eTECH nxt

NEW FRONTIERS IN POWER GENERATION:

Re-assessing India's Energy Mix for Clean Baseload Capacities

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eTECHnxt

Clean Energy (R)Evolution-
Carbon Markets, Storage &
Generation

24-25 February 2025
India Expo Mart, Greater Noida
Delhi NCR

AN OVERVIEW

The energy landscape is undergoing a profound transformation, driven by the urgent need to reduce greenhouse gas emissions and transition to a more sustainable future. New energy technologies are emerging at a rapid pace, offering innovative solutions to meet the energy demands while minimizing environmental impact.

The Union Budget 2024-25 underscores India's commitment to a sustainable energy future. Commercializing indigenous Advanced Ultra Super Critical (AUSC) thermal power plant technology, promoting energy storage solutions for seamless integration of renewable energy, exploring geothermal energy potential, advancing green hydrogen production, and developing a robust carbon market are key steps towards enhancing energy efficiency, ensuring grid reliability, reducing carbon emissions, and fostering a sustainable energy landscape.

eTECHnxt platform is created to serve as a catalyst for innovation, discussing and showcasing the technologies and trends that will shape the future of electrical and allied electronics industry.

Previous editions of eTECHnxt have successfully illuminated pathways in new and cutting-edge areas like EV's, Green Hydrogen, Energy Storage, IOT and Artificial Intelligence. The conference consistently emphasizes the need for industry to seize these opportunities proactively rather than passively waiting.

KEY TRACKS

The 4th edition of eTECHnxt will delve in details on the below tracks:

Track 1

Carbon Eco System & Markets

Decarbonization is a global imperative and carbon compliance & markets are emerging as a critical tool. India is poised to play a significant role.

Focus Areas:

- Understanding carbon eco system & markets (compliance and voluntary)
- Challenges & Opportunities for the electrical and allied electronics manufacturing industry
- Carbon credit generation and trading
- Policy landscape and future outlook

Track 2

Energy Storage: Enabling Firm & Dispatchable Renewable Energy

Energy storage is pivotal for grid integration of renewables, ensuring power reliability and resilience. Battery storage technologies are advancing at an unprecedented pace, significantly transforming the energy sector with increasingly efficient, scalable, and cost-effective solutions.

Focus Areas:

- Enhancing Grid Efficiency and Reliability by Integration of Battery Storage with Renewable Energy Forecasting and Scheduling Grid-scale applications and case studies
- Role of Battery Storage in Enabling Round-the-Clock Renewable Energy Systems: Challenges, Opportunities, and Policy Implications
- Roadmap for Utilities & Industries to achieve Flexibility, Resilience, and Decarbonization
- Policy and regulatory frameworks for storage deployment
- Challenges & Opportunities for the electrical and electronics industry

Track 3

Power Generation NxT- New Frontiers

While renewables are at the forefront, conventional generation continues to play a role. New advancements and approaches are needed to blend diverse power sources and enhance their efficiency and sustainability.

Focus Areas:

- Clean & efficient coal technologies
- Small modular reactors (SMRs) for distributed generation
- Hybrid models combining renewables with conventional sources
- The evolving role of thermal and nuclear within India's energy mix till 2032

MESSAGE FROM THE DESK OF CHAIRMAN

Mustafa Wajid
Chairman, eTECHnxt 2025 & Chairman,
MEHER Group

Welcome to the 4th edition of eTECHnxt. This year's theme, "The Green Energy (R)Evolution" will focus on key technologies and business opportunities that will drive significant value creation in the green energy sector.

This edition of eTECHnxt @ ELECRAMA 2025 features three key tracks

- The emerging "Carbon Eco System & Markets"
- The rapidly evolving area of "Energy Storage: Enabling Firm & Dispatchable Renewable Energy", across the Electricity value chain
- Power Generation NxT - New Frontiers

By focusing on these key tracks, eTECHnxt aims to drive innovation, foster collaboration, and accelerate the transition to a sustainable energy future.

Join us at eTECHnxt 2025 to know more about the changing technology and policy landscape and imagine business opportunities that you can pursue.

TABLE OF CONTENTS

Executive Summary

India is the fastest growing major economy and soon to surpass Germany and Japan to be the 3rd largest economy by 2027. Moreover, India is targeting to be a developed economy by 2047 and a net zero country by 2070. This would entail transformational changes in physical and digital infrastructure in the country, manufacturing capabilities, industrial base, transportation, employment patter and earning capabilities, and social sectors- including health, education, housing, skill development, rural and urban development etc. Sustaining this level of growth combined with higher per capita energy consumption due to higher income levels and upward mobility of working class would require much higher inputs in different walks of economy. As per IIT Bombay- VIF study on "India's Energy Transition in Carbon Constrained World", under the most cost-optimum scenario, India's electricity generation is projected to be 24470 TWh by 2070, way higher than the current electricity consumption of 1407 TWh. For other scenarios, the projected figures are still higher.

Under the backdrop of global climate challenges, India has committed to undertake clean energy transition and achieve net zero status by 2070. It would require scale-up of clean energy capacities in the country and progressive phase out of fossil fuel-based processes and power generating units. However, as we assess India's electricity mix, we find that baseload capacities have been instrumental in reliable power supply to the grid and in ensuring its stability and flexibility. Currently, fossil fuels based power plants make up the biggest chunk of the baseload capacities.

With a mandate for clean energy transition, these fossil fuel-based power plants which currently supports the 76% of the electricity supply in the country have to replaced with equally effective and reliable clean power sources such as nuclear, hydro, solar thermal, geothermal, RE with RTC arrangements (with batteries+ hydrogen+ hybrid) etc. All these baseload options can help supply firm, flexible, and reliable power supply to grid system and serve the end consumers' requirements in a most satisfactory way. Penetration of solar PV and wind without RTC arrangement and without adequate baseload capacity in the energy mix would make grid system highly unstable that would have major repercussions on power supply, electricity cost, and emission levels as dependency on fossil fuel would never go away. In the long run, climate and economy would be the major sufferer if reliable clean baseload capacities are not mainstreamed in the energy mix of the country.

All clean baseload capacities offer unique advantages and challenges to go ahead and the paper is an attempt to discuss on related developments in the Indian power sectors. The focus has been kept on the mainstreaming of nuclear and solar thermal in the energy mix and highlighting the opportunity areas for more decentralization, private participation, international collaborations, and sectoral reforms as India strives to be a developed and decarbonized economy.

1

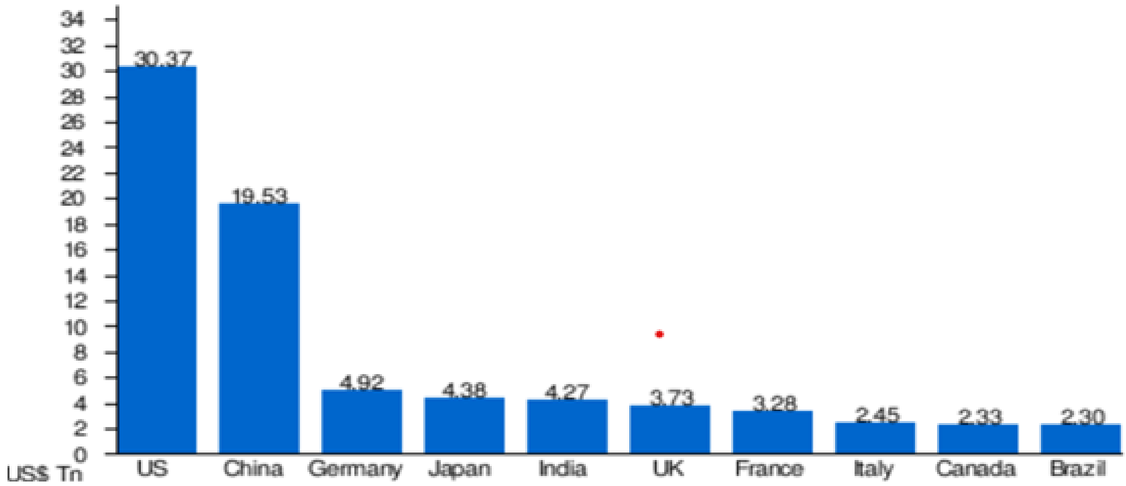
Introduction

1. Introduction

India's energy landscape is undergoing a significant transformation as the country strives to balance its economic growth with environmental sustainability. The focus is on reassessing India's energy mix, emphasizing clean baseload capacities to meet the growing energy demands while reducing carbon emissions. This comprehensive initiative involves the development of various energy sources, including renewables, nuclear, and advanced technologies, to ensure a reliable and sustainable energy supply for the future. The following sections provide an in-depth analysis of India's current energy scenario, growth targets, and the strategic steps being taken to achieve a cleaner and more efficient energy mix.

1.1 Context

Unlike the developed countries in the west, India is in a unique situation of developing and decarbonizing its economy at the same time. It is 5th largest economy with fasted growth all major economies. Post-Covid, India witnessed a V-shaped growth and striding fast to surpass Germany and Japan to be the 3rd largest economy by 2027. The long term developmental strategy of India is aimed to be a developed economy by 2047.



Largest economies in the world by GDP (nominal) in 2024

The country is simultaneously working to reduce its carbon intensity and decarbonize all segments of it economy and achieve net zero goal by 2070. Power sector is crucial to be looked at to ensure convergence of India's developmental and climate objectives. A cleaner, reliable, flexible and cost-effective electricity mix will help India successfully transit into a future of economically advanced net-zero country. Therefore, electricity mix has to be nurtured with such technologies that could provide required stability and flexibility to the grid systems as more clean transition goes on and support all economic segments without power interruptions.

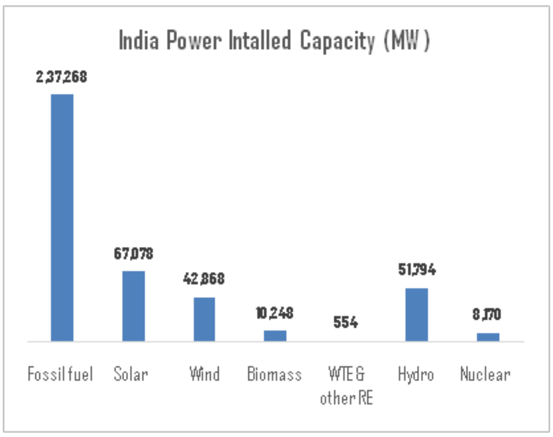
As we assess electricity mix, we find that baseload capacity is very crucial to allow grid function optimally. It refers to the minimum amount of electric power delivered or required over a given period of time at a steady rate[1]. This type of power is essential for maintaining the stability and reliability of the electrical grid, as it ensures that there is always a consistent supply of electricity to meet the basic demand. It is normally operated to serve loads on a round-the-clock basis[1]. These power plants are designed to run continuously and produce electricity at an

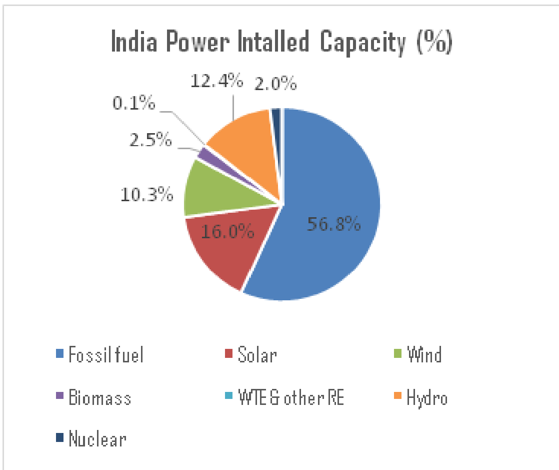
essentially constant rate. They are typically high-efficiency steam-electric units that maximize system mechanical and thermal efficiency while minimizing system operating costs.
The value of baseload plants is primarily economic, as they are not designed to follow the constantly varying system demand. Instead, they provide a stable and reliable source of power that forms the backbone of the electrical grid. This stability is crucial for ensuring that other, more variable sources of power can be integrated into the grid without causing disruptions. Coal-fired and gas-fired power plants are baseload sources that have played a crucial role in power supply. However, they are a big source of carbon emissions. Among clean energy sources nuclear powerplants, solar thermal, geothermal etc qualify to be baseload power stations. These plants are capable of operating continuously and efficiently, making them ideal for providing the steady supply of power needed to meet the base load. By operating at maximum or near-maximum output, these plants ensure that there is always enough electricity to meet the minimum demand. With new advancements, baseload power sources can also operate flexibly to adjust for varying power frequency and modulate electricity generation as per the grid requirements. In France, nuclear power plants can reduce their loads from 100% to 20% by load flowing mode to cope up with the grid requirements.

1.2 India's Energy Sources and Consumption Pattern

India relies on a diverse mix of energy sources, including coal, natural gas, oil, hydro, nuclear, and renewable energy.Coal remains the dominant source, accounting for a significant portion of the country's energy consumption. Despite its environmental impact, coal continues to be a critical component of India's energy strategy due to its abundance and cost-effectiveness. Natural Gas and Oil also play crucial roles in India's energy landscape. These fossil fuels are essential for various industrial processes and transportation needs. However, their consumption contributes to greenhouse gas emissions, prompting a shift towards cleaner alternatives.

Amongst the clean sources, hydropower and nuclear energy have been vital for providing stable and reliable electricity. Hydropower leverages India's vast river systems, while nuclear energy offers a low-carbon option for meeting the country's growing energy demands. Renewable Energy has picked up very well over the past decade, and witnessed substantial growth, with significant investments in solar and wind power. India aims to increase the share of renewables in its energy mix to achieve its climate goals and reduce carbon emissions. The electricity mix of India in 2023-24 look like as depicted below:

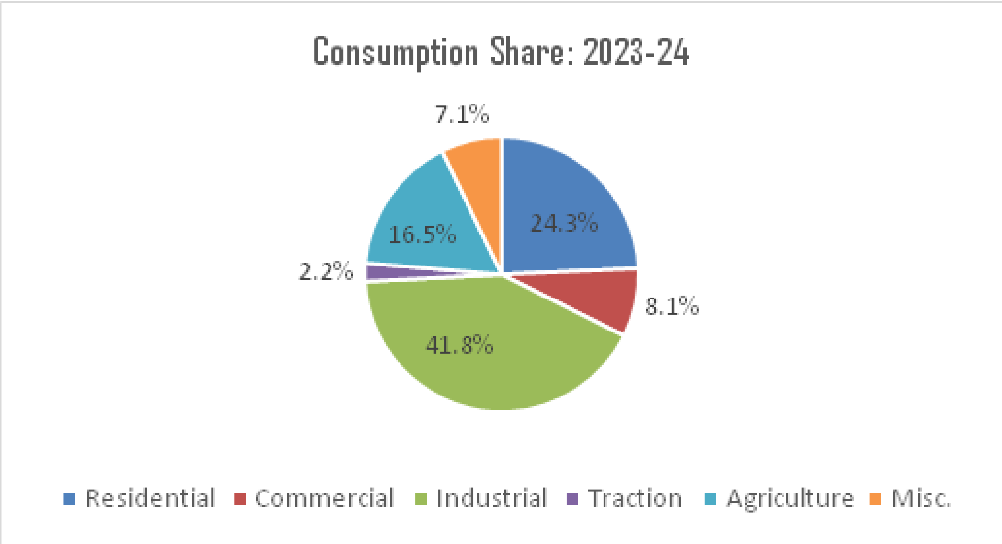




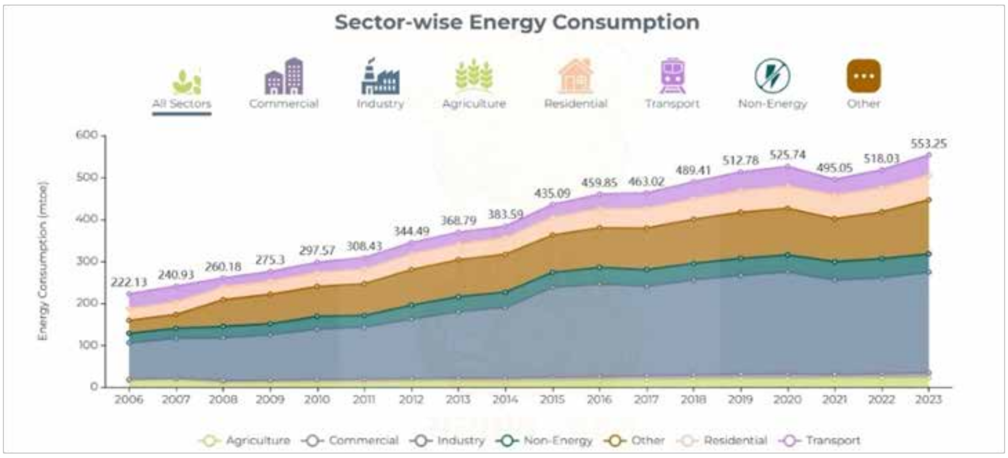
Source: CEA &MoP, India Data (Hydro includes Large + Small hydro+ PSP)

The dashboard highlights the share of different electricity sources in the electricity mix of the country. Rapid expansion has happened in the installation of solar and wind capacities which collectively make up more than 1/4th of country's installed capacities in 2023-24, reflecting the country's commitment to sustainable energy. However, fossil fuel still dominates the power mix and would continue to be so for coming few years as country prepares for its new clean baseload capacities to replace coal power plants.

In terms of power consumption, industries take away major of 41.8%, followed by residential, agriculture, and commercial segments. Transportation is catching up as more electrification drives is underway for long distance trains and metro rails.



The data also shows a steady increase in energy consumption across various sectors, including residential, industrial, and commercial. This trend is indicative of India's economic growth and development, driving the need for a robust and diversified energy supply.



India's Sector-wise Energy Consumption
Source: NITI Ayog Report

1.3 India's Electricity Market

India stands as the third-largest producer and consumer of electricity worldwide, boasting an installed power capacity of 446.18 GW as of June 30, 2024[3]. This significant capacity underscores the country's robust infrastructure and its commitment to meeting the growing energy demands of its population and industries.As of June 30, 2024, India's installed renewable energy capacity, including hydro, reached 203.19 GW, which represents 45.5% of the overall installed power capacity[3]. This substantial share of renewable energy highlights India's strategic shift towards sustainable and environmentally friendly energy sources. Solar energy leads the renewable sector with a contribution of 85.47 GW, followed by wind power at 46.65 GW, biomass at 10.35 GW, small hydropower at 5.00 GW, waste-to-energy at 0.59 GW, and hydropower at 46.93 GW[3].

