will also reflect on the cost of building storage facilities and help in mitigating the health and environmental impact associated with nuclear waste management. Considering these benefits, thorium is highly attractive for countries like India looking to find a balance between nuclear energy production and waste management. Also, the socio-political issues can be addressed through the implementation of thorium-based reactors to an extent.

Some other significant characteristics related to thorium-based reactors are regarding safety concerns. In addition to the shorter lifespan of waste material and lower proliferation possibility, other key advantages include the production of lesser prompt neutron flux, favourable thermo physical properties, and the inertness of ThO_2. The phenomenon of immediate release of neutrons after nuclear fission from the reactor is called the prompt neutron flux. They are crucial in the sustenance of the chain reaction. However, the safety of the reactor is affected by the rate and intensity of these neutron fluxes. A high number of this neutron flux can potentially cause rapid changes in the power levels and, in turn, could result in the reactor going supercritical state (Matejka, Kropík, and Kolros, n.d.). Hence, reactor designs are always considerate of the produced neutron flux to ensure a balance between safety and efficiency. This fact is crucial as thorium reactors could act as a potential alternative to this issue. They are inherently safer as the thorium fuel cycle produces lower amounts of prompt neutron flux compared to the fission from uranium-235 or plutonium-239, reducing the risk of unstable reactions from rapid power surges. The reduced prompt neutron reflux helps in case of an unexpected accelerated reactor activity by providing more time for operators to intervene as the reactor's response in this case will be slower than the traditional reactors (Internationale Atomenergie-Organisation 2005). This property enhances the overall stability of the reactor by reducing the likelihood of any unprecedented accidents. Additionally, the inertness of ThO_2 helps simplify the interim storage issue of the spent fuel. The oxidation of UO_2 in the uranium-based reactors into U_3O_8 and then UO_2 complicates the interim storage in the long run. The favourable thermophysical properties of ThO_2 in comparison with the UO_2 ensure the effective in-pile performance of the ThO_2-based fuel. This allows for a multitude of advantages for thorium-based reactors. The enhanced heat dissipation and safety margin are crucial as ThO_2 can efficiently transfer heat away from the fuel pellets to the coolant thanks to its better thermal conductivity. This property contributes to the safety margin as localised overheating could be avoided. The much higher melting point of the thorium-based fuel compared to uranium gives leverage to the structural integrity in higher temperatures. The risk of fuel degradation under high temperatures can be avoided due to the quality of thorium-based reactors. This enhanced thermal property results in a lower fission gas emission from the reactor. It helps prevent pressure buildup within the fuel rods (Internationale Atomenergie-Organisation 2005). Such improved thermo physical properties of thorium-based fuel cycle enhance the nuclear reactors' overall structural stability, longevity and efficiency. The thermo physical qualities enable the thorium-based fuel to withstand prolonged irradiation in the core and increase longevity. The overall economic benefits are improved due to these benefits. The improved in-pile performance and better physical properties can translate into optimised operation and power output, efficient fuel usage and longer fuel cycles, reduced fuel refillings, reduced operational costs and less downtime. Figure 4.2 shows the significant thorium advantages-based fission reaction.

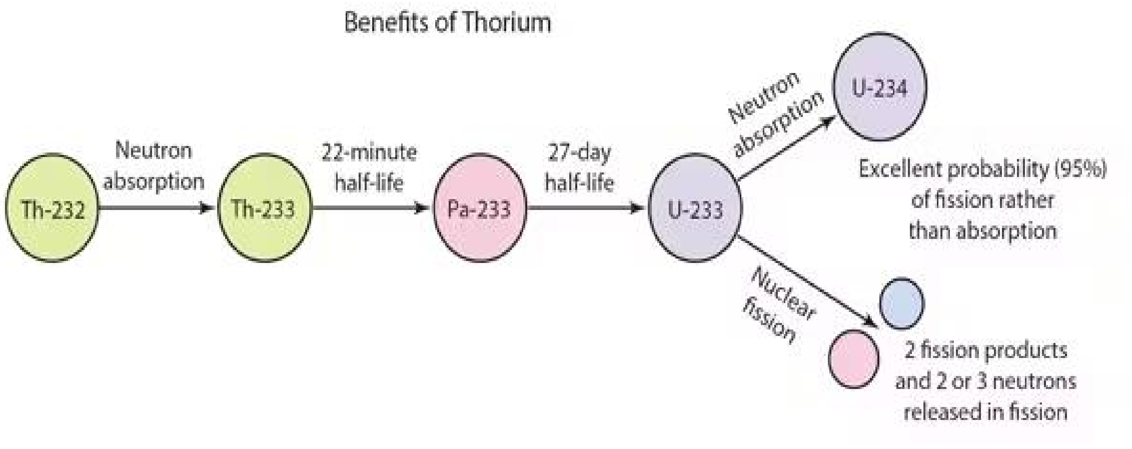

Figure 4.2 Advantages of thorium-based nuclear fission (Sorensen 2016)

Such advantages are substantial economic benefits and enhanced safety measures. Also, these benefits involve different processes in the whole fuel cycle, ranging from mining to storage. Efficient and longer fuel cycles ensure that the mining, spent fuel reprocessing, and storage process is not as vigorous as uranium. This way, the overall environmental impact of the thorium-based reactors could be reduced to a great extent.

Analysing such significant benefits out of many others could potentially be one of the most effective alternative strategies for addressing India's growing energy demand problem at the same time keeping its environmental emissions in check. According to various projections, India currently ranks first as the most populated country while ranking only seventh in land area ("World Bank Open Data-Land Area" 2024). According to "World Bank Open Data-Population Density" (2024), India has a population density of 473 people per sq. km of land area. Along with these demographic data, the ever-increasing urban development ("World Bank Open Data-Urban Land Area" 2024) and urban population of the country ("World Bank Open Data-Urban Population" 2024) calls for any advantages, even a minor benefit in its nuclear programme. In this scenario, thorium's favourable properties contribute to safer and more efficient reactor operations for the country. On top of that, they also support mitigating some of the socio-political issues that might arise in the country.

