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CLEAN POWER DAY AND NIGHT - THE NUCLEAR ENERGY ADVANTAGE



Dr. B Venkataraman
Dr. C Manikyamba

Academy for Science, Technology and Communication

A Platform to Share Knowledge & Insights

Academy for Science, Technology and Communication

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To Organize science communication activities by disseminating information to the general public with participation of academic industrial and scientific institutions through popular lectures, seminars/ symposia, workshops, refresher courses, panel discussions etc., besides publication of books on science/ newsletter / journals etc.

To conduct periodical academic enrichment programmes, with innovative projects for promotion of science and engineering, involving teachers and students, to pursue curiosity and creativity among budding scientists and to stimulate scientific temper.

To provide an unique forum for scientific community to discuss matters of current interest, bring out publications and encourage with academic Fellowships & Awards for Excellence.

To promote temperament of Science and Technology among Youth.

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Preface



One of the indicators of a nation's development is its per capita energy consumption. India is advancing rapidly, especially in recent years, creating an immense energy demand by the vast and growing population. Meeting this need without suffocating our cities in air pollution is a Herculean challenge. Solar, hydroelectric, tidal, and wind energies offer promising alternatives, though each comes with limitations in scalability and reliability.

Nuclear energy stands out as the cleanest and most sustainable option. The general public, however, remains fearful of it. What fuels this fear? A handful of accidents, say Chernobyl in the Soviet Union and Fukushima in Japan that dominated headlines, but over the last two to three decades, these are the only major incidents. Public apprehension largely stems from these events, amplified by the tragic events of Hiroshima and Nagasaki. This is fear driven by perception, not hard data. Compared to the daily toll of disasters, traffic accidents, and industrial mishaps, nuclear mishaps are statistically negligible. We can think of a large number of distributed mini nuclear reactors for electricity production which will minimize the impact of any unforeseen disaster at the same time optimize power distribution logistics.

Dr. B. Venkataraman and Dr. C. Manikaymba are eminent scientists; Dr. Venkataraman is an expert in non-destructive evaluation in the context of nuclear energy systems and Dr. C. Manikyamba is an expert geologist and geochemist with vast experience, *inter alia,* atomic minerals and rare earth elements. The authors, with their vast experience elegantly outline our options for meeting growing demands. In addition to providing much needed, relevant information, they dismantle misconceptions with rigorous scientific and technical knowledge, showing that nuclear power as the cleanest, scalable, sustainable, and safe source available. This small booklet aims to spark a major mindset shift, paving the way for nuclear energy alongside renewables. After all, the ultimate energy source, the Sun itself, is powered by nuclear reactions.

Dr. Ch. Mohan Rao
Chairman-Scientific Advisory Council, ASTC

* Former Director CCMB, Hyderabad and Professor & Head, Department of Biological Sciences, BITS Pilani, Hyderabad.

Editor's Vision



The Academy of Science, Technology, and Communication (ASTC) has released a series of booklets under the title "ASTC COMMUNICATIONS," which present contemporary scientific topics to a wide audience. This publication, "Clean Power Day and Night - The Nuclear Energy Advantage", is the sixth in the series and was jointly written by Dr. B. Venkataraman, Distinguished Scientist and the DAE–Homi Sethna Chair at the Department of Atomic Energy & Senior Professor at Homi Bhabha National Institute and Dr. Chakravadhanula Manikyamba, DAE–Raja Ramanna Chair at CSIR National Geophysical Research Institute.

Dr. Venkataraman, a prominent nuclear scientist and Former Director of the Indira Gandhi Centre for Atomic Research, Kalpagam. He has made significant contributions to the advancement of India's nuclear technology. His contributions span fuel cycle safety, PFBR steam generator qualification, radiometric testing of shielding structures, and NDE innovations that strengthened national programmes from KKNPP to ISRO's launch vehicles. Dr. Venkataraman has consistently bridged the gap between advanced nuclear research and public understanding by articulating the significance of fast reactors, fuel cycle technologies, and national nuclear programmes in accessible formats.

Dr. Chakravadhanula Manikyamba is a distinguished geologist and former Chief Scientist & Head of the Geochemistry Division at CSIR-NGRI. She is highly regarded for her work on Precambrian tectonics, crustal evolution, and critical mineral systems. Her groundbreaking geochemical research across major Indian cratons has deepened global insight into Archean subduction, greenstone belt development, and the formation of BIF/BMF. With over 135 high-impact publications, Dr. Manikyamba is celebrated for her analytical precision, field expertise, and lasting contributions to Indian geoscience, as well as for mentoring future researchers.

In this booklet, the authors provides a comprehensive educational overview of nuclear energy's role in addressing climate change, with a focus on India's energy future. They discussed the urgent climate challenges, the limitations of renewable energy, the advantages and safety of nuclear power, and India's strategic plans to expand nuclear capacity as part of a balanced clean energy system. The communication highlights the need to address misconceptions about nuclear energy by presenting information regarding its safety and potential. It encourages informed public engagement in developing a sustainable energy future, emphasising the critical role of nuclear power in providing reliable, low-carbon electricity around the clock and supporting grid stability.

The ASTC is committed to promoting scientific literacy and understanding by regularly publishing the "ASTC Communications" series, which covers a broad range of contemporary scientific topics. This ensures people from all backgrounds can stay informed about the latest developments in science and technology. Your feedback and suggestions are essential for us to improve the quality and relevance of the "ASTC Communications" series.

Dr. RBN Prasad
Chief Editor - ASTC Publications &
Hony. President, ASTC

*Former Chief Scientist & Head, Centre for Lipid Research, CSIR-Indian Institute of Chemical Technology, & Former President, Oil Technologists' Society of India.