The non-hydro renewable energy capacity addition in FY23 stood at 15.27 GW, up from 14.07 GW in FY22[3]. This growth reflects India's ongoing efforts to enhance its renewable energy portfolio and reduce its reliance on fossil fuels. In fact, India's power generation witnessed its highest growth rate in over 30 years in FY235, with power generation increasing by 6.80% to 1,452.43 billion kilowatt-hours (kWh) as of January 2024[3].

According to data from the Ministry of Power, India's power consumption stood at 1,503.65 BU in April 2023, and the peak power demand in the country reached 249.85 GW in June 2024[3]. These figures indicate the substantial and growing demand for electricity in India, driven by economic growth, urbanization, and industrialization. The performance of coal plants also saw improvements, with a plant load factor (PLF) of 73.7% for the first nine months of FY23, compared to 68.5% in FY22 for the same period [3]. The thermal power plant load is estimated to improve by 63% in FY24, fueled by strong demand growth along with subdued capacity addition in the sector[3].

In a global context, India's electricity production in September 2024 was notable. The country produced 159,167 GWh of electricity, making it one of the top three producers, alongside the People's Republic of China and the United States[4]. Net Electricity Production in September 2024 in GWh for top 3 producers is tabulated below:

Sep 2024 (in GWh)	China	USA	India
Electricity	829447	366471	159167
Nuclear	33382	62664	4631
Hydro	129675	17916	22016
Coal, Peat and Manufactured Gases	485545	57198	104840
Oil and Petroleum Products	766	2321	381
Natural Gas	23439	166040	4408
Combustible Renewables	15971	3847	1390
Other Combustible Non-Renewables	627	657	143
Total Combustible Fuels	526349	230063	111162
Geothermal	15	1230	
Solar	61721	25708	11488.55

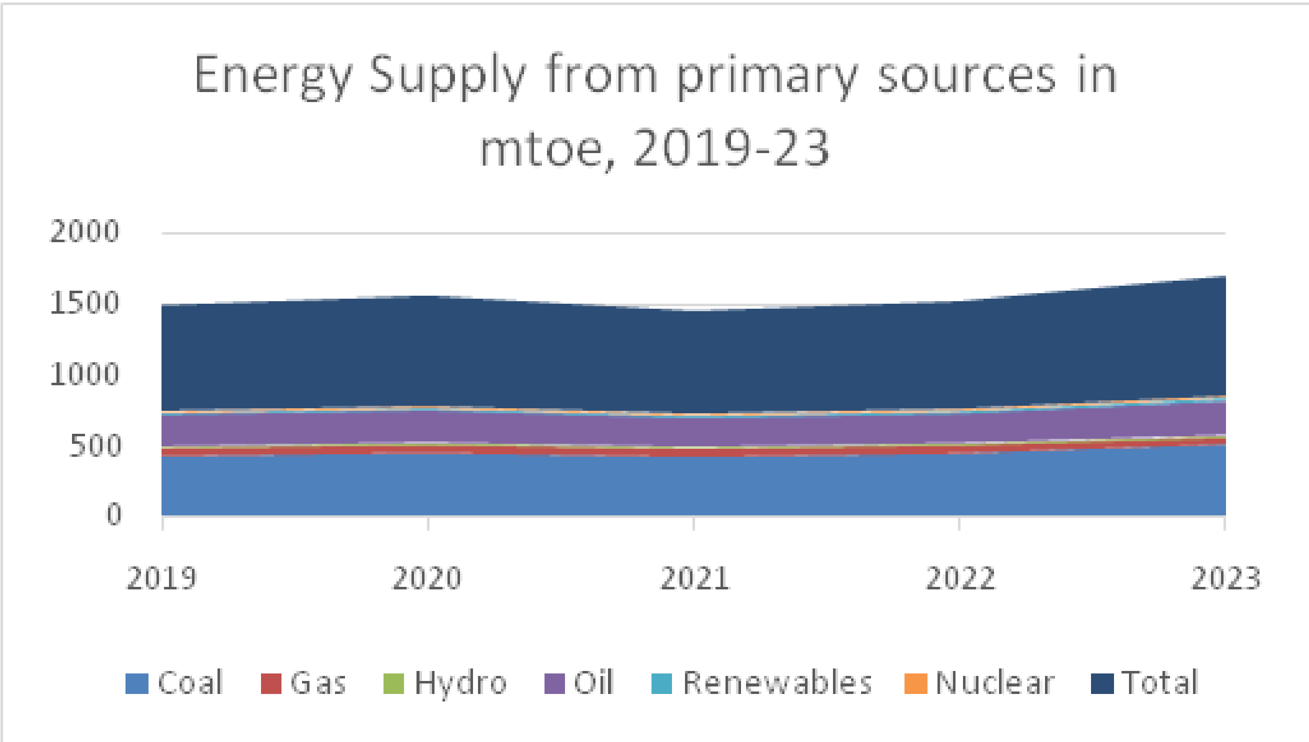
Wind	78304	28795	9870.26
Not Specified	1	94	
Total Renewables (Hydro, Geo, Solar, Wind, Other)	285687	77497	44764.34

Source: Iea

India's commitment to expanding its clean energy capacity and improving the efficiency of its power plants positions it as a key player in the global energy market. The country's strategic initiatives and investments in the energy sector are crucial for meeting its future energy needs and achieving sustainable development goals.

1.4 Outline of Energy Mix

India's energy mix has evolved significantly over the years, reflecting the country's growing energy demands and its efforts to diversify its energy sources. The energy supply in milliontonnes of oil equivalent (mtoe) from 2019 to 2023 showcases the contributions from various primary energy sources[5].



Source: NITI Ayog Report

In 2019, coal was the largest primary energy source, contributing 422.66 mtoe, followed by oil at 232.95 mtoe[5]. By 2023, coal's contribution had increased to 502.46 mtoe, and oil's contribution had risen to 245.46 mtoe[5]. This significant increase in coal and oil usage highlights the country's reliance on these conventional energy sources to meet its growing energy needs. Gas, another important energy source, saw fluctuations in its contribution over the years. In 2019, gas contributed 55.18 mtoe, which increased to 58.5 mtoe in 2020 but then decreased to 54.63 mtoe in 2023[5]. Hydro energy, on the other hand, remained relatively stable, with a slight increase from 11.62 mtoe in 2019 to 13.97 mtoe in 2023[5].

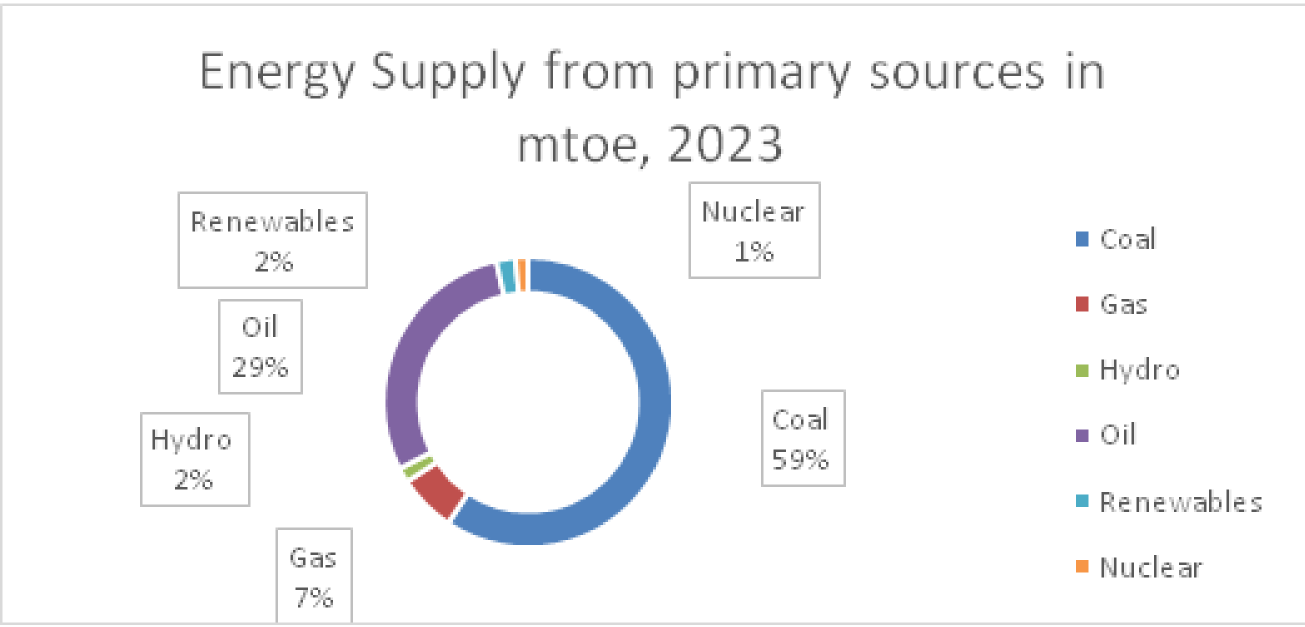
Renewable energy sources have shown a promising upward trend. In 2019, renewables contributed 11.22 mtoe, which steadily increased to 18.27 mtoe by 2023[5]. This growth reflects India's commitment to expanding its renewable energy capacity and reducing its carbon footprint.Nuclear energy has also been a part of India's energy mix, with contributions ranging from 9.85 mtoe in 2019 to 11.95 mtoe in 2023[5]. Despite being a smaller portion of the overall energy mix, nuclear energy plays a crucial role in providing a stable and reliable energy supply.The total energy supply from primary sources increased from 743.48 mtoe in 2019 to 846.74 mtoe in 2023[5]. This growth underscores the rising energy demand in the country and the need for a diverse energy mix to ensure energy security and sustainability.

Energy Supply in mtoe from 2019 to 2023 for India[5]

	2019	2020	2021	2022	2023
Coal	422.66	443.68	416.88	440.62	502.46
Gas	55.18	58.5	55.47	58.48	54.63
Hydro	11.62	13.43	12.95	13.07	13.97
Oil	232.95	237.23	213.43	218.34	245.46
Renewables	11.22	12.44	13.28	15.28	18.27
Nuclear	9.85	12.11	11.21	12.28	11.95
Total	743.48	777.39	723.22	758.07	846.74

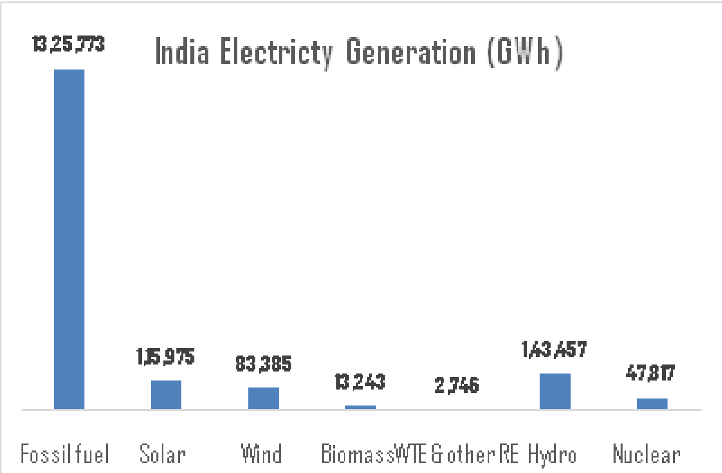
Source: NITI Ayog Report

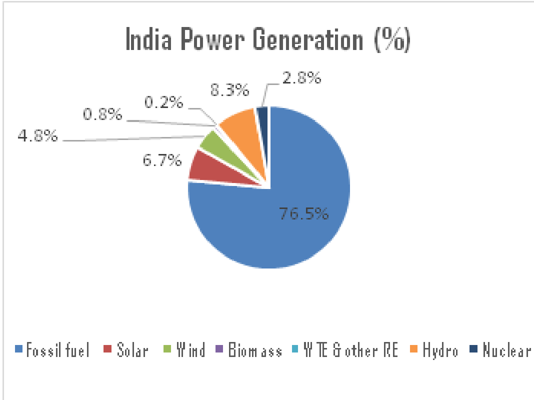
In terms of the percentage share of each energy source in 2023, coal accounted for 59%, oil for 29%, gas for 7%, renewables for 2%, hydro for 2%, and nuclear for 1%[5]. This distribution highlights the dominance of coal and oil in India's energy mix, while also showcasing the growing importance of renewable energy sources.



Source: NITI Ayog Report

When it comes to the electricity mix of India, fossil fuels (majorly coal and gas)are the prominent sources of power supply with a whopping share of around 3/4th of the total electricity generation mix. Additionally, there has been a generation of 215 BU of electricity from captive power plants in 2023-24, which are also majorly fossil fuel based. It accounts for major chunk of India's carbon emissions and hence needs suitable replacement as they age. Source wise contribution of different power sources is depicted below:





Source: CEA & Mop, India Data for 2023-24

2

India’s Growth Targets and Climate Objectives

2.1 Economic and Developmental Objectives of India

India's economy is set to grow at 6.6% in 2025, maintaining its position as a major driver of global growth[6]. It is one of the fastest-growing economies in the world and is poised to continue on this path, with aspirations to reach high middle-income status by 2047. The country is committed to ensuring that its continued growth path is equipped to deal with the challenges of climate change. Between 2011 and 2019, India is estimated to have halved the share of the population living in extreme poverty, defined as living below $2.15 per person per day [7]

India's growth is driven by public investment in infrastructure and rising household investments in real estate. Government initiatives have sought to boost the manufacturing sector by improving the business environment, enhancing logistics infrastructure, improving tax efficiency, and rationalizing tax rates. As a result, the industry grew by 9.9% in FY23/24[7].

India's energy landscape has seen a significant transformation, with a strong emphasis on renewable energy sources. Over the past decade, the country has made remarkable progress in diversifying its energy mix, reducing its reliance on traditional fossil fuels. At the COP26 summit, India set an ambitious target of achieving 500 GW of non-fossil fuel-based energy by 2030[8]. As of November 2024, India's installed non-fossil fuel capacity has surged by 396% over the last 8.5 years, reaching more than 205.52 GW, which accounts for approximately 42% of the nation's total capacity[8].

Solar power has experienced a dramatic increase, with installed capacity growing from just 2.5 GW in 2014 to about 94.16 GW by November 2024[8]. This growth reflects the government's commitment to promoting solar energy through initiatives like the International Solar Alliance, which involves collaboration with over 120 signatory countries.

The Indian government has also allowed 100% Foreign Direct Investment (FDI) under the automatic route for renewable energy generation and distribution projects, in accordance with the provisions of the Electricity Act 2003[8]. At the COP26 summit in November 2021, India announced its goal to achieve net-zero emissions by 2070, highlighting the vast potential of the renewable energy sector beyond just creating a cleaner future[8].

The shift towards renewable energy not only focuses on environmental sustainability but also has the potential to create numerous job opportunities and drive inclusive growth. India's commitment to expanding its renewable energy capacity and promoting sustainable energy solutions is evident in these developments, positioning the country as a leader in the global energy transition.

2.2 Energy Demand Projections and Growth Drivers

India, as the third-largest consumer of energy globally, has seen its peak demand reach unprecedented levels[9]. In June 2023, the peak demand hit a record high of 223 gigawatts (GW), marking a 3.4% increase from the highest level recorded in 2022[9]. This upward trend in energy consumption is expected to continue, driven by several key factors.

Industrial growth and urbanization have been significant contributors to the rising energy demand. Over the past decade, India has achieved an installed capacity exceeding 400 GW, supported by favorable government policies and geopolitics[9]. The country's power sector is currently dominated by fossil fuels, but there are ambitious plans to significantly increase the share of renewable and nuclear energy.

Central Electricity Authority (CEA) conducts Electric Power Survey (EPS) of the country every five years for estimating the electricity demand of the country on medium-term and long-term basis[10].

Electrical energy consumption, T&D losses, electrical energy requirement and peak electricity demand for the years 2021-22, 2026-27 and 2031-32 on all-India basis as per 20th EPS Report

Particulars	Year			CAGR (in %)	
	2021-22	2026-27	2031-32	2021-22 to 2026-27	2026-27 to 2031-32
Total Energy Consumption - MU	11,38,408	16,10,053	21,33,380	7.18	5.79
T&D losses - MU	2,43,237	2,97,782	3,40,396		
T&D losses (Ex- Bus) - %	17.60	15.61	13.76		
Energy Requirement (Ex-Bus) - MU	13,81,646	19,07,835	24,73,776	6.67	5.33
Annual Load Factor - %	77.65	78.57	77.07		
Peak Electricity Demand (Ex-Bus) - MW	2,03,115	2,77,201	3,66,393	6.42	5.74

Urbanization is projected to add approximately 270 million people to India's urban population by 2040[11]. This rapid urbanization will lead to a massive increase in residential floor space, from less than 20 billion square meters today to more than 50 billion square meters in the next two decades[11]. Consequently, there will be a substantial rise in demand for energy-intensive building materials and a transition in household energy use from solid biomass to electricity.

The rising ownership of appliances and the growing demand for air conditioners will further drive the increase in electricity consumption in the buildings sector. The share of energy demand taken by electricity in this sector is expected to rise from a quarter today to around half by 2040[11]. Additionally, the transport sector, currently the fastest-growing end-use sector in terms of energy demand, will see further growth due to urbanization. Poor air quality has prompted various policy initiatives focused on clean fuel, efficiency, mass transit, and the electrification of transport.

Industry remains the largest end-use sector for energy, with its share in total final consumption projected to rise from 36% now to 41% by 2040[11]. The expansion of the industrial sector will also lead to rapid growth in road freight and railways, which eventually will give rise to increased energy demand [11]. Thus, driven by the GDP growth India's energy demand is experiencing rapid growth, which underscores the importance of strategic planning and investment in the energy sector to meet the future energy needs of the country.

2.3 India's Climate Objectives

India has set ambitious climate objectives to address the pressing issue of climate change and to transition towards a more sustainable and low-carbon economy. One of the key targets is to reduce its emissions intensity by 45% below 2005 levels by 2030, excluding Land Use, Land-Use Change, and Forestry [13]. This goal is part of India's broader commitment to mitigating the impacts of climate change and promoting sustainable development.At the COP26 summit, Prime Minister Narendra Modi announced a target of achieving 500 GW of non-fossil fuel capacity by 2030[13]. This target underscores India's dedication to increasing the share of renewable energy in its energy mix and reducing its reliance on fossil fuels. Additionally, India has pledged to become net zero by 2070[13]. To support this commitment, a "net zero emissions" bill was introduced in the upper house of the Indian parliament in December 2022, providing a framework for achieving net zero emissions by the year 2070[13].