4.4. Technological Advancements and Innovation On Thorium

India is concerned with many socio-political issues related to nuclear energies and the construction of new nuclear reactors. In the previous section, some of the significant technical advantages of thorium-based nuclear reactors were explored to mitigate such issues to some extent. However, the subject has a good side, too. By investing in thorium fuel-based nuclear reactors, India could benefit significantly in the technological research and innovation sector. India has the potential to invest in and grow its indigenous thorium reactor design and technology industry. The shift towards thorium reactors would open up multiple avenues for technological advancement. There is already research on different types of reactor architecture to utilise thorium-based fuel cycles. Liquid Fluoride Thorium Reactor (LFTR), Molten Salt Reactor (MSR) and Accelerator-Driven Systems (ADS) are some of the examples for these different architectures. These designs have their advantages and benefits. For instance, the LFTR has significant benefits regarding its safety, fuel efficiency and production of nuclear waste materials in comparison to the light water reactors (LWR) (Bahri, Majid, and Al-Areqi 2015)The ADS can increase the minor actinide content, and these actinides help burn more transuranic elements (TRU) produced as part of fission. This particular process will, in turn, reduce the reactivity swing in the core due to burn up and make the reactor much safer than the traditional uranium reactors (Vu and Kitada 2015). In the case of MSRs, they have the benefits of fuel breeding, higher operating temperature, fuel flexibility, etc (Gehin and Powers 2016). However, it is essential to note that the thorium-based nuclear reactor research is still ongoing, and we are nowhere near to inventing a perfect design or architecture. Along with the benefits of different designs, they come with specific technological and other challenges. India can follow this trend and accelerate the process. Every country has their own requirements and challenges. Considering India's technological, social, environmental and economic challenges and requirements, the country can invest and grow its own technology. In that case, India will have its own reactor designs tailored to the local conditions, which ensures energy independence. A very closely associated sector is the research and development in fundamental nuclear science along with the industry. As the investment in the industry goes up, India's R&D in nuclear science will automatically be affected. The country needs a solid R&D program to accelerate its output. Investments in the field could motivate the country's scientific community to indulge more in nuclear science in order to bring the country to the forefront of nuclear research. The Bhabha Atomic Research Centre (BARC) is the last word in Indian nuclear science research at the moment. Increased investment in thorium-based nuclear technology could produce a whole new set of research institutes, scientists and other skilled professionals in the country, aiding its growth and development. It is inevitable to enhance the country's technological capacities and remain competent in the field. Such investments in R&D and the thorium industry will definitely open new possibilities for international collaborations and partnerships for India. There are other countries far ahead of India in terms of nuclear technology. Countries like the United States of America (USA), Norway, and Canada have already kick-started their research programmes in thorium-based nuclear reactor technology. Establishing bilateral or multilateral relations with these countries would greatly benefit India by accelerating its nuclear research. A great deal of technology and capacity exchange with these countries could initiate a new wave of collaborative efforts such as joint research programs, shared funding, student exchanges, etc. Along with establishing relations with foreign countries, India can also approach multiple international organisations like the International Atomic Energy Agency (IAEA), the World Nuclear Association (WNA), etc. These organisations are at the forefront of international nuclear cooperation for peaceful and sustainable use of nuclear energy.

A significant sector where India could benefit from increased investment and international collaboration is the mining of thorium. As mentioned before, India has a massive deposit of thorium resources, and it could lead India as a major player in the thorium-based fuel market. The coastal regions of Kerala, Tamilnadu and Odisha present possibilities for domestic mining operations. These coastal regions hold the lion's share of thorium deposits in India and optimum locations to initiate the thorium mines. Investments in this sector mean a steady and sustainable supply chain of thorium for the domestic and international markets. It is evident beyond the point of doubt that the economic benefit of being a fuel supplier to the domestic and international markets is a considerable advantage for the country. Due to the nonexistence of a well-structured thorium-based industry, a direct market comparison of thorium with uranium is not possible at the moment. However, a fair approximation could be made, and it can be predicted that the price for extracting thorium would be less compared to that of uranium because thorium would most probably be extracted along with other marketable materials. Such materials include rare earth elements, titanium, etc. The fact that most of the exploitable materials are open air could facilitate the less complicated recovery of materials and lower costs ("Perspectives on the Use of Thorium in the Nuclear Fuel Cycle" 2015). The significant expenses in the existing uranium-based nuclear reactor technology are in the mining, interim storage, reprocessing of spent fuel, and recycling of spent fuel sectors ("Perspectives on the Use of Thorium in the Nuclear Fuel Cycle" 2015).

The financial benefits of thorium mining compared to uranium mining are already discussed above. Similarly, from the previous sessions, thorium has clear advantages when it comes to interim storage, reprocessing and recycling of spent fuel from thorium-based reactors. The enhanced waste management and safety features give an edge to thorium-based reactors and bring down the overall cost compared to uranium-based reactors.

The mining industry requires combining several other sectors to ensure successful operations. It requires massive human resources, including skilled and unskilled labourers, massive machinery, elaborated logistics, etc. The materialisation of such requirements needs a lot of help from international collaborations, and growth in all these sectors will directly impact the domestic job market. Employment opportunities for the domestic population will see a rise, and it will boost economic progress. Employment opportunities and industrial growth will benefit from all aspects of the thorium reactor sector. Outside mining, the construction, operation, and maintenance sectors also require a highly skilled workforce. This will create opportunities for a multitude of sectors. The development of ancillary sectors will also see a rise. The specialised industries like metallurgy, chemical engineering, electronics, etc., are some of the major examples of such ancillary sectors. The regions where such activities and industries are concentrated will benefit from economic growth and prosperity. However, all these advantages come with a price. Developing the nuclear industry can cause severe environmental impact and damage to human health if not done correctly. Aside from the challenges in nuclear waste management, as mentioned in the previous section, Mining is another sector where a great deal of challenges exists. The government should concentrate on strict regulations and guidelines to ensure sustainable mining of thorium resources. Minimal impact on the local ecosystem and indigenous community is extremely important, and efficient policies should be implemented to ensure its co-existence.