From Secretary's Desk

India's journey towards Viksit Bharat@2047 depends critically on how wisely energy is produced and utilised. As economic growth and electrification drive rising electricity demand, the global challenges of climate change and air pollution make a rapid yet reliable transition to low-carbon energy imperative. Clean power systems must deliver electricity across all seasons and meet peak demands. In this context, nuclear energy emerges as a practical and dependable partner, providing round-the-clock electricity with a compact land footprint and very low life-cycle emissions. This booklet, Clean Power Day and Night – The Nuclear Energy Advantage, is designed as a public-awareness and student-friendly resource to encourage informed discussion on an issue that often evokes strong opinions. It aims to promote scientific temper by explaining, in clear and accessible language, how nuclear power works, how safety is ensured, and how used fuel and wastes are responsibly managed.

The author, Dr. B. Venkatraman, Ph.D., D.Sc. (Hon.), is a distinguished nuclear scientist, holding the DAE–Homi Sethna Chair and serving as Senior Professor at the Homi Bhabha National Institute. He is the former Director of the Indira Gandhi Centre for Atomic Research, specialising in nuclear materials and advanced non-destructive evaluation with extensive experience. Dr. Venkatraman is a widely published researcher and a dedicated science communicator, known for initiating the Anu Yatra outreach programme and for his nationally and internationally recognised contributions to science. The Co-author, Dr. C. Manikyamba, presently the DAE–Raja Ramanna Chair and formerly Chief Scientist and Emeritus Scientist at CSIR–NGRI, is an eminent geologist and geochemist , contributed towards the discovery of new rock types in India. She has published over 140 widely cited research papers, supervised 13 Ph.D. scholars, and received several prestigious honours, including the CSIR Young Scientist Award, the National Mineral Award (Ministry of Mines), and Women Scientist Awards from the Ministry of Earth Sciences, GoI and the Geological Society of India.

The Academy for Science, Technology and Communication (ASTC) gratefully acknowledges the valuable contributions of Dr. R. B. N. Prasad, Chief Editor and Hony President of ASTC, in bringing out ASTC Communications. His sincere commitment, sustained efforts, and dedication to moulding scientific content in a clear, appealing, and accessible manner for the benefit of the general public are deeply appreciated.

ASTC is a premier, independent institution committed to promoting scientific temper, strengthening science communication, and advancing the societal reach of science and technology. The Academy's academic vision and strategic direction are guided by its Scientific Advisory Council. For over two decades, ASTC has functioned through voluntary collaboration and community support, with major initiatives undertaken without government funding, reflecting its strong mission-driven ethos.Through lectures, seminars, symposia, refresher courses, scholarly publications, and outreach programmes, ASTC fosters informed dialogue, nurtures young scientific talent, and recognises excellence through fellowships and awards. With Life, Annual, NRI, and Institutional memberships, ASTC invites academicians, researchers, and industry professionals to join as Fellows, strengthen academia–industry interaction, and contribute ideas that inform, inspire, and innovate for the benefit of society.

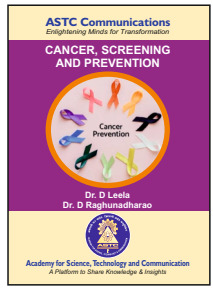
On behalf of ASTC, I place on record our sincere appreciation to the scientists, engineers, and professionals whose sustained efforts have strengthened India's indigenous capabilities in energy and safety.

Sri C.L. Narasimha Rao
Secretary, ASTC

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Review on recently published ASTC Communications entitled "A Handbook on Cancer, Screening and Prevention," written by Dr. D Leela, and Dr. D Raghunadharao

(Review provided by Sri Divyaamrita Sai, Sri Sathya Sai Divyaamritam, Vijag)



Cancer today stands not only as a medical challenge but as a test of our collective conscience. While science has made remarkable progress in diagnosis and treatment, the real gap continues to lie in prevention, early detection, accessibility, and equity. This book addresses these realities with clarity, responsibility, and a deeply humane outlook.

Having read this work with careful reflection, I appreciate the author's sincere effort to present cancer not merely as a disease to be treated, but as a condition that must be anticipated, understood early, and addressed through structured systems rooted in public awareness and compassion. The emphasis on screening, prevention, and community-based intervention reflects a mature understanding of public health and social responsibility.

What makes this work particularly valuable is its balance—scientific in approach, yet sensitive to the human and social dimensions of cancer care. The author does not restrict solutions to advanced technology alone, but rightly draws attention to timely screening, education, and inclusive healthcare delivery as the most powerful tools to reduce suffering and mortality.

This book serves as both a guide and a reminder: that healthcare must move beyond affordability and availability, and rise to the level of moral duty. I believe this work will be of immense value to healthcare professionals, policymakers, institutions, and all those committed to building a more compassionate and effective cancer care ecosystem. I commend the author for contributing meaningfully to this critical field and for offering insights that can inspire action, not just awareness.

We at Sri Sathya Sai Divyaamritam stand as a living expression of the very principles articulated in this book. 1. Shared Philosophy: Prevention, Not Just Cure; 2. Equity and Free Access to Care; 3. Comprehensive and Integrated Care Model; 4. Community-Centric Outreach; 5. Service as a Sacred Responsibility

This book provides the intellectual and ethical framework for a new approach to cancer care. Sri Sathya Sai Divyaamritam stands as its practical embodiment—where knowledge is translated into service, and compassion into action. Together, we affirm a simple yet powerful truth: When healthcare is guided by humanity, healing becomes complete.

[We are delighted to receive the above review. It is encouraging to hear that Sri Satya Sai Divyaamritam is establishing India's first comprehensive, free cancer and kidney dialysis hospital at Sri Sai Palle, Thatipudi Reservoir, S. Kota Mandal, Vizianagaram District. ASTC is pleased to share these comments for our valued readers. – Chief Editor and Honorary President, ASTC]

1. The Urgent Challenge

Over the past two decades, the impacts of climate change have become increasingly apparent in daily life, with higher summer temperatures, prolonged heatwaves, heavier downpours in some regions, and droughts in others. The science is unambiguous: 2024 was officially recorded as the warmest year to date, while the period from 2015 to 2024 marked the hottest decade on record. In 2025, global temperatures also remained elevated, reaching approximately 1.44°C above the 1850–1900 baseline.