India's climate objectives also include sector-specific action areas, targeting the power, industry, transport, building, and urban sectors. These sectors are critical for reducing greenhouse gas emissions and promoting sustainable practices across the economy. For instance, India aims to create an additional carbon sink of 2.5 to 3 billion tons of CO2 equivalent through additional forest and tree cover by 2030[14]. This initiative highlights the importance of afforestation and reforestation in mitigating climate change.

Furthermore, India has introduced a new framework for transitioning to cleaner energy for the period 2021-2030[15]. This framework aims to increase green jobs, boost the manufacturing of low-emission products such as electric vehicles and super-efficient appliances, and promote innovative technologies like green hydrogen. These measures are designed to support the country's transition to a low-carbon economy and create economic opportunities in the green energy sector.

India is also committed to stronger adaptation targets, enhancing investments in development programs focused on sectors and areas vulnerable to climate change, particularly agriculture, water resources, health, disaster management, the Himalayas, and coastal regions[15]. These adaptation measures are crucial for building resilience to climate impacts and ensuring sustainable development.

2.4 Energy Options and their Potential

India has made significant strides in diversifying its energy portfolio, focusing on various renewable energy sources to meet its growing energy demands and reduce its carbon footprint. The country's energy options include solar energy, wind energy, hydropower, clean hydrogen, and energy storage, each with substantial potential for development and contribution to the energy mix.

Solar Energy: India has seen remarkable progress in solar energy, with the installed capacity increasing from 2.5 GW in 2014 to approximately 94.16 GW as of November 2024[16]. The government aims to achieve 500 GW of non-fossil fuel-based energy by 2030, with a significant portion coming from solar power[16]. This ambitious target underscores the potential of solar energy to play a pivotal role in India's energy transition.Along side solar PV, solar thermal also presents good opportunity for India to go ahead with.

Wind Energy: Wind energy capacity in India has more than doubled since 2014, reaching 47.95 GW[16]. The government plans to expand this capacity to 99.9 GW by 2029-30, with major wind energy-producing states including Andhra Pradesh, Gujarat, Karnataka, Maharashtra, Rajasthan, and Kerala[16]. The expansion of wind energy capacity highlights its potential to contribute significantly to the country's renewable energy goals.
Hydropower: Hydropower remains a crucial part of India's energy mix, providing a stable and reliable energy supply. Currently, hydroelectric power projects with an aggregate capacity of 15 GW are under construction[17]. The hydro capacity is expected to increase from 42 GW to 67 GW by 2031-32, marking a substantial rise in capacity. This growth reflects the potential of hydropower to support India's energy needs sustainably[17].

Clean Hydrogen: India launched its National Hydrogen Mission on January 4, 2023, with the goal of becoming a global leader in green hydrogen production by 2030[18]. The mission aims to achieve an annual production capacity of at least 5 million metric tonnes (MMT) and attract investments exceeding Rs. 8 lakh crore (US$ 95.9 billion) [18]. Clean hydrogen is poised to play a crucial role in India's transition to a low-carbon economy, offering a clean and affordable energy solution.

Energy Storage: To ensure a successful energy transition and energy security, India is focusing on developing an ecosystem for energy storage systems (ESS) that are independent of technology and financially feasible. According to the National Electricity Plan (NEP) 2023, the projected energy storage capacity requirement is 16.13 GW by 2026-27, with a storage capacity of 82.32 GWh[19]. By 2029-30, the energy storage capacity is expected to reach 60.63 GW with a storage capacity of 336.4 GWh[19]. Energy storage systems are essential for integrating renewable energy into the grid and ensuring a stable power supply.

Nuclear Power: India has set a target to triple its nuclear power capacity and take it up from current level of 8170 MW to ove 21000 MW by 20230-21. Last year, India brought online 1400 MW nuclear capacity, fuel loading of a 500 MW prototype latest fast breeder reactor, which would set a trend for more fast breeder plants in the future, aiming to utilize Thorium reserves in the country.

India's diverse energy options and their potential reflect the country's commitment to achieving a sustainable and low-carbon energy future. By leveraging these renewable energy sources, India aims to meet its growing energy demands, reduce its dependence on fossil fuels, and contribute to global efforts to combat climate change.

3

Renewables with RTC Backup Support

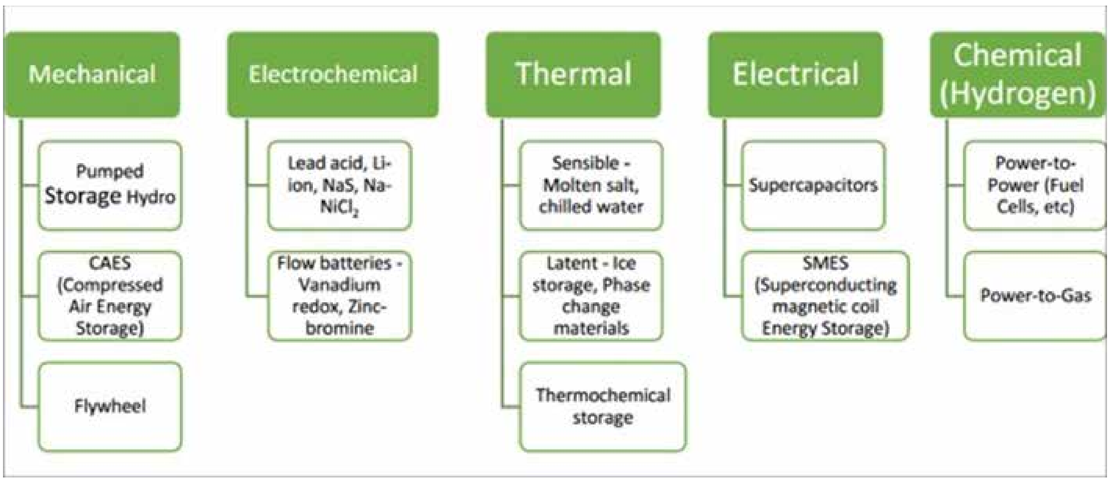
3.1 Renewables with BESS

Renewable energy sources, such as solar and wind, are essential for a sustainable energy future. However, their intermittent nature poses challenges for consistent power supply. To address this, integrating renewable energy with round-the-clock (RTC) backup support, particularly through Battery Energy Storage Systems (BESS), is crucial.

Battery Energy Storage Systems (BESS) comprise of electrochemical devices that store energy from the grid or power plants and discharge it when needed . These systems are widely used in electricity grids, electric vehicles, solar power installations, and smart homes. BESS technology enables power system operators and utilities to store energy for later use, ensuring a reliable power supply even when renewable sources are not generating electricity.The opportunities presented by energy storage systems are significant. They help mitigate the variability of renewable energy generation, improve grid stability, enable energy and peak shifting, provide ancillary support services, and facilitate larger renewable energy integration. Additionally, energy storage systems can reduce peak deficits and tariffs, lower carbonemissions, defer transmission

and distribution capital expenditures, and offer energy arbitrage.

According to the National Electricity Plan (NEP) 2023 of the Central Electricity Authority (CEA), the projected energy storage capacity requirement is 82.37 GWh by 2026-27, with 47.65 GWh from pumped storage plants (PSP) and 34.72 GWh from BESS[30]. This requirement is expected to increase to 411.4 GWh by 2031-32, with 175.18 GWh from PSP and 236.22 GWh from BESS. By 2047, the energy storage requirement is projected to reach 2380 GWh, with 540 GWh from PSP and 1840 GWh from BESS, driven by the addition of more renewable energy to meet net zero emissions targets[30].Several energy storage technologies are available, including mechanical, thermal, electrochemical, electrical, and chemical storage systems.



Source: MNREFigure 4 : Energy storage technologies

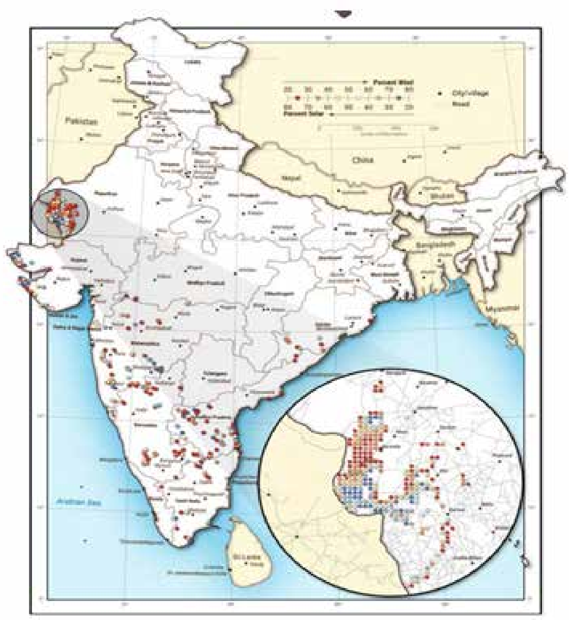
One notable example is India's first commercial standalone BESS project, approved by the Delhi Electricity Regulatory Commission (DERC)[31]. This 20 MW/40 MWh BESS project, supported by the Global Energy Alliance for People and Planet (GEAPP), IndiGrid, and BSES Rajdhani Power Limited (BRPL), will be installed at BRPL's 33/11 kV Kilokarisubstation[31].

The project aims to improve power quality and provide 24/7 reliable power to over 12,000 low-income consumers. GEAPP, in collaboration with its alliance partners, targets 1 GW of BESS commitments in India by 2026, aligning with India's goal of deploying 47 GW of BESS by 2032[31].

Integrating renewable energy with RTC backup support through BESS and other energy storage technologies is vital for ensuring a stable and reliable power supply. These systems not only enhance the efficiency and reliability of renewable energy sources but also contribute to reducing carbon emissions and achieving sustainable energy goals.

3.2 Hybrid Renewables Plants

Hybrid renewable energy systems, which combine multiple renewable energy and/or energy storage technologies into a single plant, are increasingly recognized as key to achieving maximum efficiency and cost savings in future decarbonized grids. These integrated power systems are gaining traction due to improving battery technology and the growth of variable renewable generation.In India, wind and solar PV are expected to play a major role in achieving the country's renewable energy capacity goals. One effective strategy to increase the deployment of these technologies is through the co-location of wind and solar PV plants to form a single hybrid power plant. By building wind and solar PV in the same location, hybrid plants can reduce transmission infrastructure costs and variability in the output power profile compared to stand-alone plants with a single technology. This is particularly advantageous in India, where wind speeds tend to increase during and after sunset hours, complementing the generation profile of solar PV.



Estimated locations for hybrid wind and solar PV plants / *Source: nrel.gov*

(Red dots indicate a higher proportion of solar PV and blue dots indicate a higher proportion of wind)

Suitable locations for hybrid plants are most prevalent in western Rajasthan, western Gujarat, and various sites across southern India. As of 2024, hybrid projects with a solar component had an installed capacity of 2.77 GW [33]. The potential for wind-solar hybrid systems is significant due to the high availability of both wind and solar resources across various locations in India. The Ministry of New and Renewable Energy (MNRE) adopted the National Wind-Solar Hybrid Policy in 2018 to promote the development of WSH power plants, offering certain waivers and incentives to developers[32]. The above map shows the locations that, after optimizing for the mix of solar PV and wind at each site, theoretically meet the criterion from India's Ministry of New and Renewable Energy (MNRE) national 2018 policy for hybrid plants (MNRE 2018):

Solar Energy Corporation of India Limited (SECI) tenders for WSH without storage have attracted low tariffs comparable to solar tariffs, with key participants including Adani Green

Energy, SB Energy, Greenko, and ReNewPower[34]. India's long coastline, endowed with high-speed wind and rich solar energy resources, provides a great opportunity for the wind-solar hybrid industry to thrive. The complementary generation profiles of wind and solar systems, which peak at different times of the day and year, make hybrid systems more likely to produce dependable power that meets demand[34]. Wind power plants integrated with solar power plants can effectively address the morning and evening peaks in the demand curve[34].
Key advantages associated with hybrid projects include better utilization of transmission infrastructure, enhanced grid stability, lower generation variability, better utilization of land resources, reduced possibility of undesirable power peaks, and complementary generation profiles[34]. These benefits make hybrid renewable plants a promising solution for India's energy needs, contributing to a more sustainable and reliable energy future.

3.3 Renewables with Hydrogen Generation

India's renewable energy sector has seen significant growth, particularly in solar and wind energy. The integration of these renewable sources with hydrogen generation presents a promising pathway for achieving energy security and sustainability.

Green hydrogen is produced through electrolysis, where water is split into hydrogen and oxygen using electricity generated from renewable sources like solar, wind, or hydropower. This process results in a clean and emission-free fuel with immense potential to replace fossil fuels and reduce carbon emissions. Another method of producing green hydrogen is from biomass, which involves the gasification of biomass to produce hydrogen. Green hydrogen can serve as a backup energy source for renewable energy plants, providing a constant and reliable energy supply. It has numerous applications, including powering vehicles, providing electricity, heating systems, and producing chemicals and fertilizers. Hydrogen fuel cells have a high energy density and are more efficient than traditional combustion engines, making them an attractive option for powering vehicles. Additionally, green hydrogen can be used in microgrids, providing electricity to remote areas and enabling energy independence.

The production of green hydrogen using renewable energy sources like solar, wind, and hydropower can provide energy security, reducing dependence on fossil fuels and ensuring a stable and reliable energy supply. Green hydrogen can also be produced locally, reducing the need for costly and environmentally damaging imports. Furthermore, green hydrogen produced using waste biomass provides an additional revenue stream for farmers and local communities. India has launched the National Green Hydrogen Mission with an outlay of Rs. 19,744 crores, targeting a production capacity of 5 MMT of green hydrogen per annum[37].

3.4 Geothermal Energy and its Market Scope

Geothermal energy, derived from the Earth's internal heat, is a renewable and sustainable energy source. It involves tapping into reservoirs of hot water and steam located beneath the Earth's surface. These geothermal resources can be accessed through wells, which range from a few feet to several miles deep, to bring steam and hot water to the surface for various applications, including electricity generation and heating and cooling.

To generate electricity, medium- or high-temperature geothermal resources are required. These resources are typically found near tectonically active regions where hot water and steam are closer to the Earth's surface or can be accessed at shallow depths. The levelized cost of electricity (LCOE) from geothermal power projects averaged between USD 0.049 and USD 0.085 per kWh between 2010 and 2020[38]. As a renewable resource, geothermal energy covers a significant share of electricity demand in countries such as Iceland, El Salvador, New Zealand, Kenya, and the Philippines, and meets more than 90% of heating demand in Iceland[38].

In India, the Geological Survey of India (GSI) has estimated a tentative theoretical potential of 10 GW that could be extracted from geothermal energy[39]. This potential highlights the significant opportunity for geothermal energy development in the country. In 2022, India's Oil and Natural Gas Corporation (ONGC) initiated plans to develop a major geothermal energy power facility in Ladakh[39]. Although the first drilling attempt was abandoned due to uncontrolled water volumes and lack of advanced equipment, ONGC is gearing up for a fresh geothermal campaign in Ladakh to meet India's growing energy needs[39].

The water temperature at the first drill well in Puga, Ladakh, is expected to be around 220 F, which is sufficient to pipe hot water or steam to the surface and power a turbine to generate electricity[39]. Puga and Chumathang in eastern Ladakh are considered the most promising geothermal fields in India. Additionally, efforts are being made to utilize geothermal energy from existing oil and gas wells in ONGC's Gandhar oil field in Ankleshwar, Gujarat, followed by the Cambay Basin in Gujarat[39].

The development of geothermal energy in India presents several advantages. It provides a reliable and continuous source of power, reduces dependence on fossil fuels, and contributes to the country's renewable energy goals. Moreover, geothermal energy has a low environmental impact and can be integrated with other renewable energy sources to create a diversified and resilient energy mix.

Geothermal energy holds significant potential for India's energy future. With the right investments and technological advancements, India can harness this renewable resource to meet its growing energy demands and contribute to a sustainable and low-carbon economy.

4

Solar Thermal and Emerging Opportunities

4.1 Solar Thermal: Key imperatives

Solar thermal technology holds significant potential for India, given its abundant solar resources. Solar thermal energy is a form of renewable energy that captures and utilizes the sun's heat to generate thermal energy. This technology employs solar collectors, such as flat-plate collectors, evacuated tube collectors, or concentrating solar power (CSP) systems, to absorb and concentrate sunlight. The captured heat can be used directly for residential and commercial heating, industrial processes, or converted into electricity through steam turbines. As a renewable energy source, solar thermal systems offer a sustainable and environmentally friendly alternative to fossil fuels, reducing greenhouse gas emissions and promoting energy independence. With advancements in technology and increasing efficiency, solar thermal energy is becoming an integral part of the global transition to clean and renewable energy sources.

Here are some key imperatives for solar thermal in India:

Energy Security: Solar thermal can help reduce dependence on imported fossil fuels, enhancing India's energy security. With vast solar potential, India can harness this renewable resource to meet its growing energy demands.

Decarbonization: Solar thermal systems can play a crucial role in reducing greenhouse gas emissions by replacing fossil fuels in industrial processes and power generation. This aligns with India's climate goals and commitments under the Paris Agreement.

Cost-Effectiveness: While the initial investment in solar thermal systems can be high, the long-term savings on energy costs make it a cost-effective solution. Government incentives and subsidies can further enhance the financial viability of these projects.

Technological Advancements: Ongoing research and development are improving the efficiency and cost-effectiveness of solar thermal technologies. Innovations in thermal energy storage and hybrid systems are making solar thermal more reliable and practical.

Policy Support: Strong policy frameworks and government support are essential for the widespread adoption of solar thermal technology. Initiatives by the Ministry of New and Renewable Energy (MNRE) and other agencies are crucial in promoting and scaling up solar thermal projects.

Sustainability: Utilizing solar thermal energy contributes to sustainable development by reducing reliance on finite fossil fuels and promoting renewable energy sources. This supports India's transition to a low-carbon economy.

Implementing solar thermal technology can significantly contribute to India's energy transition and sustainability goals. These key imperatives highlight the importance of solar thermal in achieving a cleaner, more sustainable energy future for India.

4.2 Solar Thermal Market Scenario and Scope

As of 2022, India's cumulative installed capacity for solar thermal power stood at 232.5 MW, with projections indicating a compound annual growth rate (CAGR) of over 2% from 2022 to 2035[45]. The market is driven by several factors, including:

- Government Initiatives: The Indian government has implemented various policies and incentives to promote renewable energy, including subsidies, tax benefits, and favorable regulatory frameworks. Programs like the Jawaharlal Nehru National Solar Mission (JNNSM) aim to increase the adoption of solar technologies, including solar thermal [46].