5. Assessment of India’s existing Nuclear Energy Policy Scenario

India's journey with nuclear energy predates its independence, a testament to its long-standing commitment to this sector. The country's foray into nuclear energy began with the establishment of research institutes, followed by the construction of nuclear power plants and the implementation of comprehensive policy frameworks. The nucleus of India’s nuclear programme is the Nuclear Energy Act of 1962 and the three-stage nuclear energy programme devised in 1954. These initiatives were further bolstered by supporting acts, nuclear cooperation agreements, and a range of regulatory frameworks. Given the demographical and geographical conditions of the country, it is beyond doubt that the programme should include every aspect of development and consider all major stakeholders involved. With the country's burgeoning energy needs due to economic growth and population, India is now focusing on energy production with the most diminutive carbon footprint. Nuclear energy plays a crucial role in achieving this goal, and thorium is also an alternate fuel for nuclear power plants. So, along with analysing the stakeholder involvement in the country’s nuclear policy, it is also important to evaluate the adequacy of existing policy frameworks when thorium-based advanced reactors of capacity up to 300 MWe are introduced to the system.

5.1. Assessing existing national-level policies and Stakeholder Involvement

India has a very elaborate nuclear energy programme in the country and includes different layers of acts, frameworks, industries and institutions. Every policy element affects every stakeholder at a different intensity. For the purpose of analysis, the policy elements can be generally divided into five categories. National acts, the three-stage nuclear programme, Domestic agreements and incentives by the government, international agreements and collaborations and various environmental regulations and frameworks. The national acts include the Atomic Energy Act of 1962 and other supporting acts that are in effect when dealing with nuclear energy production and consumption, ranging from mining to waste disposal. The three-stage programme is the actual driving element of India's nuclear energy programme. The domestic agreements and incentives include the various activities initiated by the national government to support the nuclear programme within the country. The international agreements and collaborations include the various bilateral or multilateral agreements with India and other countries, as well as its commitment to various international agreements. Finally, the environmental policies, regulations and frameworks that are directly affecting the local communities. As mentioned before, these policy components affect the stakeholders at varying intensities. The various stakeholders could be categorised into government and regulatory bodies, industry and PSUs, Local communities, private sector, international partners and NGOs to analyse the impact. The industries and PSUs are brought together because, at the moment, various PSUs are performing all the industrial activities in nuclear energy production. There is no private intervention. Various research institutes for nuclear energy in India have also been created as PSUs.

The Atomic Energy Act of 1962 is the cornerstone of India's nuclear energy policy framework. The act provides a comprehensive framework for the development and consumption of nuclear energy in the country. The act mandates that the use of nuclear energy should only be for peaceful purposes. It also emphasises the protection of public health and safety and the security of nuclear materials. Moreover, the act entrusts the central government with overall control over all activities related to nuclear energy production. The government is the licensing authority when it comes to all activities ranging from mining to production. The use of equipment is also controlled by the government. Along with other supporting acts, it is ensuring a holistic and cohesive approach to managing the nuclear sector of the country. The centralised control over the country's nuclear activities enables the government to have a unified plan for developing and implementing nuclear energy projects. Through such control, the government ensures that the projects align with national interests and energy goals. Every process related to nuclear power production is hierarchical and structured. AERB is the implementing authority of these national acts. AERB ensures the compliance of all projects with the required safety standards and regulations. Also, AERB's oversight extends to the design, construction and operation phases of every nuclear power plant in the country. Clearly, this policy element has a high impact on the first category of stakeholders, the government and regulatory bodies. The DoAE is the primary governmental body associated with nuclear energy in India. They are solely responsible for implementing various nuclear energy policies and frameworks. The department's activities are heavily influenced by the National Atomic Energy Act and other supporting acts. The department coordinates various projects between the institutes and industries. Outside DoAE, the Environment, Forest and Climate Change ministry is also directly affected by these acts as they work closely with AERB to ensure adherence to the regulations mentioned in these acts when a new project is planned. When it comes to the PSUs and research institutes, since they are directly involved with the R&D, designing, construction and operation of both commercial and research reactors, the acts play a prominent role. The research institutes are guided by these acts on the new technologies the adopt, and the industries have to strictly follow the regulations put forward by them. Regarding the effects of these acts on local communities and the general public, factors like safety and public perception of nuclear energy are closely associated with these acts. However, the involvement is not as direct as in the above categories. A similar trend applies to the rest of the stakeholders. The impact is moderate to minimal whether it is the private sector, international partners or NGOs. Due to the absence of the private sector at present, they face minimum consequences from the acts. The changing perception about bringing in new private players might change this in the future. NGOs also don't have any direct involvement in the process other than the activities conducted to change the public perception. More efforts should be made by the authorities to improve the public perception of nuclear energy. Other than the current activities, mostly educational materials published as part of the outreach programmes of research institutes, there should be efforts to popularise nuclear energy for its advantages among the public.

The three-stage nuclear energy programme, the driving element of India's nuclear activity, carries paramount importance as a policy element. Every new project or research initiative has been carried out based on the plan laid by the three-stage programme. Table 5.1 gives a comprehensive analysis of the current status of the three-stage programme. The programme is clear evidence that India is foreseeing the use of nuclear energy in its energy mix from the very first moment and is going forward with plans to improve and increase its capacity. The third stage includes the use of India's abundant thorium reserves, which shows the country's plan to utilise future technology. This nuclear programme has a high impact on the PSUs and research institutes as they are the institutions primarily involved in materialising the ideas into real projects. NPCIL is the primary organisation directly involved with the construction of India's nuclear power plants. The PSUs take care of the procurement of materials, construction, operation and even the skill training for the employees.