One of the clearest warning signs is the rapid loss of ice. From 2000 to 2023, the world's glaciers lost roughly 6,542 billion tonnes of ice, an average of ~273 billion tonnes every year and the rate of loss has been increasing. This melt contributes to rising seas and threatens long-term water security in many regions. At the same time, air quality has deteriorated in many parts of the world. World Health Organization notes that air pollution is linked to an estimated 7 million deaths each year, and most people breathe air that does not meet recommended standards. This is why climate change is often described as the greatest environmental challenge of our time. The present generation is already facing the effects, but if we do not act decisively, future generations will bear a far heavier burden, with extremely limited options and higher risks.

The Target - What is "Net Zero"?: Turn on the news, open a newspaper, or read corporate and government announcements, and you will often see the phrase "Net Zero." What does it really mean? Net Zero does not mean "zero emissions." In real life, some greenhouse-gas emissions will remain difficult to eliminate completely, especially in sectors like heavy industry and agriculture. Instead, Net Zero means balance. For every tonne of greenhouse gases released, an equivalent amount must be removed from the atmosphere (or avoided through credible, verifiable actions), so the net addition becomes zero.

Today, however, our planet's "balance sheet" is not balanced. Human activities release greenhouse gases far faster than natural systems are unable to absorb them with the same rate.. The result is a warming planet, shifting weather patterns, and growing stress on ecosystems and societies.

Setting the Tone - COP26 and Global Commitments: Recognizing this urgency, nearly every country has pledged to act through international climate agreements. At COP26 (Glasgow, 2021), countries reaffirmed the need to limit warming and

strengthen actions this decade. India, for example, announced the "Panchamrit" commitments, including stepping up non-fossil energy capacity and a long-term Net Zero goal. These commitments are not just diplomatic statements, they reflect a global understanding that the energy systems powering modern life must be transformed, quickly and responsibly.

The Disrupted Balance - A Simple Carbon-Cycle Story: For thousands of years, Earth maintained a steady "breathing rhythm" called the carbon cycle (Fig. 1). The inhale: Plants, forests, soils, and oceans absorb carbon dioxide (CO_2) from the air; The exhale: Respiration and decay return carbon back to the atmosphere.

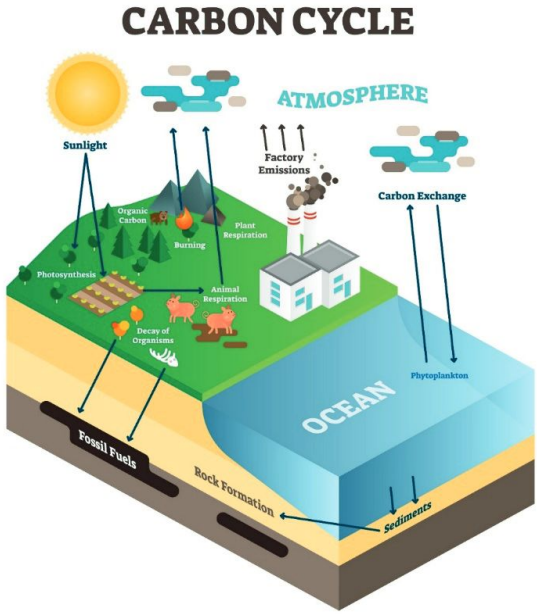


Fig. 1. A Typical Carbon Cycle

For a long time, this system stayed broadly in balance. Before industrialization, atmospheric CO_2 was ~ 280 ppm. Today it is far higher, for example, Mauna Loa measured ~427.5 ppm in December 2025 which are coinciding with the global averages of above 420 ppm.

What changed?: Beginning with the Industrial Revolution, humans started burning coal, oil, and natural gas. Carbon that had been stored underground for millions of years and released it into the atmosphere in a very short time. Nature can absorb some of it, but not at the pace we emit it, so CO_2 accumulates and traps more heat.

It is Not Just CO_2 – The "Greenhouse" Group: CO_2 is the best-known greenhouse gas, but it is not alone. Carbon dioxide (CO_2) is the he main driver because we emit so much of it, mainly from fossil fuels and industry. It also stays in the climate system for a long time. Methane (CH_4) comes from natural gas leaks, agriculture, and waste. It warms strongly in the short time. Nitrous oxide (N_2 O) linked largely to fertilizer use and farming practices. Though all of them matter, but CO_2 is central because it is tightly connected to how we produce electricity, run industries, and fuel transport.

Where Do Emissions Come From?: Emissions are woven into modern life. Broadly, major sources include, i. Energy production and use: Electricity, heat, transport, and industrial energy; ii. Agriculture and land use: Livestock, rice cultivation, fertilizers, and deforestation; Industry and waste: Cement and steel production and waste management.

The Double Dilemma - Less Carbon, More Energy: The hard truth is that the world faces a double challenge. We must cut emissions sharply to limit climate risks. We must still provide more reliable energy, because development, public health, education, and modern livelihoods depend on it and billions of people still need better access to clean, dependable electricity.

As we electrify transport (Evs), heating, and parts of industry, electricity demand will rise. The transition therefore requires energy sources that are Scalable (large amounts of power); Reliable (available 24×7, not only when the sun shines or wind blows) and Clean (very low emissions during operation)

We need every effective clean option available. Wind and solar are vital, and create new challenges that must be addressed through a balanced, reliable clean-energy system.

2. The Renewable Gap & India's Renewable Reality

The Sunshine Revolution: In the last decade, the world has witnessed a quiet miracle in energy technology. Solar panels have become dramatically cheaper,

wind turbines have grown into giant machines, and many countries including India, now build renewable power rapidly than anyone anticipated. There are vast solar parks and wind farms spreading across ridgelines along the countryside which gives the feeling that the solution is already in front of us. We simply capture abundant sunlight and run everything on the sun and wind. The difference lies in the difference between gathering energy and powering a civilization. A modern society does not need electricity only when nature provides it, it needs electricity every hour of every day, for homes, hospitals, railways, factories, water supply, digital networks, and national security infrastructure. That requirement, reliability is where the "renewable gap" appears.

The Problem of Intermittency - When Nature Takes a Break: The fundamental limitation of wind and solar is not that they do not work, they work extremely well. The limitation is that they are weather-dependent.