- Industrial Applications: As per the MNRE-GEF-UNIDO Report , the industrial market potential of CST technologies in India is around 6.45 GW [47]. Industrial sectors in India with reportedly good potential for CST implementation include dairy, food processing, paper and pulp, chemicals, textiles, fertilizer, breweries, pharmaceuticals, rubber, electroplating, and desalination. CST systems use a solar field of mirrors, or other reflective surfaces to concentrate sunlight onto a receiver, which captures the heat and stores it in a thermal energy storage (TES) medium (such as oil, molten salt, or phase change material), which can be used to directly decarbonize industrial processes (solar industrial heat)[48]. These systems provide high-temperature heat for processes, reducing reliance on fossil fuels and lowering carbon emissions.

- Technological Advancements: Innovations in solar thermal technology, particularly in thermal energy storage and hybrid systems, are enhancing efficiency and reliability. These advancements make solar thermal a more viable option for continuous and large-scale applications.

Key Players: Several key players are actively contributing to the growth of the solar thermal market in India. Notable companies include Tata Power Renewable Energy Ltd, Geetanjali Solar Enterprises, EspeeSolaar, Enolar Systems Marketing Pvt Ltd, and Andromeda Energy Technologies (P) Ltd. These companies are involved in developing and expanding solar thermal projects, driving market growth and innovation.

The Solar Energy Corporation of India (SECI) has facilitated growth by organising solar power auctions, leading to competitive tariff rates that make solar power one of India's most cost-effective energy sources. In some auctions, solar tariffs have fallen below Rs. 2.50 (US$ 0.030) per kWh, often cheaper than conventional coal-fired power [49]. India's involvement in the International Solar Alliance (ISA) has also strengthened the country's international partnerships, bringing foreign investment and shared expertise to its solar industry[49].

4.3 Solar Thermal: Recent Developments and Opportunities

Solar thermal technology harnesses the sun's energy to generate heat for various applications, including electricity generation, water heating, and industrial processes. In recent years, India has made significant strides in solar thermal technology, driven by technological advancements, government initiatives, and large-scale projects. These developments present numerous opportunities for sustainable energy growth and economic development in the country.

Recent Developments:

A. Technological Advancements:

Concentrated Solar Power (CSP): CSP technology has seen significant improvements in efficiency and cost reduction. Projects like the Gujarat Solar One and Rajasthan Sun Technique Energy are leveraging CSP to enhance energy output [50][51]. These projects use parabolic troughs and solar towers to concentrate sunlight and generate high temperatures for power generation.

B. Thermal Storage:

Innovations in thermal storage systems, such as molten salt storage, are enabling solar thermal plants to provide energy even when the sun is not shining. This is crucial for ensuring a stable and reliable power supply[52].

C. Government Initiatives:

SECI, a nodal agency for implementing government's renewable energy projects, is expected to float a tender for 500 megawatt (MW) of solar thermal capacity by the end of FY25 [53]. This will be the first time in India that such a tender would be floated on this scale.

Opportunities:

Rural Electrification: Solar thermal projects can play a vital role in rural electrification, providing reliable and sustainable energy to remote areas. This can improve the quality of life and support economic activities in rural regions.
Research and Development: Continued investment in R&D can lead to further advancements in solar thermal technology, making it more efficient and cost-effective. Collaboration between government, industry, and academic institutions is essential for driving innovation.

Energy Security: Solar thermal technology can significantly reduce India's dependence on fossil fuels, enhancing energy security and reducing greenhouse gas emissions.

Economic Growth: The expansion of solar thermal projects creates job opportunities and stimulates local economies. The development of solar parks and rooftop installations can provide employment in construction, maintenance, and operations.

India's commitment to solar thermal technology is evident through its ambitious projects and supportive policies. With continued advancements and strategic investments, solar thermal energy can play a pivotal role in meeting India's growing energy needs sustainably.

4.4 Industry and Market Challenges

Solar thermal technology, despite its potential, faces several significant challenges that hinder its widespread adoption and development in India.One of the primary challenges is the technology barrier. The sector suffers from a lack of extensive research and interest, which has resulted in the absence of widely established performance norms for the equipment used. Some manufacturers continue to use unsuitable equipment and configurations, leading to suboptimal system performance [47].

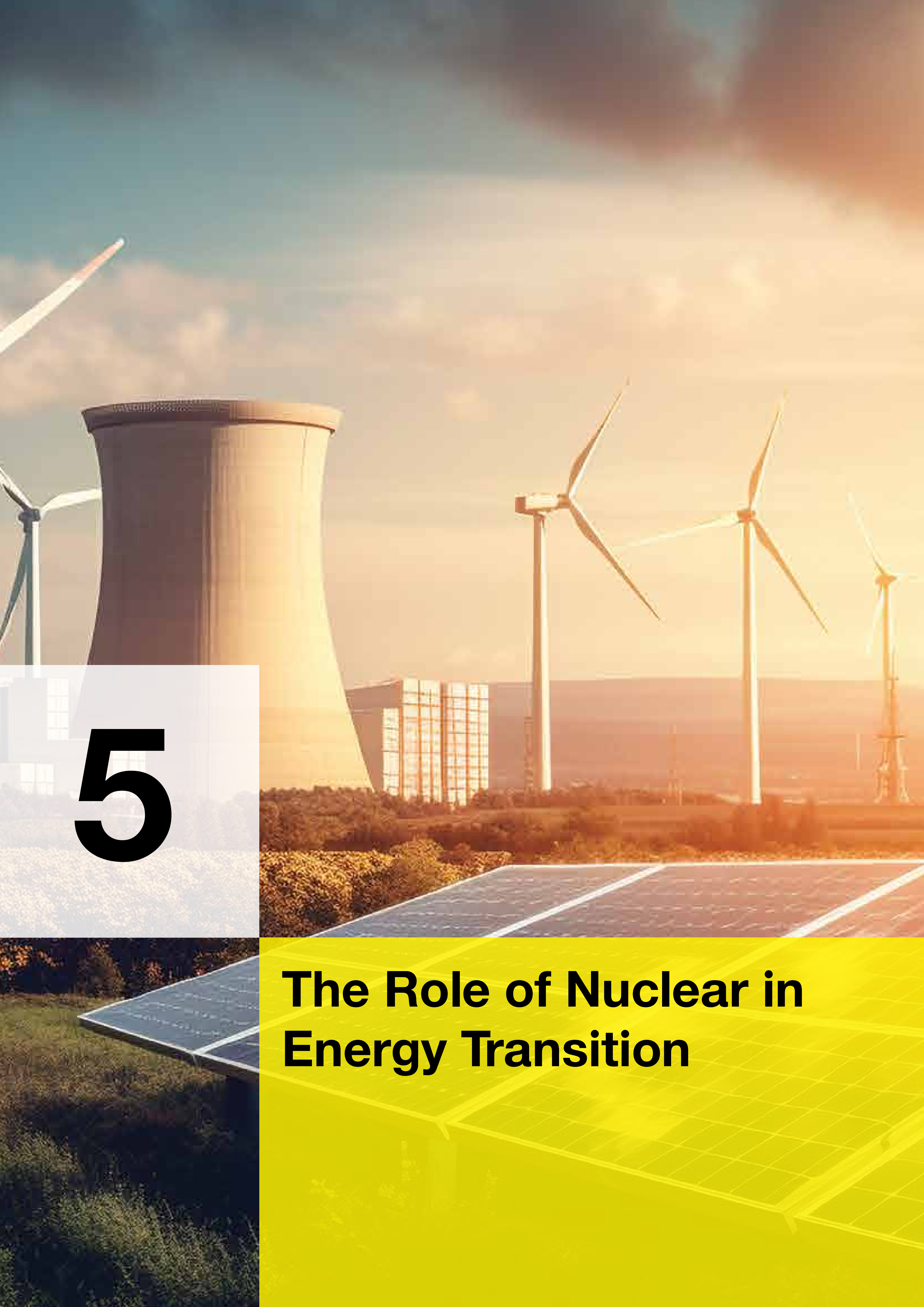
Another significant challenge is the lack of awareness. Compared to photovoltaic (PV) technologies, there is a general lack of knowledge about Concentrated Solar Thermal (CST) technologies. This lack of awareness extends to educational curricula, media, and publications, where CST technologies are often overshadowed by PV technologies [47].

The supplier limitations also pose a challenge. The current market size for CST is not very attractive, despite its potential. The sector is still in its early growth stages, and the technologies and business models have yet to mature. This slow growth has led to several suppliers closing their operations, resulting in a loss of expertise in the sector [47].

The financial barrier is another significant hurdle. The high upfront costs for system installation, coupled with slow payback periods, make CST a risky investment for many industries. There is also a lack of significant models that benefit both industry owners and investors, further exacerbating the issue[47].

Lastly, the policy barriers hinder the growth of CST. Although the Central Government provides subsidies, tax benefits, and support programs, the policies and regulations in place do not significantly promote the usage of CST. The return on investment is not very high, which discourages significant initial investments in the sector [47].

Overcoming technological barriers, increasing awareness, improving supplier dynamics, addressing financial constraints, and enhancing policy support are essential steps towards realizing the full potential of solar thermal energy.



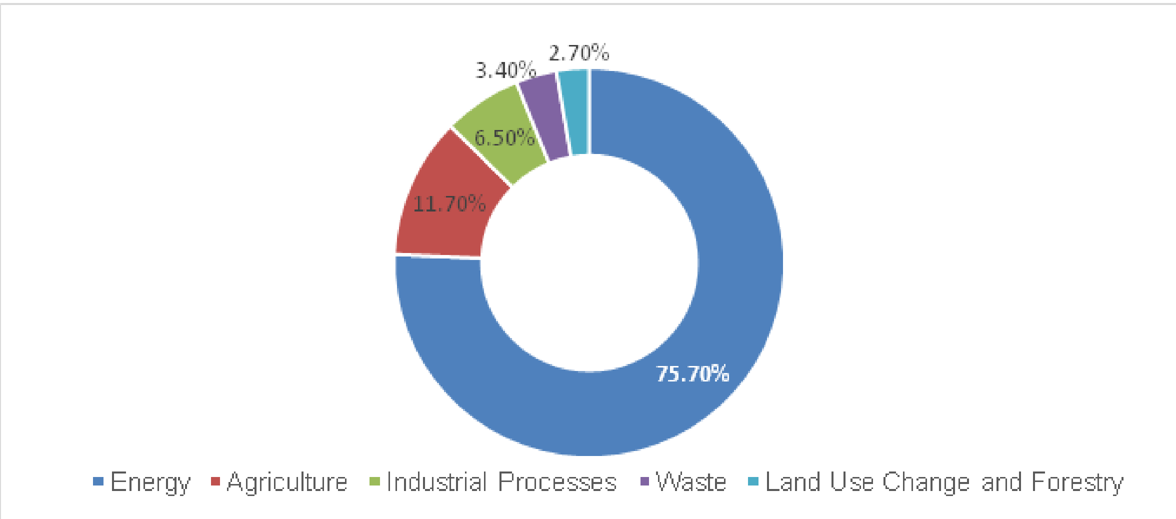
5

The Role of Nuclear in Energy Transition

5.1 Global Climate Change and EnergyTransition

Global climate change is one of the defining challenges of the current generation.The Intergovernmental Panel on Climate Change (IPCC) has been engaged in shedding the light on global climate change, contributing to the understanding of its causes and consequences and the options for risk management through adaptation and mitigation. They have reported that the emissions of greenhouse gases (GHG) due to human activities, global warming, rise in sea levels have continued since the beginning of the industrialization. It isestimated that human activities have caused approximately 1.0 C of global warming above pre-industrial levels, with a likely range of 0.8 C to 1.2 C. Global warming is likely to reach 1.5 C between 2030 and 2052, if it continues to increase at the current rate. The primary cause has been GHG emissions that have continued to increase, with ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between and within countries, and among individuals. Continued climate change would lead to long-term alterations in temperature, weather patterns, and other atmospheric conditions on Earth.

Production and use of energy account for more than75% of total GHG emissions, making the energy sectorone of the largest contributorof GHG emissions. It can be said that energy and climate change– the two most significant and interconnected challenges facing the world today have profound implications for environmental, social, and economic systems. Therefore, energy production and utilization must be an important focus of the global response to climate change. Since energy infrastructure tends to have a lifespan measured in decades, immediate action is needed to make this rapid transition possible.



Global greenhouse gas emissions by sector, 2021

IPCC recommends limiting the average global temperature increase to 1.5 C, need of global energy production and use to be fully decarbonized by around 2050, with rapid reductions in emissions starting immediately.Despite this, energy-related CO2 emissions reached record high, growing to 37.4 Gt in 2023, a 1.3% increase from 2022.

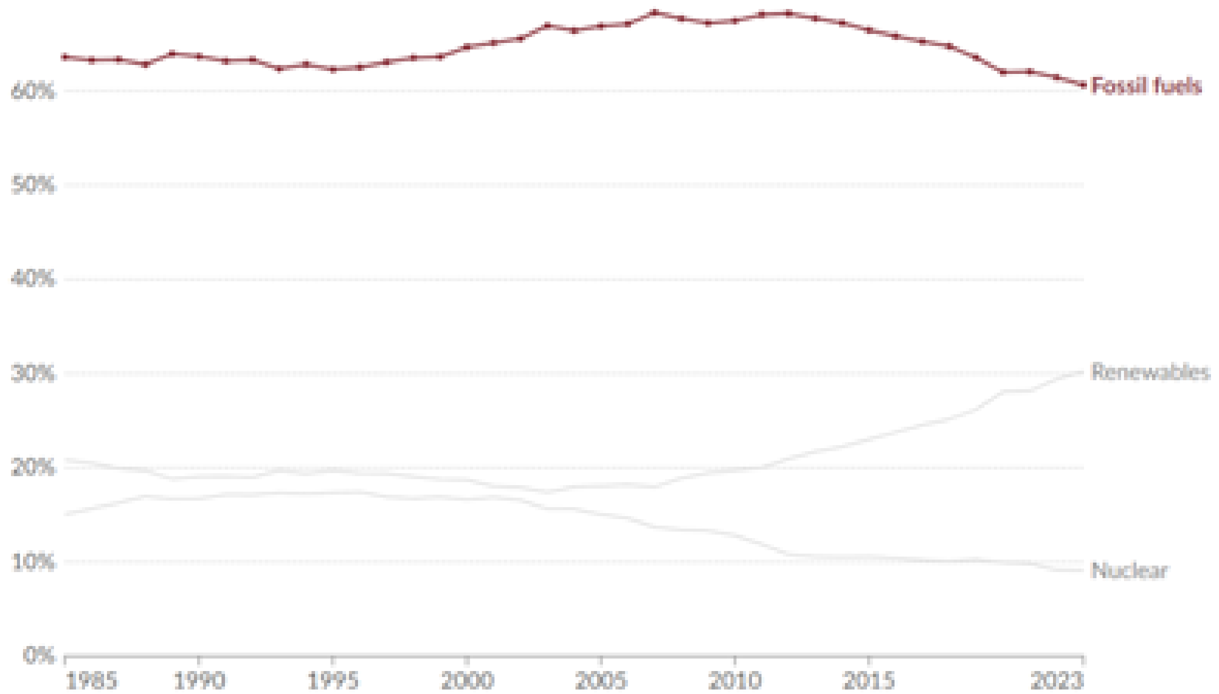
Emissions from energy comprise predominantly CO2 from the burning of fossil fuels, methane released mainly during fuel extraction and nitrous oxide formed during combustion. Around half of total energy emissions are produced from the direct use of fossil fuels in industry, transport, and buildings. Electricity generation accounts for approximately one third of total emissions from energy production and use, highlighting its increasing importance for climate change mitigation. However, electricity production, like other energy sectors, faces the immense challenge of shifting almost entirely to low carbon energy sources in just 30 years, from a system dominated today by fossil fuels.

Countries are off-track to limit global warming in line with the IPCC 1.5 C scenario and the window for action is narrowing rapidly. NEA (Nuclear Energy Agency) analysis concludes that tripling global installed nuclear capacity provides a realistic and practical path to meet net zero goals by 2050. The world could avoid 87 Gt of cumulative emissions between 2020 and 2050 with a combination of long-term operation (LTO) of existing reactors, new large-scale reactor builds, and the deployment of small modular reactors (SMRs).

5.2 Nuclear Advantages and Challenges

The need for ambitious mitigation coincides with continued growth in global population and economic activity, as well as efforts to ensure "access to affordable, reliable, sustainable and modern energy for all" to achieve the United Nations Sustainable Development Goals, in particular Goal 7 (Ensuring access to clean and affordable energy, which is key to the development of agriculture, business, communications, education, healthcare and transportation). The trend towards increased electrification of global energy demand, brings into focus the critical role of power generation in the clean energy transition. The power system in the future will rely on a broad range of technologies working in synergy in a more integrated and complex system. However, the available technology options exhibit different characteristics, such as power densities, capacity factors, carbon intensities, modularity, deployment requirements (resources, capital etc.) and capabilities to provide services to the electricity system. These differences influence the suitability of each technology option to contribute to a low carbon, affordable and reliable power system.

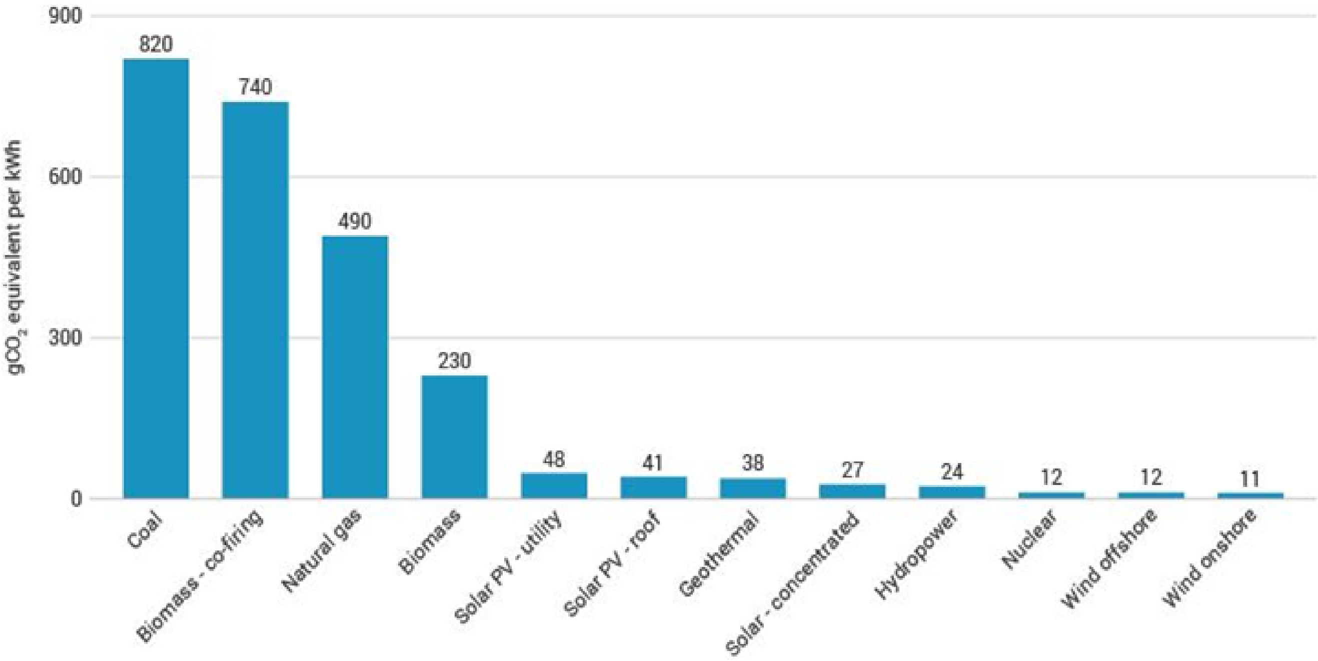
Concerted international efforts over the past 20 years have increased the amount of electricity generated by wind, solar and other renewable sources, but have failed to displace fossil fuels from the mix. As a matter of fact, in 2023, fossil fuels produced more electricity. In its 2018 report, IPCC warned that we are likely to breach the 1.5 C threshold by as early as 2030. Considering the climate emergency, there is an urgent need for building clean energy capacities at a rapid pace, by utilizing all low carbon sources and supplement the ongoing initiatives for renewable energy across different countries.