Table 5.1Current status of the three-stage programme

Stage	Description	Status	Notes
1	Deployment of PHWRs using natural uranium as fuel to produce plutonium-239	●	Existing conventional reactors

2 a	Construction of Fast Breeder Reactors (FBRs) to utilise plutonium-239	🟡	Recently commissioned the first prototype reactor
2 b	Breed uranium-233 from thorium	🔴	Not there yet
3	Integration of Thorium-Uranium fuel cycle for sustainable and thorium-based nuclear energy production.	🔴	In the future

Besides, NPCIL, Barc and IGCAR play key roles in the research and development of the nuclear programme. BARC is at the forefront of nuclear research and innovation in the country, and IGCAR primarily focuses on the development of new reactor technologies, including the FBRs. Outside the PSUs and research institutions, government authorities oversee the implementation of these initiatives. Hence, they have a significant impact on these programmes as well. When it comes to the local community and NGOs, again, the interaction is limited. Outside the legal correspondence, there are significantly fewer efforts to ensure their participation in the ongoing participation. Due to the technology exchange and fuel supply requirements, the international partners are involved to a certain extent.

The several domestic agreements and various economic benefits schemes are mainly focused on motivating in-house research and development along with the participation of in-house entrepreneurs. Even though the participation of private industries is limited at the moment, the government has initiated the process of public-private partnerships in the sector. By reducing entry barriers and financial risks, the government is planning to attract private investors and partners into the nuclear energy field. Various subsidies and discount schemes will potentially attract the country's initial partnerships. The government also disperse a variety of funds for startups and medium-scale industries to step into the nuclear field. Along with the support for the industries, funds and resources have been allocated to research institutions as well. Besides the dedicated nuclear research institutes, funds have been allocated to researchers and other educational institutions across the country to encourage further R&D in this field. However, with all these initiatives and benefits, the nuclear energy field remains highly regulated by the central government. The PSUs come first, followed by the private partnerships. However, the involvement of local communities will see a rise in the future as the industries grow and offer more employment opportunities. It might not always be true regarding the skilled professionals required in the industry due to employee migration, but it will definitely benefit the supporting industries and unskilled labourers. Also, with more private partnerships, the corporate social responsibility funds will be spent in the local community. The involvement of the NGOs remains limited in this element as well.

Even though India has a comprehensive programme for the development of its nuclear energy, various international partnerships and agreements are crucial. Especially when it comes to fuel supply, technology exchanges and capacity building, India seeks support from its international allies. India is already party to various bilateral and multilateral agreements with countries like the USA, Japan, France and Russia. Such agreements ensure a stable fuel supply and technology exchange for the country. Also, such international collaborations bring joint R&D projects to the country and it will help in developing the newest technologies for maximum production. Outside international partners, the stakeholders benefiting the most from such partnerships and collaborations are the PSUs including the research institutes as they are the direct benefactors of all the resources from foreign countries. Then come the government authorities and regulatory bodies, who coordinate the relationship between the international parties and regulatory bodies to ensure the safety standards of the technologies which are brought in. With international agreements outside the foreign governments, India gets involved with foreign companies, too. Outside India, the involvement of the private sector is much more in the nuclear sector, and India depends on certain private players for specific requirements like reactor technologies and uranium supply. However, local communities or NGOs have no role in such international agreements.

Environmental regulations, policies, and frameworks are the policy elements that most impact local communities, NGOs, and other civil organisations. This element primarily affects the local communities when their safety and well-being are concerned. The government authorities and regulatory bodies are responsible for keeping the citizens safe and sound. Also, the communities are directly affected when land acquisition and socio-political changes are associated with a new power plant. The authorities are responsible for conducting public hearings, environmental and social impact assessments and similar activities to ensure inclusivity. NGOs and civil organisations don't play a direct role but instead act as a social lubricant between communities and the government. They support or protest the new initiatives based on how they affect the local ecosystem and indigenous communities. So, it is essential to conduct awareness programmes to improve public opinion regarding nuclear energy. Table 5.2 shows the policy elements-stakeholder impact matrix based on the abovementioned observations.

Table 5.2 Policy elements-stakeholder impact matrix

Policy/stakeholders	Govt. and regulatory Authorities	PSUs	Local Communities	Private Sector	Intl. Partners	NGOs
National Acts	H	H	M	L	M	L
Three-stage Plan	H	H	L	L	M	L
Domestic agreements &subsidies	H	H	M	M	L	L
Intl. Collaborations	H	H	L	M	H	L
Env.Frameworks	H	M	H	L	L	M

The table shows the intensity of each policy element's impact on different stakeholders. The categorisation of policy elements and stakeholders has been done from the preliminary analysis of existing nuclear policies in India, and they are grouped for ease of understanding. The letter **'H'** in red colour denotes the impact of **HIGH** intensity, **'M'** in blue represents the impact of **MEDIUM** intensity and **'L'** in orange represents the impact of **LOW** intensity. From this analysis, it is evident that India has a comprehensive policy that covers essential aspects of the nuclear energy sector. It also gives significant importance to the central government as the sole authority to oversee every activity related to nuclear power production in the country. PSUs share almost the same importance as government authorities and regulatory bodies in the country, and their impact on the rest of the stakeholders varies depending on the different policy elements.