Solar power is strongest around midday, but it falls rapidly in the evening and becomes zero at night, precisely when households switch on lights, cook dinner, watch TV, and increasingly charge phones and electric vehicles. In winter, when days are shorter and demand can rise, solar output is naturally lower.

Wind power can be even more unpredictable. Wind may blow strongly for days, then weaken for days or even weeks. Some regions experience periods when both wind and solar are low, a "dark wind lull" which becomes a serious stress test for any grid that relies heavily on these sources.

A helpful way to visualize this is the well-known "duck curve" (Fig. 2): solar generation rises sharply during the day and then disappears in the evening, just when demand often climbs. The gap between evening demand and falling solar output must be filled instantly by other sources, otherwise, the grid becomes unstable.

Capacity Factor - What we Buy vs. What we Get: This brings us to an important concept. Capacity Utilisation Factor (CUF) (or Plant Load Factor (PLF). It explains why "installed capacity" and "electricity delivered" are not the same thing. If we build a 1,000 MW coal or nuclear station, it can operate close to full output for most of the year. But if we build a 1,000 MW solar park, full power will be obtained for few hours on sunny days only. Over a year, solar typically delivers only a fraction of its "nameplate" capacity.

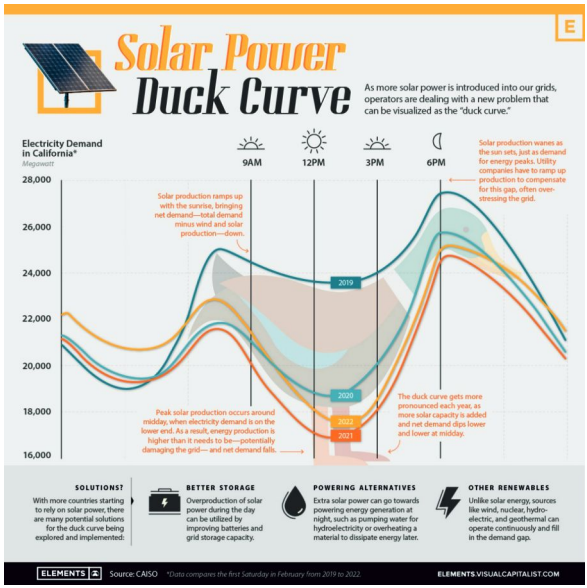


Fig. 2 : The Typical Duck Curve

(Source : https://elements.visualcapitalist.com/the-solar-power-duck-curve-explained/)

That is why, to produce the same annual electricity (units or kWh) as one 1,000 MWe firm, high-availability plant, we need multiple times more solar capacity, often three to four times and further requires a system to supply power at night and during weather lulls. In simple terms, installed capacity does not guarantee reliable generation. Always there will be a gap between total capacity and available power.

The Battery Question - Powerful Tool, not a Complete Substitute (Yet): A common question follows naturally. "If solar produces extra electricity in the afternoon, can't we store it in batteries and use it at night?" Batteries are indeed a crucial part of modern grids. They are excellent for short-duration balancing, supporting the grid for a few hours, smoothing fluctuations, and helping to meet evening peaks on many days. But powering an entire country through multi-day weather lulls (and doing so affordably) is still beyond what today's battery systems are designed to do at scale.

A simple analogy helps: Batteries are the sprinters of the energy world (great for minutes to hours), but a stable, high-renewable grid also needs marathon runners, sources that can deliver dependable power day after day, regardless of weather.

The Renewable Reality – India's Green Ambition: India is rightfully taking a leadership role in the global renewable energy revolution. We have set ambitious targets, 500 GW of non-fossil capacity by 2030 and we are home to some of the world's largest renewable projects, including major solar parks such as Bhadla in Rajasthan and Pavagada in Karnataka. This scale is inspiring and necessary for a cleaner future.

But India also has unique realities such as large population, fast-growing electricity demand, diverse climates, and limited land. For India, the question is not "renewables or no renewables." The real question is, How do we build a clean energy system that is reliable, affordable, and scalable for 1.4 billion people?

The Land Challenge - A Question of Space: India supports nearly 18% of the world's population on just 2.4% of the world's land. In such a country, land is not just geography, it is food security, housing, forests, water catchments, and livelihoods. Every acre used for energy competes with other essential needs. To understand the scale, consider the land required for an installed capacity of around 1,000 MWe (roughly one large unit):

Nuclear power (the space saver): A nuclear plant is extremely energy-dense. The core power-producing facilities occupy a compact area, with the surrounding safety buffer often remaining largely green and undisturbed.

Solar power (land hungry): A utility-scale solar plant of 1,000 MW typically needs tens of square kilometres of land. This is not a criticism. Solar is valuable, but the land requirement becomes significant when scaled to national levels.

Wind power (the sprawl): Wind turbines need wide spacing to avoid "stealing" each other's wind. While farming can continue between towers, the infrastructure spreads over a very large area, including access roads and transmission corridors.

The key point is not to "compare technologies for pride," but to recognize that in India, land-efficient clean power matters.

The "Evening Peak" Problem - When India Needs Power Most: India's electricity demand often rises in the evening, roughly 7 PM to 9 PM, when families return home, lighting demand increases, commercial activity continues, and cooling load can remain high. At that time Solar output is essentially zero and Wind output is uncertain. But the grid must still deliver power reliably.

Without firm supply backing up renewables, the system risks shortages or instability during these critical hours. This is why grids that add large amounts of

renewables must also add flexibility and firmness through storage, hydro support, stronger transmission, demand response, and dependable clean generation.

What About Hydro? The Silent Giant: Hydroelectric power is a champion of clean energy and a backbone of grid stability. But hydro cannot replace coal entirely everywhere, for three practical reasons: i. Geography and saturation: Many easier sites are already developed; large remaining potential is often in fragile and challenging terrains; ii. Social and ecological cost: Big dams can submerge land, affect ecosystems, and displace communities, difficult trade-offs in a densely populated country; iii. Monsoon dependence: Hydro is seasonal. In the hot months (April–May), when demand can peak, reservoir levels may be under pressure.