Share of electricity generation from fossil fuels (1985 – 2023)

Source: Ember (2024); Energy Institute - Statistical Review of World Energy (2024)

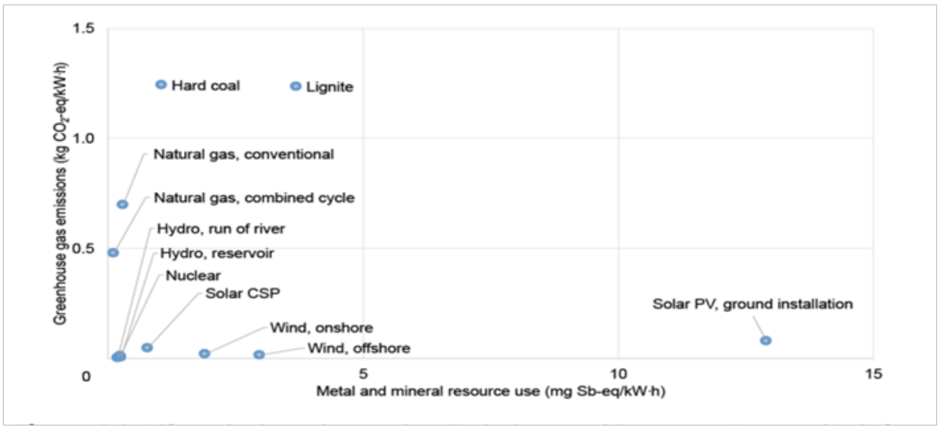
Nuclear and hydro have provided a backbone to electricity grid and reliably generated clean energy over the past several decades and helped mitigated several gigatons of CO2 emissions. Nuclear alone, over the past 50 years, has cumulatively avoided CO2 emissions by 74 Gt, and that hydro avoided over 98 Gt tons of CO2 emissions. In terms of total lifecycleCO2 emission, IPCC found that nuclear with 12 gCO2 equivalent/ kwh is one of the cleanestsources of electricity.



Total lifecycle CO2 emission

Recognizing the important role that nuclear can play in energy transition, IPCCconsidered the nuclear in the long term 1.5 C pathways for climate change mitigation and envisaged a substantial increase in global nuclear generation (100-500%) by 2050.The International Energy Agency (IEA),a special body of the Organisation for Economic Co-operation and Development (OECD), has also recognized the role of nuclearpowers in climate mitigation. Besides electricity generation, nuclear power could provide a significant contribution to decarbonizing the non-electric energy sector, an undertaking that has proved to be more challenging.

Nuclear also does better in terms of material use per kWh for different electricity generation technologies which is amongst the lowest in case of nuclear energy. This composite benefit of nuclear energy in terms of low material use and low emissions intensity illustrates their potent role in the climate change mitigation and the energy security.



F Lifecycle Greenhouse Gas Emissions and Resource Use per kWh forDifferent Electricity Generation Technologies

In 2021, in a working paper titled "Building Back Better", IMF, through an empirical econometric model estimated the GDP output multipliers of clean energy (renewable and nuclear) investments, and those associated with fossil fuel energy. They concluded that investing on clean energy, like solar, wind or nuclear ends up producing more GDP than it initially demands. By contrast, spending on non-eco-friendly energy generation, is found to crowd out other forms of domestic spending to a larger extent. Among the clean energy sources, the output multiplier of nuclear was higher than others.

Horizon	Renewable energy	Nuclear energy	Fossil fuel energy
Impact	1.40	4.11	0.62
1 year	1.46	3.97	0.58
2 years	1.49	3.88	0.54
3 years	1.51	3.83	0.51
4 years	1.53	3.80	0.48
5 years	1.54	3.78	0.47

The above table indicates that renewables and nuclear have higher Investment multiplier factor. For renewables, it increases over the period and plateaus around fifth year. Relative to other forms of clean energy (e.g. solar and wind), investments in nuclear energy lead to larger employment of both high- and lower-skilled resources for the construction of nuclear reactors relative to lighter energy producing infrastructure. While building and operating nuclear reactors tends to take time (5.1 years on average for large reactors of recent construction) spending is not sequential like in the case of renewables and tends to be more frontloaded.

Low carbon technologies differ significantly in the way they generate electricity — specifically in their dispatchability versus variability — and in their capability to provide services to the system. Unlike renewables, but like thermal power plants, nuclear plants are fully dispatchable, and their output can be adapted to the system's needs. Forced outages, unplanned shutdowns or restrictions in power production are infrequent events with which the system is well designed to cope.

In terms of capacity credit, systems services and system inertia, nuclear offers more advantages in comparison to other low carbon energy sources.

5.3 Nuclear Role in Net-Zero Scenario

Nuclear energy is positioned as a vital component in the transition to a net-zero world. Its ability to provide consistent, low-carbon power makes it indispensable for both electricity generation and decarbonizing hard-to-abate industries while integrating with emerging technologies like AI to enhance its effectiveness. Nuclear power provides a scalable and reliable source of low-carbon electricity, which is essential for balancing the intermittent nature of renewable energy sources. Nuclear power will be crucial to decarbonize hard-to-abate sectors such as heavy industry (including steel and cement production) and shipping. These sectors are responsible for nearly 40% of direct CO2 emissions and require substantial clean power to transition away from fossil fuels. Nuclear can provide high-temperature process heat and support the production of clean hydrogen through electrolysis, which is essential for these industries. By 2050, nuclear energy could displace 5 Gt of emissions each year, which is more than the annual emissions of the entire US economy today. As seen previously, nuclear power has a minimal carbon footprint, making it an attractive option for achieving net-zero goals.

With the growth of AI and powerful computing capabilities and data analysis tools, nuclear sectorhas gained tremendous popularity amongst big tech giants to power the their future data centres. For their much higher electricity demand and cooling requirements, these data centres have generated unprecedented demand for energy, that nuclear kindof highly dense and reliable source can meet.

6

Nuclear Technological Landscape and Evolving Market

6.1 Nuclear Conventional Reactors and Market

Pressurized Water Reactors (PWRs) that use enriched uranium dioxide (UO2) as fuel and normal light water as coolant and moderator make up over 70% in terms of total operable reactors and over 75% in terms of total generation capacity across the globe. PWRs finds their presence prominently in the US, France, Japan, China, and South Korean markets.

Boiling Water Reactors (BWRs) also use enriched UO2 as fuel and normal light water as coolant and moderator. However, BWRs allow water to boil in the reactor core and feed steam directly to turbine, without any intermediate loop that involve steam generators. Ther are over 60boiling water reactors with a 60 GWe generation capacity, forming a second largest chunk both in terms of global numbers and capacity.

Pressurized heavy water reactors (PHWRs) are third most popular reactor type with 46 operable reactors of 24 GWe capacity. They utilize natural UO2 as fuel and heavy water as coolant and moderator. In terms of process and system layout they are similar toPWRs andare built majorly in Canada and India. But, countries such as South Korea, China, Romania and Argentina also have operating PHWRs.

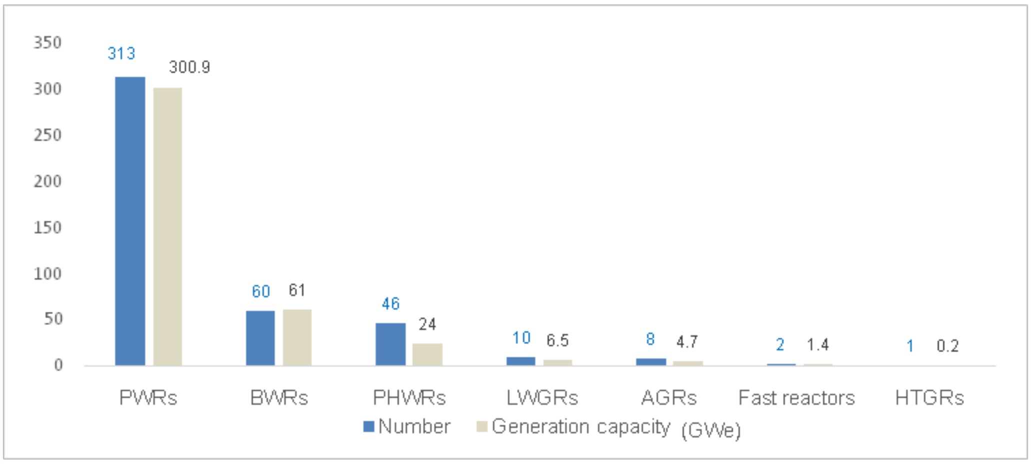
Currently, there are 10 Light Water Graphite Reactors (LWGR) of 6.5 GWe capacity, primarily operating in Russia. Their main design is RBMK that employ UO2 as fuel, graphite as moderator, and light water as coolant which is allowed to boil in the core. For inherent design issues, they have never been built outside the Soviet Union.

Advanced Gas-Cooled Reactors (AGR) are the second generation of British gas-cooled reactors, using natural uranium metal as fuel, graphite moderator and carbon dioxide as primary coolant. There are over 8 such reactors of 4.7 GWe capacity.

Apart from these operable conventional reactors, two advancedFast Neutron Reactors (FNRs) and one High Temperature Gas Cooled Reactor (HTGR) have been brought online by Russia and China respectively. Fast reactors or FNRs do not have a moderator and utilise fast neutrons. They generate power from plutonium while making more of it from the U-238 isotope in or around the fuel.If they are configured to produce more fissile material (plutonium) than they consume they are called Fast Breeder Reactors (FBR). There are two operating FNRs in Russia. India has taken construction of a 500 MWe prototype FBR for which currently fuel loading is under process. Generating very high temperature steam (above 700 C), HTGR employTRISO fuel design, and is cooled by helium and moderated by graphite. More of such reactors are in developmental stage in other different countries.

Reactor type	Fuel	Coolant	Moderator
Pressurized water reactor (PWR)	enriched UO2	water	Water
Boiling water reactor (BWR)	enriched UO2	water	Water
Pressurized heavy water reactor (PHWR)	natural UO2	heavy water	heavy water
Light water graphite reactor (LWGR)	enriched UO2	water	Graphite
Advanced gas-cooled reactor (AGR)	natural U (metal), enriched UO2	CO2	Graphite
Fast neutron reactor (FNR)	PuO2 and UO2	liquid sodium	None

High temperature gas-cooled reactor (HTGR)	enriched UO2	helium	Graphite



Conventional nuclear reactors (number and capacity)

6.2 Emerging Large Reactor Technologies

Leveraging the operational experienceand industrial expertisegained from current fleet of conventional reactors viz. PWRs, BWRs, PHWRs, AGWRs, and LWGRs etc,nuclear industry is now engaged in new type reactors technologies which are technically more sound and economically optimized. These reactors are of various designs and put more emphasis on passive systems and inherently safe design features.

Countries such as the US, France, Russia, China, India, South Korea etc have developed some new large reactors technologies which are currently being implemented across different parts of the world.

European pressurized water reactor (EPR): It is a four-loop design derived from the German Konvoi types with features from the French PWR N4, and was expected to provide power about 10% cheaper than theN4. It was accepted as the new standard design for France and received French design approval in 2004. It will operate flexibly to follow loads, have fuel burn-up of 65 GWd/t and a high thermal efficiency, of 37%, and net efficiency of 36%. It is capable of using a full core load of MOX. Availability is expected to be 92% over a 60-year service life. EDF and Areva NP are further optimizing and EPR design, offering the same characteristics as the original EPR but with simplified construction and significant cost reduction – about 30%.

Westinghouse AP1000: Westinghouse developed AP1000 as a two-loop PWR by harnessing the evolved design experiencefrom the smaller AP600. With an overall objective of design simplification across overall safety systems, normal operating systems, the control room, construction techniques, and instrumentation and control systems AP1000 provides cost savings with improved safety margins. It has a core cooling system including passive residual heat removal by convection, improved containment isolation, passive containment cooling system to the atmosphere and in-vessel retention of core damage (corium) with water cooling around it. No safety-related pumps or ventilation systems are needed.

GE-Hitachi ABWR and ESBWR: GE Hitachi Nuclear Energy's Economic Simplified Boiling-Water Reactor (ESBWR) is an improved design "evolved from the ABWR" but that utilizes passive safety features including natural circulation principles. It is the ninth evolution of the original BWR design licensed in 1957, and was developed from a predecessor design, the SBWR at 670 MWe. GEH says it is safer and more efficient than earlier models, with 25% fewer pumps, valves and motors, and can maintain cooling for seven days after shutdown with no AC or battery power. The emergency core cooling system has eliminated the need for pumps, using passive and stored energy. The used fuel pool is below ground level.Two Advanced boiling water reactors (ABWRs) built by Hitachi and two by Toshiba have been in commercial operation in Japan (1,315 MWe net), with another two under construction there and two in Taiwan. More are planned in Japan and four are planned in the UK.

APR1400, EU-APR, APR+, APR100: South Korea's APR1400 advanced PWR design incorporates enhanced safety and seismic robustness and was earlier known as the Korean Next Generation Reactor. Design certification by the Korean Institute of Nuclear Safety was awarded in May 2003. It is 1455 MWe gross in Korean conditions according to an International Atomic Energy Agency (IAEA) status report, 1,350-1,400 MWe net (3,983 – nominal 4,000 MWt) with two-loop primary circuit. The first of these are operating in Korea – Shin Kori 3&4 – with Shin Hanul 1&2 under construction. It was chosen for the UAEnuclear programme on the basis of cost and reliable building schedule. KHNP is also developing a more advanced 4,308 MWt, 1,560 MWe (gross) version of the APR1400, the APR+, which gained design approval from NSSC in August 2014. It was "developed with original domestic technology", up to 100% localized, over seven years since 2007, with export markets in view.

Russian VVER-1200 / 1000: The third-generation VVER-1,200 reactors of 3,212 MWt is an evolutionary development of VVER-1000, with longer operating lifetime (60 years for non-replaceable equipment), greater power, and greater efficiency (34.8% net instead of 31.6%) and 60 GWd/t burn-up. Cogeneration heat supply capacity is 300 MWt. It retains four coolant loops and has 163 FA-2 fuel assemblies, each with 534 kg of UO_2 fuel enriched to 4.95%. Core outlet temperature is 329 C.VVER-1000 units with enhanced safety have been built in India and China. Two more were planned for Belene in Bulgaria. The VVER -1000 has four coolant loops, 163 fuel assemblies, and is rated 3,000 MWt.

Hualong One, HPR1000: CNNC developed the ACP1000 design, with 1100 MWe nominal power and load-following capability, and 177 fuel assemblies. In parallel but somewhat ahead, CGN led the development of the 1,100 MWe ACPR-1000, with 157 fuel assemblies. After rationalization of both designs HPR1000 was developed. Both companies formed a joint venture to co-promote a rationalized version of their designs for the international market under the brand Hualong One for HPR1000. The Hualong One thus has 177 fuel assemblies 3.66 m long, 18-24 month refuelling interval. It has three coolant loops delivering 3,050 MWt, 1,170 MWe gross, 1,090 MWe net (CNNC version). It has double containment and active safety systems with some passive elements, and a 60-year design lifetime. Average burnup is 45,000 MWd/tU, thermal efficiency is 36%

Developer	Reactor	Size – MWe gross	Design progress, notes
GE Hitachi, Toshiba	ABWR	1,380	Commercial operation in Japan since 1996-7. US design certification 1997. UK design certification application 2013. Active safety systems.
KHNP	APR1400 (PWR)	1,450	Operating at Shin Kori 3&4 in South Korea and at Barakah in UAE. Under construction: Shin Hanul 1&2 in South Korea. Korean design certification 2003. US design certification August 2019.
Gidropress	VVER-1200 (PWR)	1,200	Operating at Novovoronezh II and Leningrad II in Russia, and at Ostrovets in Belarus. Under construction at Akkuyu in Turkey and Rooppur in Bangladesh.
OKBM	BN-800	880	Beloyarsk 4, demonstration fast reactor and test plant.
Westinghouse	AP1000 (PWR)	1,250	Four units operating in China; two under construction in the USA; many units planned in China (as CAP1000).
Framatome (& EDF)	EPR (PWR)	1,750	Two units operating in China, under construction in Finland, France and UK.
CNNC & CGN	Hualong One (PWR)	1,170	Main Chinese export design, operating at Fuqing in China, and at Karachi in Pakistan.

Operational Advanced power reactors

6.3 New Nuclear Projects

The global trend in nuclear power generation has experienced fluctuations over the past few decades, influenced by various economic, political, and environmental factors.
Today there are about 440 nuclear power reactors operating in 31 countries plus Taiwan, with a combined capacity of about 400 GWe. In 2023 these provided 2,602 TWh, about 9% of the world's electricity.

About 65 power reactors are currently being constructed in 15 countries. About 85 power reactors with a total gross capacity of about 80 GWe are planned, and over 300 more are proposed. Most reactors currently planned are in countries in Asia, characterized by fast-growing economies and rapidly rising electricity demand, hence Asia is leading in terms of new construction. Around 48 reactors of over 54 GWe are under construction in Asia. China alone is working on 36 reactors, followed by India, Japan, and South Korea.