5.2. Adequacy of current policies in promoting thorium-based advanced reactors up to 300 MWe

Analysing the existing policy framework in India for the utilisation of nuclear energy, it is safe to say that India has a long-standing and comprehensive policy framework to support its initiatives. The policy's multifaceted approach accounts for the country’s energy security, economic growth, and environmental goals. It is also noteworthy that the policies consider various types of stakeholders and their contributions in shaping the nuclear energy contribution. However, from the previous sections, it has been clearly identified that India as a country, due to its various specialities, could benefit in all fundamental aspects of sustainable development from implementing thorium-based advanced nuclear reactors of capacity up to 300 MWe. Such reactors have the potential advantages to contribute to technical, socio-political, economic and environmental aspects of India’s developmental portfolio. So, the focus here is to identify whether India's existing nuclear policies are adequate to promote thorium-based advanced nuclear reactors in its nuclear energy programme.

India’s three-stage nuclear programme, the research institutes, and the numerous PSUs could be considered significant constituents of the technical aspects of the nuclear energy programme. Together, they produce results, and India has come a long way since the inception of its nuclear programme, dating back to pre-independence times. The three-stage programme is a holistic approach carefully designed so that India uses both uranium and thorium for its nuclear energy purposes, considering present and future possibilities. Based on this approach, the country achieved its first goal by operating active nuclear reactors and also made some considerable strides towards phase three, which is to utilise thorium. The significant development in that area is the development of the designs of AHWR and IMSBR by itself. However, considering that India envisaged using uranium from the inception of its three-stage programme and is still not making significant achievements related to thorium reactor research, most of the policies and initiatives are still focused on traditional uranium-based reactors. All commercial reactors being operated in India are large uranium reactors. Other than the very few research initiatives, the technical aspects of India's nuclear policy are still focused on uranium. A revision in its policies is highly recommended in this matter. Developing and commercialising thorium-based reactors of capacities up to 300 MWe requires complex and significant technological advancements. India should focus more on R&D to develop smaller, advanced nuclear reactors based on thorium. India requires a design optimised for its local conditions as smaller reactors can be accommodated to specific conditions. Since smaller reactors have the advantage of off-site manufacturing, factories to build the reactors are critical, and it is a new territory for India. Currently, there are no policies or regulations regarding building the extra infrastructure required to commence thorium-based activities. Along with the research in reactor designs, technological advancement in auxiliary industries is also essential. From constructing the reactors to reprocessing and storing the waste, a multi-faceted approach is required. Additionally, the mining of thorium will be a new venture as far as the country is concerned. Unlike uranium, the abundance of thorium in India opens up the possibility of thorium mining in various locations, some closer to populated regions, too. Also, the mining process of thorium is different from that of uranium in terms of the materials recovered and their processing. There should be policies and regulations to monitor the technical aspects of the thorium mining process precisely and to build extra infrastructure. Such policies, explicitly focusing on thorium-based reactors, are inevitable in developing indigenous technology and ensuring energy security.

In the socio-political aspect, the main constituents are the national acts, government authorities and regulatory bodies and community engagement policies. It is safe to say that India has adequate detailing in policies when it comes to centralised regulations and oversight. The central government and regulatory bodies control and monitor everything regarding nuclear energy. This helps streamline the process and ensures the country's common goal and vision are maintained. However, when thorium based advanced reactors are considered, there are certain basic differences compared to the traditional uranium reactors. The thorium-based advanced reactors bring in certain advantages, like the possibility of standardisation and economies of scale. Currently, the uranium-based reactors of larger capacity are built on-site once the project is approved. The current policy structure is highly hierarchical and takes a long time to straighten out bureaucratic processes. This process is valid for uranium-based reactors, which are built separately and may use different technologies every time. The design and manufacturing of thorium-based advanced reactors, being modular and scalable, could be industrially standardised and produced quicker and in multiple quantities. To accommodate this basic difference in building a thorium-based advanced reactor, some revisions in existing policies and regulations are necessary, especially with the bureaucracy. Along with revising bureaucratic policies, community engagement policies also require prompt revision. The public needs to be well informed about the newer technology, and the process has to be transparent. As mentioned, once implemented, the thorium-based 300 MWe reactors are going to be larger in numbers and different from the reactors the general public is used to. This could potentially create a commotion among them and hinder the process. Hence, more initiatives to educate the public about newer technologies are essential to ensure the timely implementation of such advanced reactors.

Considering the economic policies and related aspects, the major contributors are the subsidies and incentives offered by the central government, international collaborations and public-private partnerships. At present, the latter is very minimal as the nuclear sector is limited to private players. Currently, government incentives and funds, along with the various international collaborations, significantly help the nuclear energy sector. The system is designed to suit the operation of traditional uranium reactors where a high initial investment is required. This could potentially limit the number of private players as not everyone could afford a 1000 MWe nuclear plant. However, the story is different for thorium-based advanced nuclear reactors with capacities up to 300 MWe. They offer the advantage of considerably less initial investment. It is an excellent attraction for various investors outside the central government. Since the number of power plants will also be greater, it has the potential to attract public-private partnerships more than usual. These economies of scale need to be carefully addressed as they are completely different from the existing uranium reactors. Another important aspect where policies are currently lacking is the possibility of developing new markets for the by-products from thorium-based reactors. There will be new opportunities in the medical field, such as hydrogen generation. The critical point to consider is accommodating more investors and keeping tight regulations as it is a long-term investment into the country's energy portfolio. Attracting investors from within the country will automatically boost economic development and employment opportunities. Last but not least, India lacks policies in the areas of future development, especially when it comes to exporting thorium or reactor technologies. Considering the abundance of thorium deposits, India could very well be looking at being one of the top exporters of thorium in the future. Similarly, the successful development of indigenous reactor technologies also provides the same opportunity. As of now, the country hasn't looked into the possibility of becoming an exporter in the nuclear industry.