Hydro remains essential, especially for flexibility, but it alone cannot provide the full round-the-clock replacement for coal at national scale.

Need for Baseload or Firm Power - The Grid's Steady Rhythm: A modern electricity grid is like an orchestra. To keep everything in sync, it needs a steady rhythm like stable frequency and dependable supply. Renewables are invaluable instruments, but naturally variable with periods of high availability coupled with low generation conditions. A reliable system therefore needs firm power, clean sources that can run 24/7 and support the grid through nights, monsoons, heatwaves, and wind-solar lulls.

Historically, coal provided much of this steady rhythm. As we phase down coal to protect the climate and air quality, we must replace its reliability with clean alternatives that can perform the same role.

To conclude, We Need a Partnership, not a Comparison and debates on energy sources. This is not an argument against renewables. Solar and wind are essential especially for cutting emissions and reducing the usage of fossil fuel during daylight and windy periods. The message is simply that renewables need reliable partners.

For India, a clean power system must combine: Large-scale solar and wind, stronger transmission and grid management, an effective storage system, hydro for flexibility where feasible, and firm, low-carbon power that can supply electricity day and night.

As coal is phased down, nuclear energy stands out as a practical firm partner because it can provide large quantities of carbon-free electricity 24/7, with a

compact footprint—supporting grid stability while renewables expand rapidly. Let us evaluate how nuclear energy works and why it is uniquely suited to provide dependable, carbon-free electricity alongside renewables.

3. Nuclear Energy – The Power of The Atom

To many people, a nuclear reactor can look like a mysterious "black box." In reality, a nuclear power plant works on the same basic principle as a coal or gas power station.

Heat → Steam → Turbine → Electricity

The difference is simply the source of heat. In a **coal plant,** heat is produced by burning carbon (a chemical reaction). In a **nuclear plant,** heat is generated by splitting certain atoms (a nuclear reaction).

Everything after that involves in producing steam, spinning a turbine, generating electricity following conventional engineering approaches.

The Core Idea - Fission (Splitting the Atom): The main fuel used in most reactors is uranium, a naturally occurring metal found in rocks (and even dissolved in seawater). Uranium comes in different forms (called isotopes). One particular form, uranium-235, has a special property which can split when struck by a tiny particle called a neutron.

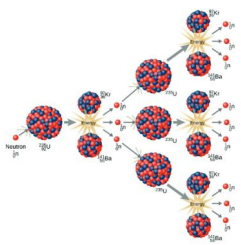
Here is the process inside the reactor core, in simple steps:

The Spark: A neutron hits a uranium-235 atom.

The Split: The uranium atom absorbs the neutron, becomes unstable, and splits into two smaller atoms. This is fission.

The Heat: The split releases a large burst of heat energy.

The Chain Reaction: The split also releases more neutrons, which can strike other uranium atoms and continue the process, forming a self-sustaining chain reaction (Fig. 3).



The important point is that a nuclear reactor is not an uncontrolled explosion. It is a carefully controlled chain reaction, kept steady by design. The reactor has systems that can slow down, speed up, or stop the reaction safely.

Why Nuclear Fuel is so Powerful: Energy Density: Nuclear energy's true "superpower" is energy density. When we burn coal or gas, we release energy from the outer electrons of atoms (chemical energy). Nuclear fission releases energy from the nucleus of the atom where the forces are vastly stronger. That is why a very small amount of nuclear fuel contains an extraordinary amount of energy. A nuclear fuel pellet is a small ceramic cylinder of uranium oxide, roughly the size of a fingertip. One uranium fuel pellet can produce as much energy as one ton of coal, 149 gallons of oil, or 17,000 cubic feet of natural gas (Fig 4)

That is why nuclear plants do not need endless daily fuel deliveries. The fuel is compact, energy-rich, and easy to store.

Visualizing the Scale: Coal Trains vs. Small Truckloads: As coal has much lower energy density, a large coal plant needs enormous quantities of fuel to run continuously. When we translate this into annual requirements for a large power station, we realise that coal stations typically consume millions of tonnes of coal

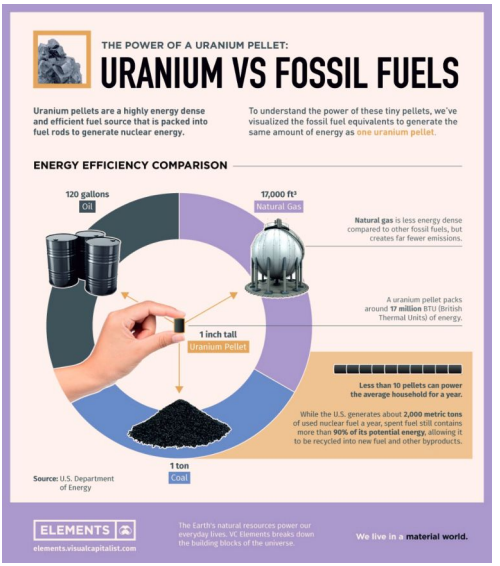


Fig. 4. Energy Density comparison
(source : https://elements.visualcapitalist.com/the-power-of-a-uranium-pellet/)

each year, which means constant transport, handling, storage, and ash management.

For nuclear, the annual fuel quantities are dramatically smaller. A World Nuclear Association overview notes that a 1,000 MWe reactor requires about 27 tonnes of fresh fuel per year (typical light-water reactor fuel).

In the Indian context, a Government of India (PIB) reply similarly notes that a 1,000 MW LWR needs about 25 tonnes of fuel (UO_2) per year at high capacity factor.

Therefore, the difference is not just about emissions, it is also concerns about logistics including fuel mining volumes, transport convoys, storage yards, and waste streams.

"Lifetime Energy in a Soda Can": Another way to understand energy density is to look at the total fuel associated with one person's electricity use. A Canadian nuclear industry analysis estimates that a person's lifetime electricity use, if supplied entirely by nuclear, would correspond to a small volume of used fuel that fits within a standard 355 ml soda container.