In Europe, the UK is constructing 2 nuclear reactors of ,3.5 GWe capacity. Similarly, France, Slovakia, Ukraine are some of the other countries in Europe that constructing new nuclear plants. Russia has taken up the construction of 4 reactors of aggregate capacity 4 GW.

After Vogtle-3&4, no new construction project has been announced in the North America. However, pre-project activities and intensive development works are going on for new advance reactors and SMRs. In addition, nuclear plant life extension has also emerged as good economical options for the stakeholders to meet clean energy requirements.

6.4 Challenges with Large Reactors and the Push for SMRs

Large reactors offer advantage in terms of the economy of scale, however they too face several challenges and some of these forms a hindrance for operational efficiency while paving ways for technological advancements:

High Upfront Capital Cost: Nuclear power plants are expensive to build. A conventional nuclear power plant will have upto 60% of the LCOE attributed towards the capital cost, and this large chunk of the capital has to be made available upfront at initial stage of the project.

Construction Time: A large nuclear reactor typically takes 6-8 years for completion. However, regulations and regional market risks can shoot this period up raising questions on project feasibility, ROI and turnaround time.

Radioactive Waste Management: A detailed waste management plan including segregation and disposal, detailing the type of disposal, and reduce the risks of radioactive radiations to the surrounding is required to be in place for any nuclear power plant.

Regulatory and Political Challenges: A nuclear plant faces the most stringent sets of challenges against its initiation in any geography compared to any other clean energy projects. Layers of approvals from safety requirements to waste management and radiation containment, impacted by national policies and international agreements impacts not only the construction of a nuclear power plant but also the long-term risk pertaining to changes in any such policies still linger around.

Aging Infrastructure: Typical large nuclear power plants have a life span of 30 years; however newer reactors have expanded on this and doubled upto 60 years. The problem arises with the maintenance of such aging reactors and related infrastructure. Any negligence on the maintenance part is risky, but even the cost of maintenance of such infrastructure is a big chunk on the balanced sheet.

Market Competition: Nuclear, although a source of clean energy still has a lot of parameters linked to it, which questions the feasibility, such as high upfront capital costs and ease of project kickoff. Moreover, solar and wind projects has been easier to set up in advanced and developing economies while the challenge from conventional sources in Asian and African nations is still on the cost of production. However, considering the life cycle of a nuclear power project, the LCOE is lower than most clean sources of energy.

Country	SMR Technology	Output MWe	SMR Type	Developer	Features	Status
Russian Federation	KLT-40S	2 35	PWR in floating NPP	JSC Afrikantov OKBM	Floating SMR for cogenerating heat as well as electricity	In operation
		2 55	PWR	JSC Afrikantov OKBM	For floating and land-based NPPs, integral design, inherent safety features	Detailed design
USA	RITM-200N	6 * 77	PWR	NuScale power Corporation	Has extended time available for cooling of core, does not need AC / DC power, water addition or operator action	Received standard design approval for 50 MWe
		160	PWR	Holtec International	Defence-in- Depth with passive safety cooling systems and active non-safety systems; critical components below grade.	Preliminary design completed
	VOYGR	272 to 290	BWR	GE-Hitachi Nuclear Energy and Hitachi GE Nuclear Energy	Natural circulation BWR, integral RPV isolation valves, isolation condenser	Pre-licensing
France	SMR -160	2 170	PWR	EDF, CEA, TA, Naval Group	Integral PWR, Main components of Nuclear; Steam Supply Systems (NSSS) contained within Reactor Pressure; Vessel (RPV), Submerged Containment	Basic design stage
Republic of Korea	SMART	107	PWR	KAERI and K.A.CARE	Coupling with desalination and process heat application, integrated primary system	Standard design approval received
UK	UK SMR	470	PWR	Rolls Royce and Partners	Modularization facilitates speedy and economical construction	Conceptual design
Argentina	CAREM	30	PWR	CNEA	Natural circulation for core heat removal, containment with pressure suppression	Under construction

7

New Reactors Development

7.1 SMRTechnologies (water based) and Market Landscaping

Considering the challenges of upfront capital cost and project uncertainties associated with large reactors, now industry has focussed its efforts in developing many advanced reactor designs that are small in size- under 300 MWe, and modular design. The modular design allows for systems and components to be factory-assembled and transported as a unit to project site for installation. Thus, SMRs have clear advantage in removing construction uncertainty at the site and save on the project time and upfront capital cost. Considering their size compatibility, SMRs are well suited to be easily retrofitted at the sites of retiring coal power plants and can also be suitably added to the small grids that otherwise could not accommodate large reactors. Most of the SMRs that have taken a lead in developmental cycle are mostly water based that have evolved as a scale down version of the conventional PWR and BWR reactors. The USA, the UK, France, Russia, China, South Korea, Argentina are working on such SMR concepts.

Emerging new SMRs deploy the latest technological designs and safety features by harnessing the operating experience from traditional large reactors, as well as from small-scale reactors used in nuclear submarines and other nuclear-powered vessels, such as icebreakers.SMRs have inherent safety systems, which reduces dependence on additional safety systems (passive or active). They utilize natural passivesystems, simpler designs, a reactor core with lower core power, and larger fractions of coolant.

SMRs safety principles mostly rely on simple phenomena like natural circulation for the cooling of the reactor core, so that even during incident or accident situations requiring very limited, or even no operators' actions to bring the reactor to a safe state in case of need.These passive safety systems also allow elimination of a range of components, valves, safety grade pumps, pipes and cables limiting de facto the risk of their failure. Different countries working on various key SMR designs are tabulated below along with the development status for major technology types has been

7.2 Generation-IV Reactors and Market

Apart from water based small modular reactors, different countries are also working on innovative advanced reactor technologies that are non-water based and make use of gas, molten salt, liquid metal, as coolant medium. Such advanced reactors offer several advantages in terms of safety performance, operational flexibility, and cost reduction, but being innovative in nature will have to assessed for the safety and regulatory requirements or adapted for commercial deployment.

These reactors are based on several technologies and depending on that would find applications in different areas.

There are six Generation IV reactors technology systems:

- Very-High-Temperature Reactor (VHTR)
- Molten Salt Reactor (MSR)
- Gas-Cooled Fast Reactor (GFR)
- Sodium-Cooled Fast Reactor (SFR)
- Lead-Cooled Fast Reactor (LFR)
- Supercritical-Water-Cooled Reactor (SCWR)

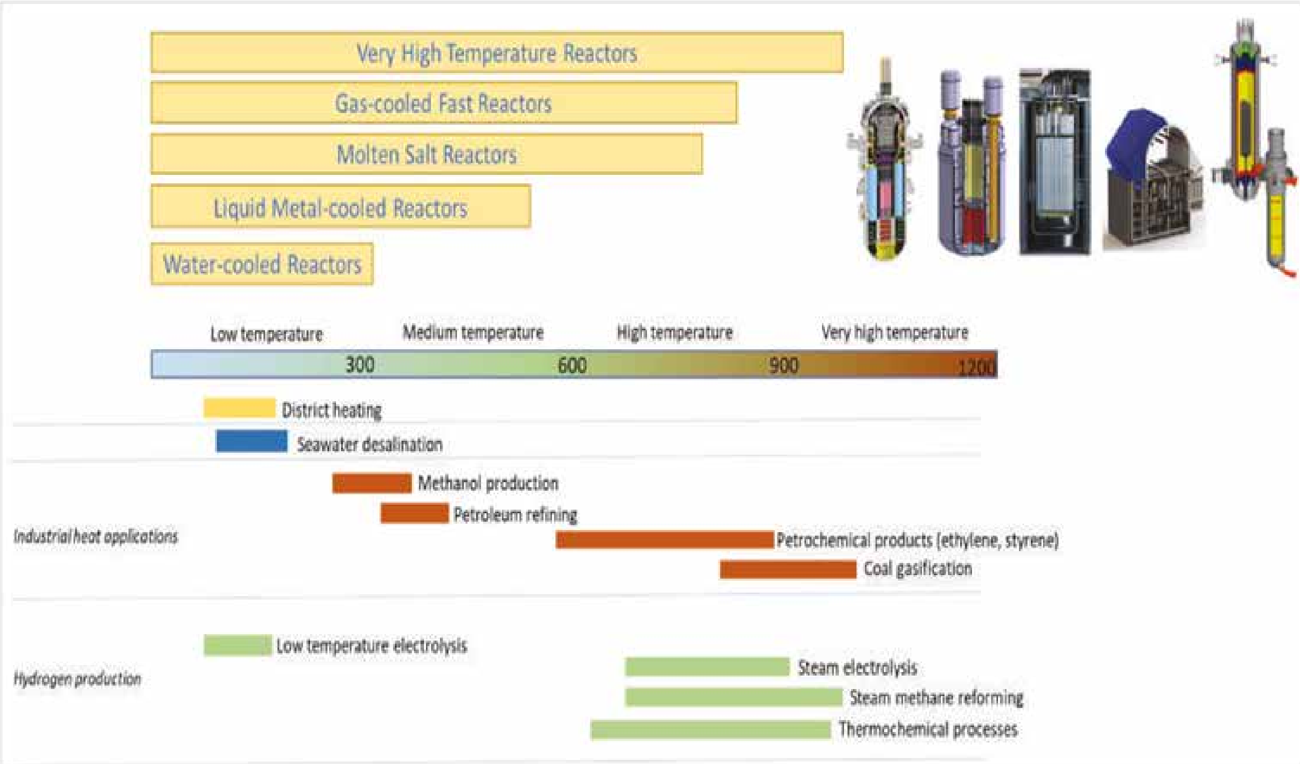
Generation IV Internation Forum (GIF), representing governments of 13 countries is coordinating the international initiatives and co-operation in research and development for the next generation of nuclear energy systems. Regulatory approaches for these advanced reactors will be different from the water based SMRs or large reactors. These reactors could be small in size (upto 300 MWe) or still smaller with less than 20 MWth power capacity.

Some of the Generation-IV reactors undergoing development across different parts of the world are tabulated as below:

Reactor Category	Type	Technology	Output MWe / Size	Developer	Country	Features	Status
High Temperature Gas Cooled Reactors	HTGR	HTR-PM	210 MWe/ SMR	INEET, Tsinghua University	China	Inherent safety features, offsite emergency measures not required	In operation
	HTGR	GTHTR 300	100 - 300 MWe/ SMR	JAEA	Japan	Multiple applications of power generation, cogeneration of hydrogen, process heat, steelmaking, desalination, district heating	Pre-licensing
	HTGR	Xe-100	82.5 MWe/ SMR	X-Energy LLC	USA	Online refueling, core cannot melt and fuel damage minimized by design, independent radionuclide barriers, potential for advanced fuel cycles	Basic design; Selected by Amazon to power its data centres
	HTGR	U-battery	4 MWe/ Microreactor	Urenco	United Kingdom	Simplicity, established technology basis, demonstrated fuel	Conceptual design

	HTGR	MMR	5-10 MWe / Microreactor	Ultra Safe Nuclear Corporation	USA, Canada	No core meltdown; adjacent non-nuclear power conversion plant; no EPZ required; load following / fully dispatchable; nuclear reactor isolated from load via molten salt loop; <6 months assembly at site	Conceptual design
Fast Neutron	Gas cooled fast reactor (GFR)	EM2	265 MWe / SMR	General Atomics	USA	Silicon carbide composite cladding and fission gas collection system	Conceptual design
	Sodium cooled fast reactor (SFR)	SVBR	100 MWe / SMR	JSC AKME engineering	Russian Federation	Integral monoblock primary circuit where reactor, steam generators and pumps are installed in one vessel	Conceptual design
	Lead cooled fast reactor (LFR)	BREST OD 300	300 MWe / SMR	NIKIET	Russian Federation	Natural properties of lead, fuel & core and cooling process design lend inherent safety to design	Under construction
	Liquid metal cooled Fast Neutron	Aurora	1.5 MWe / Microreactor	OKLO Inc	USA	Low decay heat term, removed by inherent and passive means, Water not required for safety-related cooling	Conceptual design
Molten Salt Reactors	MSR	Integral MSR	195 MWe / SMR	Terrestrial Energy Inc	Canada	Core-unit is replaced, completely as a single unit every seven years	Conceptual design; Schnieder Electric is partnering for co-development
	MSR- Pebble bed salt cooled reactor	KP-FHR	140 MWe / SMR	KAIROS Power, LLC	USA	Longer than 72-hour coping time for core cooling without AC or DC power, or operator action	Conceptual design: Selected by Google to power its AI data centres

Current league ofwater cooled SMRs and Gen IVadvanced reactors find applications not just in power production, but also in non-electric applications as well. Some SMR technologies such as HTGR lie on the higher side of the temperature range. Some of these designs are in the prototype stage since many years but are now getting renewed impetus because of global interest in SMR development.



7.3 Fusion Reactor Technology Development

Fusion based reactors have pulled the attention of global community as an ultimate clean energy source for climate change mitigation. Fusion reactors are based on sub-atomic level fusion process by which two light atomic nuclei combine to form a single heavier one while releasing massive amounts of energy. This energy is tapped and converted into electricity by using such reactors. Fusion reactors replicate the way energy is produced in the sun. The reaction takes place in a state of matter called plasma — a hot, charged gas made of positive ions and free-moving electrons with unique properties distinct from solids, liquids or gases. Fusion could generate four times more energy per kilogram of fuel than fission (used in nuclear power plants) and nearly four million times more energy than burning oil or coal.
Nuclear fusion and plasma physics research are carried out in more than 50 countries. Recently researchers have finally achieved some breakthroughs and energy gains in fusion experiments. Experts have come up with different designs and magnet-based machines in which fusion takes place, like Tokamarks and Stellarators, and also the approaches that rely on lasers, linear devices and advanced fuels. Most of the fusion reactor concepts under development will use a mixture of deuterium and tritium — hydrogen atoms that contain extra neutrons.

ITER is an international megaproject that aims to demonstrate the scientific and technological feasibility of fusion energy production and prove technology and concepts for future electricity-producing demonstration fusion power plants, called DEMOs. The facility is being built in France and currently the machine assembly work has been launched. The first phase of experiments is likely to start from 2035. It is expected that an electricity-producing fusion power plant could be built and operating by 2050.

Apart from inter-governmental and public sector initiatives, private sector is also now deeply involved in fusion. Over 45 private companies are reported involved in their fusion initiatives. Over USD 7 billion investment has been made in the fusion sector so far with over USD 900 million coming in 2023 alone. Government finding has also risen to USD 420 million in the past years, indicating towards a strong public-private participation in fusion.

The industry is aiming to reach a goal of commercializing this technology during 2030 to 2035 period. The U.S. leads in commercial fusion, with 25 companies involved in fusion. The U.K., Germany, Japan and China have three companies each. Fusion firms are also located in Australia, Canada, France, Israel, New Zealand and Sweden.Companies such as Commonwealth Fusion, Helion, TAE, General Fusion, Zap Energy and Avalanche Energy etc. are working aggressively on their demonstration plant to be made ready in next 5-10 years.

7.4 Industry and Regulatory Standardization

SMRs represent a significant evolution in nuclear technology, characterized by their smaller size, modular design, and enhanced safety features. To accelerate the development and deployment process, the IAEA has launched a new initiative bringing together policy makers, regulators, designers, vendors and operators to develop common regulatory and industrial approaches to SMRs. The Nuclear Harmonization and Standardization Initiative (NHSI) aims to facilitate the safe and secure deployment of SMRs.

NHSI work plan was developed in two separate but complementary tracks- the regulatory track and the industry track (technology holders and operators).

Under the regulatory track, focus is on

- Building a framework for information sharing
- Developing a framework for international pre-licensing regulatory design review
- Developing approaches for leveraging the reviews by other regulators

The IAEA expects that the NHSI will give an impetus to the regulatory collaboration, thus avoiding the duplication in regulatory efforts, improve efficiency of regulatory reviews and help in reaching common regulatory positions within the requirements of nuclear safety and within the realms of national sovereignty.

Under the industry track, focus is on achieving standardization in industrial approaches followed in manufacturing, construction and operation of SMRs so as to reduce the time to licensing, project costs and time to deployment of SMRs.

This is envisioned to be achieved under the four objectives of

- Harmonizing the high-level user requirements
- Sharing of knowledge about national codes and standards
- Software testing and validation for modelling of SMR designs
- Nuclear infrastructure establishment for development of SMR projects

The American Society of Mechanical Engineers (ASME) plays a pivotal role in establishing standards for SMRs. Their work focuses on ensuring that the design, construction, and operation of these reactors meet stringent safety and quality requirements. Key ASME standards relevant to SMRs include Boiler Pressure Vessel Code (BPVC), Nuclear Quality Assurance (NQA-1), Probabilistic Risk Assessment (PRA) Standards.

The future development of SMRs hinges on effective industry standardization and regulatory frameworks. Collaborative efforts among international organizations like ASME and IAEA are crucial in creating a cohesive approach that ensures the safe deployment of these innovative reactors.

8

Nuclear Program in India

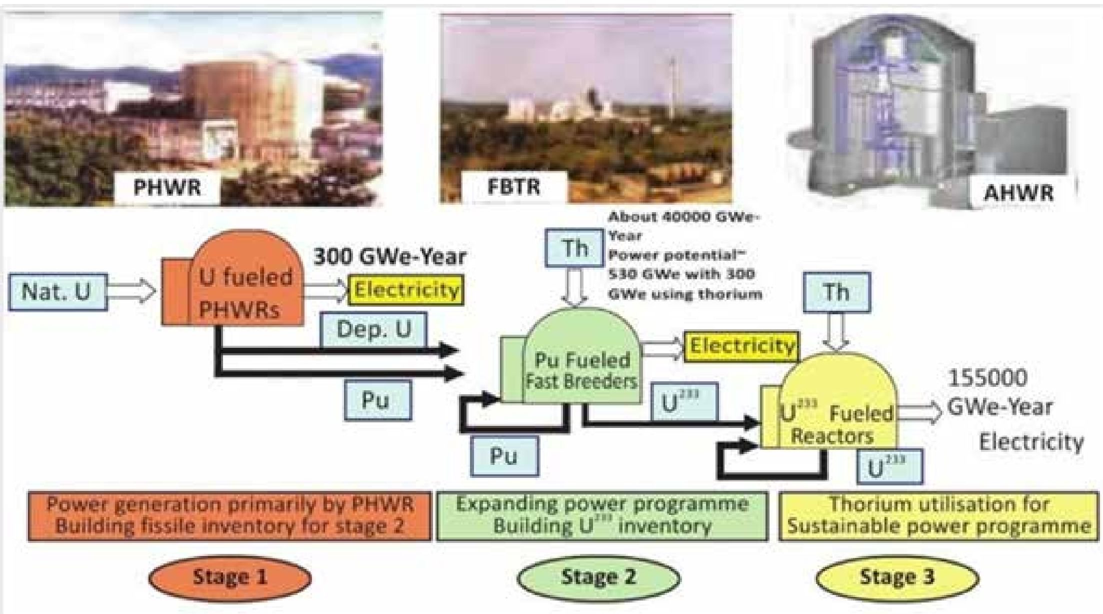
8.1 Three Stage Nuclear Program and the Current Status

In India, nuclear energy development began with the objectives of peaceful uses of atomic energy in improving the quality of life of the people and achievingenergy security. The commercial Nuclear Power program, started in 1969 with the operation of TAPS 1&2 (BWR) in cooperation with the USA. It is based on the GE-Hitachi BWR technology and is currently oldest operating NPP in the world. Later, work began on Rajastan-1 & 2 which is PHWR technology-based plants. Today, India has developed the capabilities across the front and back end of thefuel cycle, manufacturing base, operations and construction of PHWR nuclear power plants.