The current environmental policies mainly concern the safe disposal of radioactive waste and the protection of the environment. The regulations regarding handling nuclear waste are clear and also cover closed fuel systems for nuclear reactors. The strict regulations by the government ensure the safe disposal of nuclear waste, which causes minimal impact on the environment. Besides the type and quantity of waste produced, the regulations and safety standards must be as stringent as possible for thorium-based reactors. Even though thorium-based reactors have the advantage of producing less waste with a shorter long-life period, the regulations and safety standards should adhere to international standards as they do now. Similarly, every safety standard and impact assessment procedure must be followed to protect the environment. The part where a revision in policy is required is regarding public awareness. It is closely associated with the policy element identified in the socio-political aspect. However, public awareness about the positive environmental effects of thorium-based advanced reactors compared to traditional uranium reactors and fossil fuels deserves to be addressed as part of one of the environmental policies.

Table 5.3 shows the essence of this analysis. In the table, certain areas from all four categories are identified and marked separately as areas where a policy revision is **'highly recommended', 'recommended'**, and the policy is **'adequate'**.

Table 5.3 Policy sectors and revision recommendations

	Revision highly recommended	**Revision recommended**	**Policy is adequate**
Technical	Thorium mining Additional Infrastructure	R&D focusing on thorium-based advanced reactors	Resource utilisation plan
Socio-Political	Bureaucratic delay	Public Perception	Centralised

	Standardisation process		regulations and oversight
Economical	Public-Private partnerships Private investments within the country Economies of Scale	New markets from by-products Possibilities of exporting thorium and reactor technologies in the future	International collaborations
Environmental	Type of storage for the waste	Public awareness on the positive impact of Thorium reactors on the environment compared to traditional technologies	Waste disposal Protection of environment

From the analysis, it is safe to say that India has a comprehensive nuclear policy when it comes to its existing technologies and practices. However, there are certain areas that require revisions and improvement to promote the adoption of thorium-advanced nuclear reactors of capacities up to 300 MWe.

6. Policy Roadmap

As analysed in the previous sections, it is apparent that the Indian nuclear energy sector can benefit from adopting thorium-based nuclear reactors with capacities of up to 300 MWe. The comprehensive and robust policy framework India has is, even though sufficient for its current capacity, not adequate for implementing said thorium-based reactors on a large scale. The last section gave an insight into the policy areas that need revision in order to accommodate the change in India's nuclear portfolio. Two significant aspects of adopting thorium-based advanced reactor technologies are the mining of thorium and the large-scale construction of reactors with capacities of up to 300 MWe. Both these areas are new ventures for the country as the current nuclear programme doesn't account for these significant changes. Multiple auxiliary areas need attention when these two main characteristics of thorium reactors are considered. Some of them include raw material processing, fuel processing, streamlined design and construction of advanced reactors, spent fuel reprocessing, etc. A holistic revision in all four basic aspects of development is required to accommodate all of these changes in the nuclear industry with the adoption of thorium-based advanced reactors. The previous chapter tried to analyse and find out the specific areas in technical, socio-political, economic and environmental aspects where a revision is immediately required, required and not required. New policies should be implemented in these sectors to accommodate the changes thorium reactors could bring to the nuclear industries. The revision is time-sensitive and will help keep the nuclear programme updated and competent with other international players in the nuclear energy sector. This study proposes particular policy recommendations in all four sectors to accommodate the promotion and implementation of thorium-based advanced nuclear reactors with a capacity of up to 300 MWe in India's nuclear energy sector.

Technical Sector: The current three-stage nuclear programme is highly efficient in terms of the resource utilisation plan and current reactor technologies. However, certain revisions in specific areas could benefit the adoption of thorium reactors in India. The recommendations are:

- ➔ Research and Funding: The need for thorough R&D and increased funding focusing on thorium-based advanced nuclear reactors of up to 300 MWe capacity is urgent. These actions are crucial to develop Indigenous technology and ensure the successful implementation of thorium reactors in India's nuclear energy sector.
- ➔ Mining: New technical policies, safeguards, and regulations are needed to start and monitor new thorium mines.
- ➔ Reactor Construction: New policies to overlook the streamlined (mostly) off-site and on-site construction of new thorium-based reactors and the required infrastructure.

- ➔ Auxiliary Industries: Policies to support the multiple auxiliary industries will be established by adopting new technologies related to thorium mining and reactor construction.
- ➔ Innovation Hubs: Establish and support innovation hubs to promote nuclear research, thorium reactors, and other possibilities across the diaspora outside the already established research institutes. These hubs could facilitate collaborations across different sectors.

These policy recommendations are proposed to accommodate the aftereffects of adopting thorium-based advanced nuclear reactors. The technology and its commercialisation are entirely new for the country and must be examined carefully.

Socio-political sector: India has a robust approach to governmental regulations and control of its nuclear energy sector. While this approach gives certain advantages, some areas must be revised to accommodate the new technology.

- ➔ Bureaucratic complexities: Policies should be revised to accommodate the standardisation of thorium-based advanced reactor technology. A transparent and simplified administrative process is required without compromising regulations and safeguards.
- ➔ Economies of scale: The policy framework should acknowledge the potential economies of scale related to thorium reactors. Administrative and industrial policies should consider the potential rise in the number of small reactors as part of the adoption of technology.
- ➔ Dedicated regulatory and policy revision process: Creating a dedicated task force/regulatory body specifically for thorium-based reactors could streamline the administrative process significantly and keep the policies relevant and competent.
- ➔ Public perception: New policies should be implemented nationwide to increase awareness regarding new thorium-based reactor technologies.

Socio-political policies are crucial as they include the essential bureaucratic processes related to implementing new technologies in the field. Revisions are necessary, especially in a country like India, where the central government has significant control over the sector.

Economic Sector: At present, the government provides the lion's share of funding and investments in the nuclear sector. Outside of international collaborations and agreements, no private players exist in the nuclear field.