The main point is not that waste is "nothing" (it must be managed carefully). The message is that the quantity is small and limited in volume, which makes long-term management technically feasible with proper systems.

The Indian Context: Why PHWRs Matter: India is a global leader in a reactor technology called the Pressurized Heavy Water Reactor (PHWR), valued for its fuel flexibility and self-reliance.

A key point is that Indian PHWRs use natural uranium instead of enriched uranium as fuel which supports domestic capability and strengthens India's indigenous nuclear programme. It is part of long-term strategy to build reliable nuclear capacity using technologies that match national resources, supply chains, and strategic needs.

Summary: A Simple Machine, Powered by the Atom: A nuclear reactor is essentially a sophisticated heat source that uses the energy stored in the nucleus of atoms. It produces electricity the same way other thermal plants do which involves heat makes steam, steam spins a turbine, the turbine generates power. What makes nuclear unique is the extraordinary energy density of its fuel, allowing: **Very small fuel volumes for very large electricity output; Minimal**

fuel transport and storage needs and Reliable, round-the-clock generation that complements variable renewables

Let us know how nuclear plants especially in India are designed with multiple layers of safety, and why nuclear energy alongside renewables can be a strong foundation for a clean, reliable electricity system.

4. Safety & Waste — Myth Vs. Reality

Addressing the Fear: When the conversation turns to nuclear energy, it often stops at two words, **safety** and **waste** and these concerns are portrayed nuclear power as something unstable or mysterious —"glowing goo," ticking clocks, and worst-case scenarios. But the day-to-day reality of nuclear power especially as it is designed and regulated is very different. Modern nuclear plants are built around two simple ideas namely **Prevent radiation from escaping through multiple independent barriers, and Handle all wastes in a controlled, traceable way, with the smallest possible volumes.**

In India, this situation is best understood by focussing on strong safety measures and careful fuel recycling, rather than fear and uncertainty.

Part 1: Safety as a Philosophy — "Defence in Depth"

In nuclear engineering, safety is not a single switch or a single wall. It is a layered philosophy called **Defence in Depth**. Think of a fortress: to reach the inner vault, an intruder would need to cross several obstacles, each one capable of stopping the threat even if another layer fails. A nuclear reactor uses the same concept. Multiple barriers and safety systems work together so that even if one layer is compromised, the next layer continues to protect people and the environment. The Five Physical Barriers (from inside to outside) are as follows:

i. **The Fuel Pellet: the first barrier:** Nuclear fuel is not a liquid or gas. It is a hard ceramic pellet of uranium oxide (UO_2), manufactured at high temperature. Many radioactive by-products formed during operation remain trapped within this solid material. In simple terms, the radioactivity is "born" inside a solid that already holds it in place.

ii. **The Cladding: the sealed skin:** Fuel pellets are stacked inside thin, strong metal tubes (cladding), designed to resist heat and corrosion. These tubes form a tight seal around the fuel. As long as the cladding remains intact, radioactive material stays inside the fuel, and does not mix with the reactor coolant.

iii. **The Primary System: the closed loop:** The fuel tubes sit inside a closed, high-integrity coolant system. In PHWRs, heavy water circulates in a controlled loop designed for high pressure and temperature. Even if a small fuel pin defect occurs, the radioactivity remains within the plant's closed systems and is monitored and managed.

iv. **The Primary Containment - the pressure boundary:** The reactor core and primary systems are housed within a strong containment structure, designed to prevent any significant release to the environment even under unlikely accident conditions. If steam or pressure is generated inside, this structure is engineered to hold it and keep it from escaping outside.

v. **The Secondary Protection - another layer of shielding and isolation:** Among the multiple layers of protection in Nuclear safety, the primary containment keeps radiation inside the reactor, while additional building structures and safety provisions protect against external events such as earthquakes and severe weather conditions. Along with physical barriers, reactors are designed with multiple safety systems such as automatic shutdown systems that quickly stop the chain reaction, emergency cooling and heat-removal systems, backup power supplies, and continuous radiation monitoring. The goal is not just to respond to problems, but to anticipate them and prevent them from escalating.

Nuclear safety is engineered as layers of protection along with response system, so that no single failure can lead to harm the public.

Part 2: The "Waste" Question — What Happens to Used Nuclear Fuel?

The second fear is waste. Many people imagine that nuclear waste as something dumped and forgotten. In reality, nuclear waste is among the most tracked and controlled industrial wastes on Earth. A useful clarification is that "nuclear waste" is not one single thing. It includes: **Low- and intermediate-level wastes** such as protective clothing, filters, resins, and **Used (spent) fuel,** which is highly radioactive and handled with the greatest care.

India's Approach: A "Closed" Fuel Cycle: India follows a philosophy often described as a **closed fuel cycle**. The idea is straightforward. Used fuel is not treated simply as garbage and considered as a wealth material that still contains valuable components. When fuel is removed from a reactor, it has produced a great deal of energy, but it still contains significant quantities of uranium and

newly formed plutonium that can be recovered through reprocessing and used in future reactors, particularly in the context of India's long-term programme. This approach aims to extract additional energy value from the material, reduce the volume of final high-level waste, and strengthen long-term energy security.

Part 3: "Wealth from Waste" — Beneficial Isotopes

There is another significant aspect that Indian nuclear program has successfully adopted. Within nuclear materials and reprocessing streams, certain radioisotopes can be recovered and used for societal applications especially the healthcare industry (medicine). For example: **Cesium-137** has been used as a sealed radiation source in medical, blood irradiators and industrial applications; **Ruthenium-106** is used in eye plaques for certain ocular cancers, where a small, carefully controlled radiation source can treat the tumour without harming surrounding tissue.

The important information is not the technical detail of each isotope. Nuclear technology can convert some by-products into tools that help society, especially in healthcare.

Part 4: Turning the Remaining High-Level Waste into Solid Glass

After recovering useful materials, a much smaller fraction remains as high-level waste. This is managed through processes designed to lock it into stable, solid forms.

One of the widely used methods is vitrification: Liquid high-level waste is mixed with glass-forming materials and heated, then poured into stainless-steel canisters where it solidifies into a durable glass matrix.