The Indian nuclear program was conceived based on, unique sequential three-stages and associated technologies essentially to aim at optimum utilization of the indigenous nuclear resource profile of modest Uranium and abundant Thorium resources. This sequential three-stage program is based on a closed fuel cycle, where the spent fuel of one stage is reprocessed to produce fuel for the next stage. The closed fuel cycle thus multiplies manifoldthe energy potential of the fuel and greatly reduces the quantity of waste generated.

The detail of each stage is as mentioned below:

Stage-1: Pressurised Heavy Water Reactor: It envisages construction of Natural Uranium Heavy Water moderated and Cooled Pressurized Heavy Water Reactors (PHWRs). Spent fuel from these reactors is reprocessed to obtain Plutonium.
Stage-2: Fast Breeder Reactor: It envisaged construction of Fast Breeder Reactors (FBRs) fuelled by Plutonium produced in stage 1. These reactors would also breed U-233 from Thorium.
Stage-3: Breeder Reactor: It would comprise power reactors using U-233/Thorium as fuel produced in stage 2.



General schematic of the Indian Nuclear Program

Currently, India operates 24 reactors of total 8180 MWe capacity, out of which 2 are Boiling water reactors (BWRs), 2 are VVERs ((Russian version of Pressurized water reactors) and balance 20 are Pressurized heavy water reactors (PHWRs). Eleven reactors of total 8700 MWe capacity are under construction – 6 are PHWRs (700 MWe capacity each), 1 Fast breeder (500 MWe capacity), and 4 VVERs (1000 MWe capacity each) . Financial sanctions have been received for 8 more PHWRs (700 MWe capacity each) of total 5600 MWe capacity. Additionally, In-principle approval have been accorded for 6 EPRs (1650 MWe each) at Jaitapur site and 6 AP1000 reactors of Westinghouse make at Kovadda site. Discussion are undergoing with Russian Federation for constructing six more advanced VVERs (1200 MWe capacity each) at Kavali site.

India has reached a significant milestone in its three-stage nuclear power program with the commencement of core loading at the PFBR at the Kalpakkam nuclear power plant. This milestone marks India's entry into the second stage of its nuclear program, bringing the country closer to perfecting fast breeder reactor technology. Once commissioned, India will become the second country, after Russia, to operate a commercial Fast Breeder Reactor (FBR). BHAVINI, a wholly owned enterprise of the Government of India under the administrative control of the Department of Atomic Energy (DAE), is spearheading the construction of the 500 MWe PFBR at Kalpakkam. The PFBR is a precursor to future FBRs and represents a significant advancement in India's nuclear capabilities.

8.2 Evolving Market and Supply Chain Build-up

Amidst the global push for climate change and national requirement to sustain its ambitious growth targets to be a developed country by 2047, India has identified nuclear energy to a key driver to shape up its energy strategy. Apart from large reactors, Small modular reactors have been prioritized by the government to be deployed for clean energy transition.

NPCIL has brought in line two new PHWR NPPs of 700 MWe capacity and has made third such reactor critical for further connection to the grid. Its sister concern BHAVINI which has successfully executed the construction of a 500 MWe prototype fast breeder reactor (PFBR) achieved a major milestone with the initiation of the core loadingin 2024.

As the current players are progressing well, the industry ecosystem is also building up and evolving with the entry of new market players and large companies such as NTPC- thelargest power producer in India, into the nuclear sector. NTPC has formed a joint venture with NPCIL (Nuclear Power Corporationof India Ltd) to execute 4 nuclear projects of total 4200 MW capacity and has also floated a new subsidiary called NPUNL (NTPC Parmanu Urja Nigam Ltd) to build, own, and manage nuclear power plants. They have started collaborating with a US based firm on development and deployment of clean fuel for NPPs.

Government has opened the door for private investment in nuclear and has floated an RFP for the private companies that wish to own a small nuclear power plant to meet their captive power generation requirements and clean energy commitments.

Similarly, the US-India civil nuclear cooperation discussion has reached a breakthrough to do away with nuclear export control restrictions with India. With this India is likely to be included in the list of 'Generally Authorized' country for nuclear business and thus the US nuclear companies can directly negotiate with Indian players.

8.3 Scope for Nuclear Deployment – SMR and Large Reactors

India has requirements for all categories of reactors for their unique advantages under different circumstances. Having a large grid of 450+GW capacity, India has ample of scope to connect multiple large reactors. Unlike small grid system, such alarge grid can easily handle the technical, commercial, or regulatory challenges when a largereactor is made online or offline. Seismicity, population density, Emergency planning zone (EPZ) criteria, water availability, and political challenges, puts a constraint to have multiple sites. Therefore, to install large power capacity, theland available at the ideal sites can be utilized to construct multiple large reactors for electricity generation.

SMRs or upcoming microreactors on the other hand are good option for retrofitting at the sites of retiring coal-based plants andat certain land parcels which can not house large reactors for different reasons- seismic, water availability, population, political or EPZ issues. They are also useful to support energy supply in remote, sparsely populated localities, industrial applications, process heat supplies, desalination, hydrogen generation etc.

Currently, India has a total 238 GW of fossil fuel-based capacity located at different sites. With their ageing progression, they would be phased out progressively and the sites still having a usable plant asset, working systems, building infrastructure, transmission lines, colonies, access to water, roads, and other amenities could be well utilized for installing SMRs. SMRs are the ideal options for such sites as solarplantor wind farm would require much larger land area to generate equivalent power that retiring plant would be producing. SMRs being smaller in size can be accommodated within the same site and would qualify the EPZ requirements for nuclear installation.

8.4 Policy Support and Institutional Mechanism

Government of India identifies that Nuclear Power has a huge potential and can provide the country long term energy security in a sustainable manner. It regards nuclear as a clean and environment friendly base load source of electricity generation, which is available 24x7. Hence, taking several initiatives in expanding nuclear power capacity to drive country's energy transition for meeting the goal of a net zero economy by 2070.

In a message to the stakeholders at the Nuclear Energy Summit at Brussel, Dr AK Mohanty, Chairman of Atomic Energy Commission of India stated that India is committed to full international civil nuclear cooperation for the development needs of our country and is engaged in discussions with foreign companies to further expand our nuclear energy programme.

Right from the India's independence till date, nuclear power enjoys support from all successive governments. The broader objective has been to mainstream nuclear in the energy mix of India, which hardly has risen beyond 3% of the total mix. In its annual budget-2025, the federal Indian government proposed to partner with private players to develop small nuclear reactors. It also asked the states to consider setting up new nuclear power plants and replace the retiring coal base thermal powerplant with nuclear power reactors at the existing sites. Recently, state nuclear utility NPCIL floated a request for proposal for private players that want to own a small nuclear reactor for their captive generation, indicating towards big opportunities coming forth in this sector.

9

Nuclear Economics and Drivers in India

9.1 Nuclear Economics and Capital Requirements

Nuclear energy offers India an ideal solution for reliable, low-carbon electricity due to its long-term economic benefits and cost-competitiveness with fossil fuels. While nuclear plants require significant initial investment, they are relatively inexpensive to operate. Additionally, waste disposal and decommissioning costs are typically included in operational expenses, and when accounting for the environmental and health costs of fossil fuels, nuclear becomes even more competitive.

According to a joint report by the NEA and the IEA, nuclear power is expected to have the lowest Levelized Cost of Energy (LCOE) among dispatchable low-carbon technologies by 2025, ranging from USD55 to USD95 per MWh. This compares to coal, which could reach USD100/MWh, and gas at USD80/MWh. Onshore wind's LCOE is between USD40 and USD50/MWh, offshore wind ranges from USD80 to USD110/MWh, and solar PV falls between USD40 and USD80/MWh. In India, the nuclear cost could drive down further for existence of a mature industry base, project execution expertise, and low-cost market labour market. Currently, PHWR plants the capital cost 2000-3000/MW which is much lower than the global average for other available reactors technologies. Therefore, the Indian industry could also be utilized for co-manufacturing of Make in India emerging SMRs and large reactors for the Indian and global markets.

9.2 Financing Mechanisms and Innovative Business Models

A nuclear power plant project is characterised by high upfront capital costs and long construction periods, low and stable operational costs, and lengthy payback periods.This investment profile, combined with the risks associated with construction, mean that the cost of financing is a key determinant of the cost of electricity generated.Typically, it is the responsibility of owners or operators of nuclear power plants to secure financing for new nuclear power plants. For investors, the confidence provided by clear, long-term governmental commitment to a nuclear power programme remains critical.Most nuclear power plants in operation were financed in regulated energy markets, where returns on investment were generally secure. Widespread deregulation of markets has altered the risk profile related to investing in new capacity because electricity prices are less predictable.A significant number of models have been used in recent years to facilitate investment. Most combine a long-term power purchase contract, to reduce revenue risk, and a means of capping investor exposure, for example through loan guarantees.

In India, nuclear power projects are financed through a mix of debt and equity, with the government playing a key role. Currently, the Nuclear Power Corporation of India Limited (NPCIL) is responsible for the design, construction, and operation of nuclear power plants for light waterand heavy wate r reactors. BHAVINI is responsible for fast breeder reactors. Now, NTPC has also formed a subsidiary to own, build and manage nuclear power plants. Funding sources

For equity, the owner/operator (currently, NPCIL) uses its internal resources and government budgetary support for equity financing.Balance portion comes from debt financing by issuance of corporate bonds. The projects built under international collaboration, come with international credit as agreed between the negotiating parties.

The overall budget for nuclear projects increased by 10 percent to USD 734 million as the Indian government aims to partner with the private sector to set up Bharat Small Reactors (BSR) i.e. modularization of indigenous 220 MW Pressurized Heavy Water Reactor (IPHWR-220), and support R&D for Bharat Small Modular Reactors (BSMR) to develop newer SMR technologies.A key innovation with BSRs is the government's decision to partner with the private sector for their development and deployment, marking a historic shift in India's nuclear policy. Previously, the Atomic Energy Act of 1962 prohibited private sector participation in nuclear energy generation. This new approach is expected to attract financing and accelerate nuclear power growth in India.

Private companies like Tata Power, Reliance Industries, Adani Power, and Vedanta Ltd. have been invited to invest in nuclear electricity projects, with each company expected to contribute around USD 5.3 billion. Off late, with an aim to raise USD 26 billion from private investment in nuclear power, India has come out with an innovative model wherein an Indian private company can make investment to set up a nuclear plant for its captive generation requirement and transfer operational responsibility to NPCIL through an O&M contract. Entire right over the electricity produced will remain with private investor and NPCIL will charge a O&M fee for its service.

9.3 Legal and Regulatory Framework in India

India has developed a comprehensive legal and regulatory framework to govern the use of nuclear power. This framework ensures safety, security, and non-proliferation of nuclear materials, and aligns with international standards while addressing India's unique needs.

Key elements of the legal framework include:

Atomic Energy Act, 1962: This is the primary legislation governing the use of atomic energy in India. It provides for the establishment of the Atomic Energy Commission (AEC), regulates the production, use, and disposal of atomic energy, and ensures that nuclear activities are conducted for peaceful purposes.It has certain important provision like:

- Establishment of the Atomic Energy Commission, which has the authority to supervise nuclear energy projects and activities in India.
- Controls on the production and use of nuclear material and facilities.
- Penal provisions for violations related to nuclear safety, security, and misuse.

The Civil Liability for Nuclear Damage Act, 2010:

This law addresses the issue of liability for nuclear accidents and ensures compensation for victims in case of nuclear damage. Itprovides for the following:

- Establishment of the liability of operators in the event of a nuclear accident
- Provision for a framework for compensating victims of nuclear accidents.
- Limitsthe liability of the operator but allows the government to step in for further compensation in case of severe accidents.
- Introduces the concept of the "Nuclear Liability Fund" to help finance compensation.

The Nuclear Safety and Regulatory Framework:
The Atomic Energy Regulatory Board (AERB), established under the Atomic Energy Act, is the main body responsible for regulating nuclear safety in India. AERB ensures that nuclear installations and activities comply with safety standards to protect workers, the public, and the environment. It has powers to inspect nuclear facilities, review safety procedures, and issue regulations.

Environmental and Security Regulations:
Environmental laws such as the Environment Protection Act, 1986 and regulations concerning the disposal of nuclear waste ensure that nuclear energy projects comply with environmental standards.

Nuclear security is governed by laws that regulate the handling of nuclear materials and prevent their diversion for non-peaceful purposes. The National Disaster Management Authority (NDMA) also has a role in emergency response and disaster preparedness in case of a nuclear incident.

India's Commitment to Non-Proliferation:
India is not a signatory to the Nuclear Non-Proliferation Treaty (NPT) but has a strong commitment to non-proliferation through its national laws and policies.India has signed several international agreements to ensure the peaceful use of nuclear technology, including the Civil Nuclear Cooperation Agreement with several countries like the United States (2008), France, and Russia.The DA) and other government agencies are tasked with overseeing and ensuring the peaceful use of nuclear technology.

International Safeguards and Agreements:
India cooperates with the IAEA, an international organization that promotes peaceful use of nuclear energy and implements safeguards to prevent nuclear proliferation.India has entered into safeguards agreements with the IAEA to ensure that its civilian nuclear programs are transparent and meet international standards of safety and security.

Public Involvement and Transparency:
While India's nuclear regulatory framework emphasizes security and safety, it also includes provisions for public involvement, especially in the event of nuclear facility licensing and environmental assessments.Public hearings, environmental impact assessments (EIA), and regulatory review processes provide a degree of transparency and public participation in decision-making regarding nuclear power projects.

Current Institutional Set-up:
NPCIL is the public sector enterprise responsible for the construction, operation, and maintenance of nuclear power plants in India.It operates under the purview of the DAE and adheres to the safety and operational regulations set by AERB. However, now with government's push big PSUs like NTPC and other private sectors players are also getting closely involved in nuclear sectors in India.

9.4 Nuclear Liability and Insurance Regime

To align the liability and compensation in the event of a nuclear accident inline with international regime on Convention for Supplementary Compensation (CSC), India established Civil Liability for Nuclear Damage Act, 2010 (CLND Act). It is designed to cover the liability of nuclear operators in the event of a nuclear accident, ensuring the availability of compensation for victims.

The major components of the Act include:

Operator's Liability:
Under the CLND Act, the operator of a nuclear facility is strictly liable for any nuclear damage resulting from an accident. The operator is obligated to provide compensation without needing to prove fault.The liability is capped at INR 1,500 crore (approximately USD 200 million), which is the maximum amount the operator is required to pay in compensation.

Liability Cap and Insurance:
Operators must have insurance or financial security in place to cover this liability. They are required to purchase nuclear insurance policies to ensure the availability of funds for compensation claims.

Claims and Compensation:
The Indian government has established a "nuclear damage claims commission" to handle claims and ensure that victims receive compensation. In case the liability exceeds the operator's capacity to pay, the government has the option to cover the excess amount.

Suppliers Liability Under Section 17 of CLND Act:
A significant feature of India's nuclear liability regime is the inclusion of supplier liability. According to Section 17, if an accident is caused by a defect in the design, manufacture, or supply of materials or equipment used in the nuclear facility, the supplier can be held liable for damages. This provision allows the nuclear operator to seek redress from the supplier. The supplier's liability is capped at the same INR 1,500 crore (Approx. USD 200 million) limit, but this provision has been subject to criticism, particularly in terms of how it could affect the participation of foreign suppliers in India's nuclear market.

Insurance and Risk Pooling:
To address the financial security requirementfor operators and the challenges of suppliers' liability, the India Nuclear Insurance Pool (NIP) was set up in 2011, which is a consortium of Indian insurance companies. This pool is intended to provide the necessary coverage for nuclear risks. The INIP operates under the supervision of the Department of Atomic Energy (DAE) and covers the liabilities of nuclear operators and suppliers.Nuclear operators/ suppliers can obtain coverage from insurance companies, and reinsurance can also be used to share the risk.

International Conventions:
India is not a party to the Paris Convention on Nuclear Liability or the Vienna Convention, which are international treaties governing nuclear liability. However, the CLND Act was drafted in a manner that aligns with international best practices while considering India's specific needs and constraints.

However, there have certain challenges and issues with the nuclear liability in India that are elaborated below:

Foreign Supplier Liability: One of the major points of contention regarding India's nuclear liability regime is the provision of holding foreign suppliers liable for nuclear accidents. This has been criticized by foreign suppliers, particularly those from the United States, who have argued that this provision deters them from engaging in the Indian nuclear market. But, now with nuclear insurance pool in place it should not be a big challenge to deal with

Insurance Limitations: The insurance cap of INR 1,500 crore is seen as potentially insufficient in the event of a large-scale nuclear accident, especially considering the global experience of nuclear disasters (e.g., Chernobyl, Fukushima). However, the government has put in place mechanisms to provide additional compensation if needed.

10

Innovations and Digital Penetration in Nuclear

10.1 Digital/AI in Nuclear

The development and scale-up of SMR and advanced digital/AI are intertwinedwithshared dependencies and enabling characters for each other's growth. On one hand SMRs have the required potential to power the scale-up of data centres for AI revolution, the other hand deployment of SMRs can benefit significantly from advanced digital technologies and AI. By leveraging digital technologies and AI, the SMR industry can achieve faster deployment, higher efficiency, and improved safety while reducing costs and environmental impact. These technologies are critical for ensuring SMRs play a transformative role in the future of clean energy. AI's integration into SMR safety ensures that these reactors are not only more efficient but also capable of achieving the highest safety standards, addressing public concerns about nuclear safety while enabling broader deployment of this clean energy technology.