- ➔ Public-Private partnerships: Policies to encourage public-private partnerships are crucial, considering the topic's time-sensitivity. However, strict guidelines have to be followed as the investments are long-term.
- ➔ Domestic-Private Investment: Policies should encourage investments from domestic-private investors, as this would boost economic development and foster employment opportunities in the country.
- ➔ New markets: Policies should be formulated to accommodate the new market opportunities from the by-products of thorium-based reactors.
- ➔ Economies of scale: Policies should be formulated to monitor the investment pattern in building new reactors and mines. Keeping a level playing field is essential to ensure optimised resource allocation and widespread participation, as well as to maintain a fair and transparent market.
- ➔ India as an Exporter: Policies should be formulated to overlook the possibilities of exporting thorium and reactor technologies in the future.

Policy revisions in the economic sector have precedence as they affect the flow of money to support all activities related to nuclear energy production.

Environmental Sector: India adheres to international safeguards and has various internal regulations to minimise environmental impact. Revisions are only required regarding the type of materials used for new technologies.

- ➔ Storage and waste disposal: The process is different for thorium-based advanced reactors compared to traditional uranium reactors, and policies should be formulated to accommodate the changes in nuclear waste materials.
- ➔ Public Awareness: Policies for widespread public awareness initiatives to educate the general public regarding the various environmental advantages of new technology compared to traditional methods.

The attention to the environmental sector is paramount as India longs for sustainable development in the energy sector and to keep its climate commitments.

To streamline the process, the policy recommendations could be implemented phase by phase. Policies from all four sectors could be combined to formulate an implementation plan for optimum results.

Phase 1: Foundation and Framework

- ➢ Formulating new policies and revising existing ones to support adopting new technology.
- ➢ Focusing on R&D, specifically in the thorium-based reactor development area.
- ➢ Initiatives to improve public awareness regarding the new technology

Phase one could potentially be completed in 3-5 years; however, research and awareness activities are a long-term process that should continue in parallel. The time period is estimated on the basis of the variety of tasks involved in this phase. Even though some tasks may complete in a quicker time frame, complexities of certain tasks could extend over several years. Such tasks mainly involve political, societal and technical considerations. Example, revising or implementing policies take years due to the complexities in bureaucracy and politics.

Phase 2: Design and Development

- ➢ Acceleration in designing and developing indigenous reactor technologies and competence in mining.
- ➢ Initiating public-private partnerships and extra-international collaborations
- ➢ Schemes, subsidies and incentives to support development and attract investors.

A potential timeline for phase two could be 5-10 years, as India already has research and development initiatives in the nuclear sector. The initiatives could start from the beginning. However, phase two could focus on developing indigenous technology to adopt thorium-based advanced nuclear reactors of up to 300 MWe capacity. However, a longer time period would help bring out comprehensive reactor designs and technologies which are highly competent.

Phase 3: Pilot and scaling up

- ➢ Regulatory oversight and compliance
- ➢ Ensuring public stakeholder engagement
- ➢ Public-private partnerships and international collaborations

- Implementation of pilot projects, including site selection, environmental assessments and construction.
- Scaling up possibilities outside the pilot project

Phase three could be completed in 10-25 years. It will be a significant turning point. Phase three might take the longest time to complete, mainly due to its importance in the whole process. Developing a pilot project and commissioning it involves a variety of tasks, especially with the regulations and compliances involved in every stage, requiring thorough oversight and stringent controls. Ensuring the transparency of the process to provide complete stakeholder engagement, consistency in partnerships and collaborations, etc., will add to the time period.

Phase 4: Integration and export

- Optimising the new industry and economic market development to support large-scale implementation
- Full-scale integration into the national grid and optimising the reactor operation for efficient power production, transmission and distribution.
- Explore international markets to export thorium and reactor technologies
- Continuous R&D and revision of policy framework.

Phase 4 could start as soon as the pilot project is successfully completed in phase three. The potential timeline could be 15-20 years. Phase four involves maturing the technology, and it largely depends on building a supportive market around it. Then, the complexities involved on a national and international scale in materialising the export possibilities are innumerable. Such administrative and economic decisions have to be taken extremely carefully, and they can prolong the time period of the process. Might not be longer than realising phase three, but this phase will consume considerable time to fulfil all the objectives.

Figure 6.1 represents a condensed version of the phase-by-phase implementation process mentioned above.