Why glass? Because it is chemically stable and immobilizes the waste in a solid form, making it far safer to store and manage over long timescales than any liquid.

Part 5: The Volume Reality — Small Waste, Carefully Managed

Nuclear fuel is extraordinarily energy-dense. That means the quantity of used fuel and high-level waste is small compared to the wastes produced by fossil fuels. A coal plant moves and burns enormous amounts of fuel and produces massive volumes of ash and other pollutants year after year. Nuclear plants produce far smaller volumes of high-level waste and importantly, that waste is contained, measured, and managed, not dispersed into the air. A popular way to visualize this is the "soda can" comparison. Over a lifetime, the amount of high-level

nuclear waste attributable to one person's electricity use which is very small and fits into a compact volume whereas, the waste from fossil-fuels would be many orders of magnitude larger and spread widely throughout the environment.

Summary: Clear Risks, Strong Controls, Responsible Management

Nuclear energy is not risk-free like all other industries. But nuclear power is distinctive in three important ways: **Safety is built as layers upon layers** ("Defence in Depth"), so no single failure is allowed to become a public hazard; **Used fuel is handled as a managed material**, not an uncontrolled pollutant, often with recovery of valuable components; **The final high-level waste volume is small and immobilized in solid forms**, stored and monitored with full accountability.

What About Chernobyl and Fukushima? Lessons from Two Very Different Accidents: It is important to know "If nuclear power is safe, what about Chernobyl and Fukushima?" These two events are often mentioned together, but they were very different in cause, design, and consequences and both led to major improvements in global nuclear safety.

Chernobyl (1986) - A design + operation failure without a robust containment:

Chernobyl involved an RBMK reactor design that had a dangerous feature under certain conditions such as a positive void coefficient and it did not have the kind of strong containment structure used in most power reactors. During a late-night test, multiple safety systems were disabled and operating rules were violated, leading to a runaway power surge and explosions. The International Atomic Energy Agency (IAEA) analysis emphasized both design vulnerabilities and serious safety-culture/operational failures as key causes.

This accident caused acute radiation sickness among emergency responders. 28 deaths occurred within the first few months among those who received very high doses.

Long-term health impacts were dominated by thyroid cancers among those exposed as children, especially where protective measures such as avoiding contaminated milk were not implemented quickly. WHO summaries and detailed reviews document this pattern.

What the world learned is reactor designs and regulations must ensure that a single flawed condition cannot trigger unstable behavior, that robust containment

is essential, and that safety culture including never disabling protections, bypassing rules is non-negotiable.

Fukushima Daiichi (2011) - A natural disaster leading to loss of power and cooling:

Fukushima was triggered not by the reactor "running away," but by an extreme natural event such as a major earthquake followed by a massive tsunami. The reactors shut down automatically, but the tsunami caused extended loss of electrical power and cooling, leading to fuel damage in multiple units and hydrogen explosions that damaged buildings. The IAEA describes the accident sequence as driven by the tsunami and the resulting loss of critical safety functions.

A crucial point about health effects: the UN Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has stated that no adverse health effects among Fukushima residents have been documented that could be directly attributed to radiation exposure, and none are expected to be detectable in the future. However, the accident caused widespread displacement and stress, reminding the world that emergency decisions must also protect public well-being, not only radiation doses.

What the world learned about this incident is that nuclear plants must be able to withstand "beyond-design" extremes especially **flooding, loss of off-site power, and prolonged station blackout** with hardened backup power, diverse cooling options, protected equipment, and better emergency preparedness.

The Bottom Line is that Rare events teach, big lessons leading to stronger safety.

Chernobyl and Fukushima were serious accidents, but they also reshaped global nuclear safety. Modern reactors and modern regulatory frameworks emphasize: multiple physical barriers (defence in depth), robust containment, automatic shutdown and diversified cooling, planning for extreme external events, and strong safety culture and transparent oversight.

A student-friendly sentence is that nuclear safety is not based on hope, it depends on built-in protection and continuous learning from past events.

5. Green Credentials of Nuclear Energy

Beyond "Zero Carbon": Most people equate clean energy with "no smoke" and by that definition, nuclear power qualifies. A nuclear plant does not burn coal, oil,

or gas, and does not emit carbon dioxide (CO_2) and other air pollutants like sulphur dioxide, nitrogen oxides, and fine particulate matter (PM2.5) that damage public health.

But true environmental assessment revolves around the resources mined and processed, land use, and impact of ecosystem and water. When we look at the full picture from construction to operation to decommissioning, nuclear energy's "green credentials" are clear and comprehensive.

High energy and low material Footprint: Every energy technology needs materials such as concrete, steel, copper, aluminium, and sometimes large quantities of glass, silicon, and specialised minerals. The difference is how much material is needed to deliver the same amount of electricity. As nuclear plants produce large amounts of electricity from a compact facility and run steadily for many years, their materials intensity per unit of electricity delivered can be much lower than that of variable renewables. A useful comparison, drawn from a U.S. Department of Energy analysis and reproduced by the World Nuclear Association, shows materials (in tonnes) required per terawatt-hour (TWh) of electricity (excluding fuels): Coal: ~314; Gas combined cycle: ~171; Nuclear (PWR): ~168; Wind: ~1,978 and Solar PV : ~9,430

And when you look at specific materials, the contrast is striking. Solar PV requires very large amounts of glass (~2,700 t/TWh) and wind requires large amounts of steel (~1,920 t/TWh), while nuclear's metals per TWh remain comparatively small. This does not mean renewables are undesirable. Solar and wind are essential. It simply means that delivering large, reliable quantities of electricity with minimal material throughput is an environmental advantage, especially for land and resource-constrained regions and thus nuclear is essential.