Companies are utilizing AI capabilities for their SMR projects. Westinghouse uses AI to enhance the safety and efficiency of its SMR designs, NuScale integrates digital twin technology, powered by AI, for monitoring and simulation to ensure safety, and TerraPower employs AI for advanced reactor control and fault detection.

IAEA holds that AIhas a promising potential for advancing nuclear energy production. These sophisticated computer systems mimic human logic in problem solving and decision making. With its capability to enhance efficiency, automation, safety and predictive maintenance, as well as to optimize processes, AI is already making strides in some areas of the nuclear field. AI could range from simple computer programs, such as spam filters, to more advanced concepts like machine learning- where computers learn from past experiences through extensive training using large amounts of data, and deep learning- which involves artificial neural networks modelled after the human brain.

While generative AI can help with administrative tasks, as in other industries,more transparent systems called explainable generative AI hold promise for broader use in NPP operations. Developments towards such AI are underway, and when realized, it will allow for the use of AI in NPPs in the foreseeable future. The IAEA supports the AI's potential application in NPPs and is leading a coordinated research project to explore how AI and innovative technology can help to expedite the deployment of small modular reactors.

The application of AI can significantly improve the efficiency of nuclear power plants. By integrating machine learning algorithms and advanced data analysis, plants can optimize operations and improve safety measures. For instance, AI systems can analyse large amounts of sensor data in real time, identifying anomalies and predicting maintenance needs.

Despite its potential benefits, the application of AI in nuclear technology still presents certain regulatory and technical challenges that need to be addressed. Regulatory bodies need to thoroughly study AI technologies to develop appropriate guidelines and issue licenses. Additionally, these systems must be transparent, explainable and certifiable to gain the trust of operators and regulators.The IAEA is directly involved in these challenges. Since 2021, the IAEA promotes the use of AI applications in nuclear power plants, produces reports, establishes working groups and explores the potential of SMRs. Collaborative efforts between industry stakeholders, regulators and technology experts are crucial for the successful integration of AI in the nuclear sector.

10.2 Role of Digital Technology in SMR Deployment

AI and digital technologies play a pivotal role in the deployment of SMRs by addressing key challenges related to efficiency, cost, safety, and scalability. Below is a detailed look at their role:

Accelerated Design and Engineering

- AI in Design Optimization: AI algorithms analyze design parameters to optimize reactor configurations for performance, safety, and cost-effectiveness.
- Digital Twin Technology: Creating digital replicas of SMRs enables virtual testing and simulation of reactor performance, identifying potential issues before physical deployment.
- Generative Design: AI tools can generate innovative reactor designs by exploring numerous possibilities within predefined constraints.

Streamlining Regulatory Processes

- Automated Documentation: AI streamlines the preparation of regulatory documentation, ensuring compliance with local and international nuclear standards.
- Simulation and Analysis: Digital tools provide detailed simulations for safety and environmental impact assessments, expediting regulatory approvals.

Project Management and Supply Chain Optimization

- AI-Powered Project Scheduling: AI helps optimize timelines and resources, reducing delays and cost overruns in SMR construction.
- Smart Supply Chains: Digital platforms enable real-time tracking of materials, predictive maintenance for equipment, and optimization of supply chain logistics.

Construction Efficiency

- Robotic Process Automation (RPA): Robots and AI-driven automation technologies improve the precision and speed of SMR construction.
- Digital Twins in Construction: Virtual models assist in planning construction sequences and detecting potential conflicts early.

Enhanced Safety and Risk Mitigation

- Predictive Maintenance: AI algorithms monitor equipment health, predicting failures before they occur and ensuring continuous operation.
- Real-Time Monitoring: Advanced sensors combined with AI enable real-time monitoring of reactor operations, enhancing safety and operational efficiency.
- Incident Simulation: AI-based simulations model potential accidents, training operators to respond effectively to emergencies.

Workforce Training and Knowledge Retention

- VR and AR Training: Virtual and augmented reality tools provide immersive training for SMR operators, reducing training time and improving retention.
- Expert Systems: AI-based expert systems capture the knowledge of experienced engineers, providing guidance to new operators.

Public Engagement and Acceptance

- Data Transparency: AI tools can present complex data about SMR safety and environmental impact in easily understandable formats, building public trust.
- Interactive Platforms: Digital platforms facilitate dialogue with stakeholders, addressing concerns and improving acceptance.

Cost Reduction and Economic Viability

- Standardization Through AI: AI-driven insights help standardize SMR designs, reducing customization costs and enabling economies of scale.
- Optimized Energy Production: AI systems ensure that SMRs operate at peak efficiency, maximizing energy output while minimizing operational costs.

Environmental Monitoring

- Real-Time Data Analytics: AI processes environmental data to ensure compliance with environmental standards and monitor ecological impact.
- Decommissioning Planning: Digital tools aid in planning and managing the decommissioning process, ensuring environmental safety.

10.3 Engineering and Project Management

AI and digital technologies are transforming the engineering and project management of SMRs, enabling faster, safer, and more cost-effective development.

Advanced Design Optimization

- AI-driven simulations: Use AI to simulate reactor designs, optimize performance, and analyse safety scenarios.
- Generative design tools: AI-powered software can create optimal reactor components by exploring thousands of configurations.
- Digital twins: Develop a virtual replica of the SMR to test and refine design parameters without physical prototypes.

Enhanced Safety Analysis

- Predictive analytics: AI models can predict system failures and assess risks during the design stage.
- Stress and thermal simulations: Digital tools simulate stress tests, thermal gradients, and seismic resistance, ensuring regulatory compliance.

Streamlined Supply Chain Integration

- AI for material sourcing: Optimize procurement by predicting demand and identifying cost-effective materials.
- 3D printing integration: Use digital models for additive manufacturing of reactor parts, reducing lead times.

Knowledge Retention and Sharing

- AI-driven platforms help capture and manage knowledge from various engineering disciplines, ensuring data accessibility across teams.

Nuclear Project Management:Project Planning and Scheduling

- AI-based scheduling: Use machine learning to optimize project timelines, accounting for resource availability, task dependencies, and risk factors.
- Digital Gantt charts: Real-time updates help track milestones and identify delays.

Risk Management

- Predictive modelling: AI tools analyse historical data to predict risks like cost overruns, schedule delays, and quality issues.
- Scenario planning: Digital tools simulate various project scenarios to prepare for contingencies.

Collaboration and Coordination

- Cloud platforms: Centralize all project data, allowing engineers, contractors, and stakeholders to collaborate in real time.
- BIM (Building Information Modelling): Integrate digital models of SMRs into project management workflows for better planning and execution.

Quality and Progress Monitoring

- Drones and IoT: Monitor site progress and collect real-time data to ensure construction adheres to design.
- AI for anomaly detection: Identify construction errors early using image recognition and sensor data.

Cost and Resource Optimization

- AI-powered cost estimation: Use historical data and algorithms to provide accurate budget forecasts.
- Resource allocation: AI systems optimize the assignment of workforce and materials to critical project tasks.

10.4 Operation Lifecycle Management

AI and digital technologies play a transformative role in the operation of SMRs and nuclear power plants. Their applications enhance efficiency, safety, and cost-effectiveness while addressing industry challenges.

Monitoring and Predictive Maintenance

- Real-time Monitoring: AI-powered sensors collect and analyse data from reactors to ensure optimal performance and early detection of anomalies.
- Predictive Maintenance: Machine learning models analyse equipment data to predict potential failures, reducing downtime and maintenance costs.
- Digital Twins: Virtual replicas of reactors allow operators to simulate scenarios, predict system behaviour, and optimize performance.

Enhanced Safety

- Anomaly Detection: AI systems can detect abnormal patterns in reactor operations and issue alerts faster than traditional methods.
- Accident Scenarios: Digital platforms simulate accident scenarios, allowing operators to prepare for and mitigate risks.
- Emergency Response: AI tools assist in developing optimal response plans by analysing sensor data during critical incidents.

Automated and Remote Operations

- Autonomous Systems: AI enables the automation of routine tasks, such as reactor monitoring, coolant level adjustments, and fuel management.
- Remote Operation: Digital platforms allow operators to control and monitor reactors from off-site locations, ensuring safety and efficiency in remote or hazardous environments.

Fuel Management and Optimization

- AI-driven Modelling: Algorithms optimize the fuel burnup cycle, improving efficiency and reducing waste.
- Spent Fuel Handling: Robotics and AI are used for safer and more efficient management of spent nuclear fuel.

Operator Training and Decision Support

- Simulations and VR Training: Virtual reality (VR) and AI-powered simulators train operators in realistic scenarios, enhancing skill and preparedness.
- Decision Support Systems: AI provides recommendations to operators during complex decision-making processes, reducing human error.

Cybersecurity

- Threat Detection: AI continuously monitors and detects potential cyber threats to the plant's control systems.
- Incident Response: Digital tools analyse threats and coordinate countermeasures in real-time.

Grid Integration and Energy Optimization

- Load Forecasting: AI optimizes energy output based on grid demand, ensuring efficient energy delivery.
- Hybrid Systems: Digital platforms enable SMRs to integrate with renewable energy sources, enhancing grid stability and sustainability.

Cost Reduction

- Operational Efficiency: Automation and AI reduce operational costs by optimizing resource use and minimizing manual intervention.
- Digital Workflows: Streamlined digital systems replace paper-based processes, saving time and resources.

Public Engagement and Transparency

- Interactive Dashboards: AI-driven dashboards provide real-time plant performance data, enhancing public trust and understanding.
- Risk Communication: AI tools help communicate complex safety and risk information in an accessible manner.

10.5 Digitally Enabled Enterprise Management

As new digital and AI tools are evolving and adapting to the safety industry of nuclear sector, the nuclear power companies are getting more receptive to significant digital transformation aimed at enhancing their operational efficiency, safety, and cost-effectiveness. This transformation is characterized by the integration of advanced technologies and innovative enterprise management practices that leverage digital tools throughout the nuclear lifecycle.

Advanced Enterprise Resource Planning (ERP) Systemswould be required to integrate key business processes such as procurement, supply chain, HR, and finances into a unified platform. Digital Twin Integration would enablecreating a virtual replica of the SMRs/ new large reactors to simulate and monitor operations in real time.For early identification of potential issues in equipment or operations, AI-driven insights tooptimize fuel usage and reactor performance, enhanced safety protocols based on AI-powered simulations.As blockchain solutions would come handy for tracking nuclear fuel and materials securely, AI-powered inventory management will help avoid delays in construction and operations for greater transparency and efficiency in the supply chain.

To protect sensitive data and ensure the integrity of nuclear operations against potential cyber threats, there would be increased requirement for a secure cybersecurity framework. As new age work joins the nuclear, training would have to imparted utilizing AR/VR capabilities for immersive training on reactor operations and safety protocols, knowledge management systems for instant access to operational data and guidelines, collaborative platforms for global teams managing SMRs.

By employing advanced analytics, nuclear facilities can transition from reactive to predictive maintenance strategies. This shift reduces downtime, extends the life of equipment, and lowers maintenance costs by addressing issues before they escalate.

Thus by embracing innovations such as digital twins, AI-driven analytics, and improved cybersecurity measures, the industry can not only modernize its operations but also ensure its competitiveness in a rapidly evolving energy landscape. As nuclear undergoes this transformation, digital companies would have to rise to the occasion to tap this opportunity by coming out with industry compliant solutions that can resolve teething issues and challenges that nuclear industry is facing today.

11

Recommendations and Way Forward

Rebalancing of energy mix with focus on baseload and flexible capacity:

India has to grow and decarbonize with clean power playing a pivot role in this transformation. Scale-up of low carbon power generation capacities and delivery infrastructure has to be simultaneously accomplished with economic and industrial sectors undergoing a transformational change. A most reliable and efficient energy mix will be the backbone of this energy transition to sustain grid stability and resilience to support varying requirements and growing demand at the energy consumption level. A balanced energy mix with higher share of clean baseload and energy-dense sources such as Nuclear and solar thermal will not only support grid stability and energy security, but will also allow for higher capacity addition of intermittent sources like solar PV and wind. Combinedly, this will enable the prospective phase out of ageing fossil fuel based power plants as we march ahead into a net-zero future.

As AI applications and advanced digital technologies are proliferating, data centres demand and energy requirement would go up progressively. India needs to prepare itself to meet this demand by having more of the reliable clean sources for power generation. Policy interventions need to be taken up to encourage PSUs, states and private industries to take up initiatives to build nuclear and solar thermal plants.

Roadmap for progressive phase-out of ageing coal power plants:

Fossil fuel based power plants have been the backbone of the India's energy mix fuelling its growth and economic development. However, amidst the daunting climate challenges, now it is crucial time for India to prepare its industry and other walks of life for adaptation to new and cleaner forms of energy. As India ramps up its clean baseload energy capacities, it will create larger buffer to progressively go for eventual phase out of ageing fossil based power plants. However, a roadmap for such progressive phase-out across a certain timeframe would also need to be brought out in public domain to allow enough visibility to all stakeholders, interested clean power producers (prospective nuclear, solar thermal players etc.) and supply chain companies so that they can plan for their business strategies and resource allocation for implementing their strategic initiatives during such time horizon.

Broadening of industry base for building up solar thermal plants:

As a source of 24x7 power supply, solar thermal has to be prioritized for electricity generation and heating applications in the country. A separate RPO mechanisms and incentives for utility scale power plants can be introduced. International cooperation and indigenization of components need to be promoted to offer better supply chain alternatives for the developers. Government / PSUs need to come out with large tenders of higher power capacities for solar thermal plants to attract industry giants and supply chain players.

Industry awareness about solar thermal and public sensitization program need to be taken up to disseminate the information on advantages of solar thermal that not just help in power generation but in heating and other applications in the hard-to-abate sectors as well.

Promoting private participation and international cooperation in nuclear:

Currently, nuclear has a very small footprint of just 8180 MWe available power capacity in the country. The recent move of private investment by the government could be a game changer for the potential full scope participation of private companies in future. Government needs to continuously engage private industry and encourage them to venture into nuclear power generation with a liberalized policy, incentives scheme, tax credits, and easy innovative financing mechanisms for early adopters.

The entry of PSUs like NTPC in the nuclear sector is a welcome step. It will pave the way for broader and deeper decentralization of nuclear power in the country. All states and other PSUs / state companies must be engaged in discussions on the benefits of nuclear power for business growth and clean transition and encouraged to get involved in the nuclear sector. Since, several of the advanced countries have taken big lead in technology development of SMRs/ advanced reactors, India could work on a parallel track (alongside the indigenous R&D development program) to engage and collaborate with international players on SMR deployment in India. It will help the country save enormously long cycle time required for any technology development. As India's energy requirements are very high, both tracks need to be fully utilized to create capacities to fulfil the demand.

While this scenario unfolds with the new domestic and international players getting involved in the nuclear sectors, the current nuclear ecosystem has to progressively adapt to the new realities and take a lead role in driving this transition through handholding and experience sharing as new stakeholders join-in. The lead organizations in the nuclear sectors like the DAE, AERB, and NPCIL etc. will have a crucial role to play in steering the sector in right direction by imparting training on nuclear safety culture and working on industry feedback to make conducive environment for ease of doing business and smoother onboarding of domestic and international entrants.

Similarly, the boarder spectrum of civil society groups, media (MSM/SM), and climate change activists need to be involved to enable decentralization of nuclear power generation.

Legal and regulatory reforms in nuclear sector:

The recent move of the government to allow for private investment in the nuclear sector is positive move in a right direction. It needs to be followed up by the much-awaited amendment in the Atomic Energy Act,1962. It is an urgent need of the hour to be looked into and allow private players and others play a major role in nuclear power generation with full scope participation in the sector

The Civil Liability for Nuclear Damages (CLND) Act. 2010 is another area that has to be assessed and structured in line with applicable international protocols. Industry can flourish when legal frameworks are standardised in line with applicable global practices.

Sectors like nuclear are the regulated ones and face scrutiny within or without the national boundaries of any country. While India is looking up for major scale-up of the nuclear capacity, ease of doing business and investment friendly ecosystem for the new domestic and international entrants will support the growth in the sector. India can take lead in reforming the sector and make applicable administrative processes a transparent and proactive hand-holding activity, ensuring process efficiency and transparency while adhering to the highest standards of safety and quality.

Opportunities for private players and industry stakeholders:

Nuclear is well accepted by international bodies and different countries to be the key driver for their energy transition. The countries such as the USA, France, the UK, several Eastern European countries, Russia, China, South Korea, have taken a big lead in development of advanced nuclear reactors and SMRs. With emergence of AI and advanced digital, big tech companies such as Microsoft, Google, Amazon, Meta have started making big investments and collaborating with nuclear reactor developers. India and Indian nuclear companies could leverage the opportunity and collaborate with international players to construct and manufacture these SMRs / new reactors in India for the domestic as well for the international export markets.

The recently floated RFP for Bharat Small Reactor (BSR) provides a good decarbonization opportunity for energy intensive industries such as steel, chemicals, cement, petroleum refineries, fertilizers, shipping etc. On re-evaluating their business strategy and product competitiveness by factoring in clean and sustainability credentials of nuclear, nuclear would emerge as a best option for them to power their captive requirements and in making their products and offerings competitive for the domestic and export markets.

Innovative approaches for plant operations:

Innovative business models with conducive financing mechanism will play a big role in the scale-up of the sectors such as nuclear and solar thermal and will allow larger collaborations and encourage different stakeholders participate in contributing to baseload capacity addition.

Plant assets and processes have to be developed and nurtured in line with modern way of life and next generation aspirations who are actively getting involved in the job markets now. Improved automated plant systems with office modernization and increased digital/AI footprints will not only support the plant safety and operations, but also help in attracting the talent pool of next generation youth into these sectors.

Research and innovations have to continuously focussed on digital/AI adaptation in nuclear for improved safety and efficiencies. Regulations can accordingly be developed to fully integrate digital/AI solutions in plant systems.

India advantage for international players and technology vendors:

India has an ambitious target but a long way to go to be a developed country by 2047 and a fully net-zero economy by 2070. This would be accomplished with sheer scale-up of industrial base, commercial services, infrastructure buildup and rise in living standards of people. With an economic scale-up of this nature and an aspirational population of 1.4+ billion people, there is going to be several order increase in energy demand. Since nuclear and solar thermal kind of baseload sources are best alternative to fossil fuel plants and intermittent sources, there is a huge market opportunity in this space that India can offer.

As global markets are preparing for nuclear renaissance, quality, cost-effectiveness and on-time delivery of SMRs would be the next focus area for the industry to delve upon. Indian nuclear ecosystem having a low-cost industry base and fresh project management expertise in building nuclear power plants, can help support global nuclear companies achieve their growth aspirations for the export markets across the globe.

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