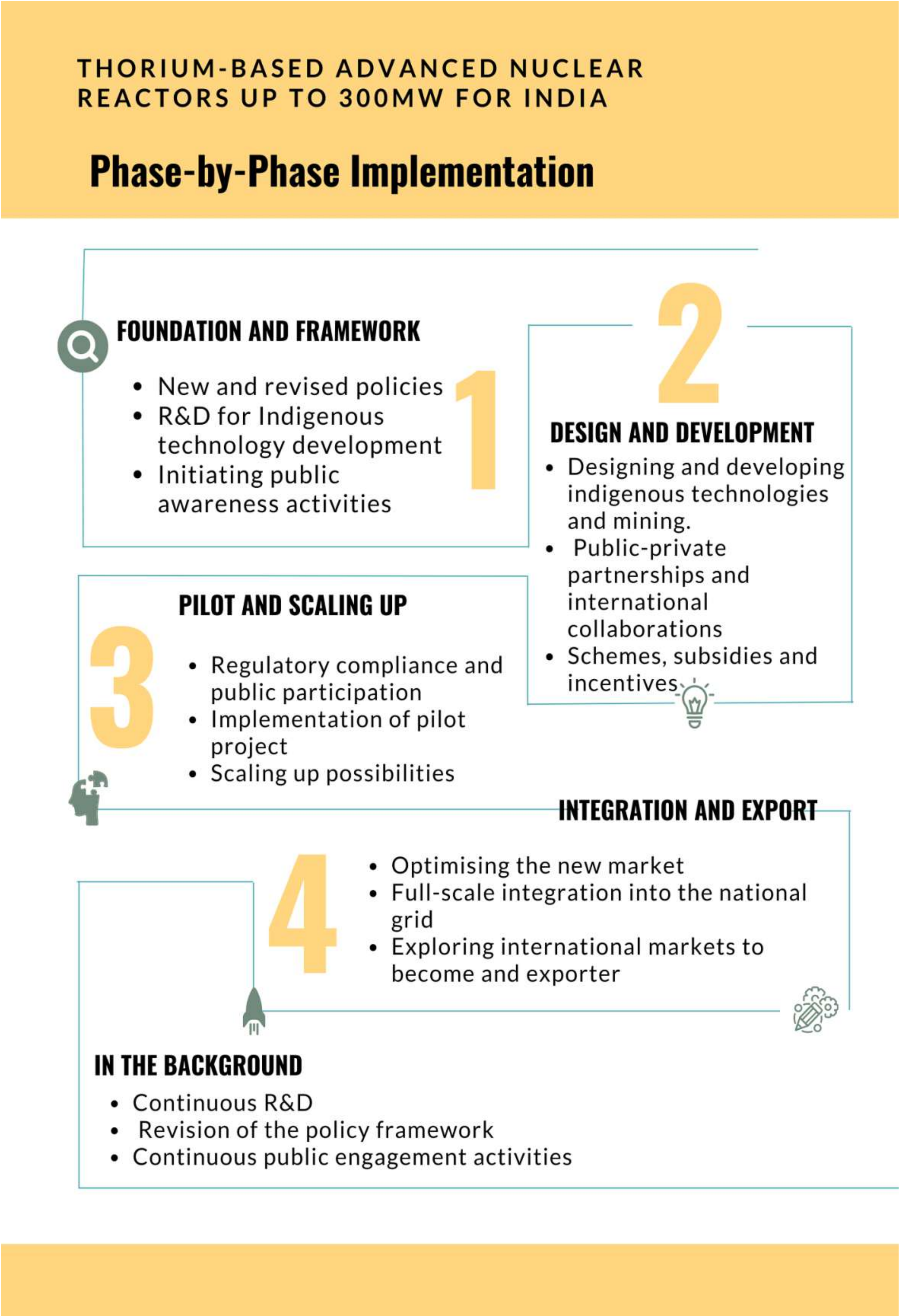

Figure 6.1Phase-by-phase implementation of new technology

Figure 6.2 is a visual representation of the implementation timeline. Consider the fact that the timeline is only an approximation.

Figure 6.2 Implementation timeline

The timeline represents the potential number of years each phase could take. On a sequential time frame, some phases can overlap, as specific tasks in certain phases can commence before the completion of the previous phase. However, the accuracy of such a timeline cannot be predicted to the last detail, as numerous unpredictable factors affect the process during its course.

7. Conclusion

National-level policies undoubtedly play a crucial role in promoting the implementation of innovative technologies, like thorium-based advances in nuclear reactors of up to 300 MWe capacity. Addressing the rapidly rising energy demand bears paramount importance for a country as diversely populated and economically growing as India. The best possible way to meet such rising energy demands while keeping the environmental impacts to the minimum is to focus more on the installation of green energy. Along with renewables like solar and wind, nuclear plays a crucial role in India's energy mix to keep up with the demand. Nuclear energy is not a new territory for India, with its nuclear programme predating the time of independence. India has a robust nuclear energy programme and is going forward with its future plans, with programs only to expand its nuclear energy production capacity. India already has multiple active nuclear reactors based on uranium as a fuel, and more are under construction. Against this backdrop, accessing the advantages of thorium-based advanced nuclear reactors with capacities up to 300MWe and the relevance of national policies to support this new technology becomes highly relevant.

An analysis of existing challenges and concerns of India's energy sector is performed to assess the range of benefits that thorium-based advanced reactors could bring to India. The analysis showed that multitudes of challenges are associated with India's current energy sector. The significant challenges identified are last-mile connectivity, land requirements, weather dependency, grid stability, the financial health of DISCOMs, regulatory and policy hurdles and fossil fuel dependency. These challenges are further analysed based on the issues, their impact on the system and their future concerns. To further understand the benefits of thorium-based reactors for the Indian energy sector, a thorough review and analysis of details regarding the advantages of nuclear reactors up to 300 MWe capacity and using uranium as an alternative fuel for nuclear reactors has been performed. It has been found that India could benefit significantly from adopting these new technologies. The advantages range from technical benefits to economic and environmental advantages. The significant advantages found from this analysis are divided into four major categories: Technical, socio-political, economic, and environmental. Some of the significant benefits from each category include scalable and flexible power production, resource abundance, passive safety features, improved essential services, energy independence, lower initial investment, improved economic growth and support for climate goals.

The next crucial step was to analyse the existing national policies and their stakeholder impact in the Indian nuclear energy sector. A detailed analysis of the existing policies revealed that India has a comprehensive and robust nuclear energy policy that emphasises the power of the central government to control and overlook activities related to nuclear energy. According to the major national acts and other policies, the central government of India has sole control over the production and consumption of nuclear energy in India. The impact of such policies on various stakeholders is analysed, and for this analysis, five policy elements and six stakeholder types were considered. The stakeholder analysis revealed that the policy elements had the highest impact on government authorities and regulatory bodies, while NGOs/Civil organisations had the most minor effects. Further, the existing policies were analysed to find their adequacy in supporting thorium-based advanced nuclear reactors, which is a crucial element of the study. It has been found that the existing policy framework is efficient and robust for India's current nuclear regime but lacks the elements required to support the adoption of a new technology. Again, the various aspects of the policy framework were divided into technical, socio-political, economic and environmental categories. In every category, gaps in the policy framework have been identified in relation to supporting thorium-based reactor technologies. Finally, a policy roadmap, with specific policy recommendations on all aspects, has been designed along with a phase-by-phase implementation method for adopting thorium-based advanced nuclear reactors up to 300 MWe capacities for India's nuclear energy sector.

It could be concluded that newer technologies like thorium-based advanced nuclear reactors up to 300 MWe bring significant advantages to India's energy profile, and national policies play a crucial role in supporting the adoption of such technologies.

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