Critical Minerals - A Quiet Constraint in the Clean-Energy Transition: Another environmental and geopolitical issue is the growing demand for critical minerals such as lithium, cobalt, nickel, rare earth elements, and large quantities of copper used in renewable supply chains, batteries, and electric motors. The World Nuclear Association, summarising IEA findings, notes that critical mineral requirements per MW are highest for offshore wind (~15.5 t/MW), followed by onshore wind (~10 t/MW) and solar PV (~7 t/MW), while nuclear is comparatively low in critical mineral requirements (along with hydropower and biomass). A balanced clean-energy pathway combines renewables with low-

mineral, high-output firm power, to decarbonise without creating a new wave of ecological damage from mining.

Life-Cycle Carbon - The Full "Cradle-to-Grave" Picture: Even "clean" energy has some carbon footprint, because mining, manufacturing cement and steel, transporting equipment, and construction all require energy. Scientists therefore compare technologies using life-cycle greenhouse gas emissions counting emissions from the entire chain, not just day-to-day operation.

Multiple authoritative reviews show a consistent result Nuclear, wind, and solar are all far lower than fossil fuels, with nuclear typically in the same low range as wind and often lower than solar when manufacturing impacts are included. The U.S. National Renewable Energy Laboratory (NREL) summarises this clearly. Life-cycle emissions from renewables and nuclear are much lower than coal, with coal being roughly an order of magnitude (or more) higher per kWh (Fig 5).

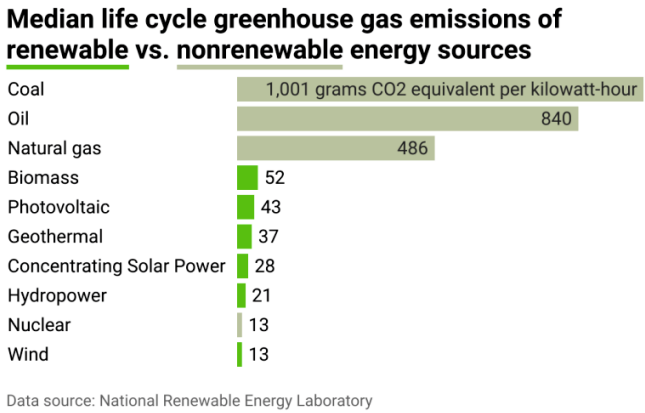


Fig. 5 Comparison of green house gas emissions over life cycle source : https://whatsupnewp.com/2023/02/how-lifetime-emissions-of-different-energy-sources-stack-up/https://whatsupnewp.com/2023/02/how-lifetime-emissions-of-different-energy-sources-stack-up/

International assessments also provide indicative ranges. For example, the UNECE life-cycle assessment report shows wind in the range of ~7.8–16 g CO_2 −eq/kWh (onshore) and nuclear around ~5.1 g CO_2 −eq/kWh (reported as an average in their dataset), while fossil fuels are far higher. When nuclear energy is described as "clean," it is not a slogan but a conclusion supported by full lifecycle accounting.

Land and Nature: How Exclusion Zones Can Become Green Buffers; A nuclear power station is not built in the middle of a crowded neighbourhood. Regulations require a controlled area around the plant. India's environmental guidance documents describe an exclusion zone of about 1 to 1.5 km around the plant, under total control, with no public habitation. An interesting ecological side-effect is that these controlled buffer areas can function as protected green spaces, with limited human disturbance, reduced hunting pressure, and fewer roads and encroachments. The purpose of the zone is safety and security, not wildlife conservation but nature often benefits when human activity is restricted.

Indian examples often cited include:

- **Kaiga (Karnataka):** The "Kaiga Bird Marathon" has reported more than 160 bird species observed around the Kaiga site and township over the years, highlighting rich biodiversity in the Western Ghats landscape.
- **Kalpakkam (Tamil Nadu):** A published checklist on the DAE campus at Kalpakkam reports 178 bird species within the campus habitats, including wetland-associated species and migratory visitors.
- **Narora (Uttar Pradesh):** The upper Ganga stretch around Narora Barrage is known as habitat for the Ganetic River dolphin which is documented by local reports and conservation groups.

These observations indicate that a nuclear plant does not automatically mean an ecological dead zone. With careful environmental management, monitoring, and controlled development, the surrounding areas can remain biologically active.

Water and Thermal Discharge - A Managed Environmental Parameter: Like most large thermal power stations (coal, gas, and nuclear), nuclear plants use cooling water and return it to the sea, river, or cooling reservoir at a slightly higher temperature. This is called thermal discharge, and it is a legitimate environmental consideration which is regulated and monitored. Indian references on cooling-water management note temperature-rise limits (commonly discussed as a "delta" limit such as about +7°C over ambient under prescribed conditions), and remote-sensing studies demonstrate how such temperature differences are assessed and controlled near outfalls.

NPCIL also notes that environmental studies including condenser cooling-water discharge studies, thermal ecological studies, and biodiversity conservation studies are carried out to meet regulatory requirements (MoEFCC, AERB, State

Pollution Control Boards), and these studies show the effect of thermal discharges is confined to a small area and is reversible in nature. Thermal discharge is not ignored, it is measured, regulated, and managed.

Summary: A Smaller Footprint for a Big Job: If sustainability means "leaving more room for nature," then we must pay attention to land use, materials, mining, air pollution, and full life-cycle carbon, not only what comes out of a chimney.

Nuclear energy offers a combination that is environmentally powerful: Very low life-cycle carbon emissions, comparable to other leading clean technologies; Very high electricity output with low materials per TWh, A compact land footprint and controlled buffer zones, which can act as green buffers and No smoke, no PM2.5, and no sulphur emissions in operation

In a world trying to decarbonise quickly and protect ecosystems, nuclear energy fits naturally as a high-density, low-carbon partner to renewables, helping to generate massive power while keeping physical footprint smaller.

6. Vision 2047 — The 100 GW Blueprint

The Resource Reality: Why Nuclear Becomes Non-Negotiable: To understand India's energy future, it helps to think of our energy resources as a bank account. A nation can grow steadily only if it has reliable access to energy that is affordable, secure, and clean. India's challenge is that much of the fuel that powers modern life is oil and gas which comes from outside, while the fuel that India holds in abundance (coal) cannot be used indefinitely without contributing to climate change and air pollution.

Energy security and climate commitments have become strategic imperatives as India's population and economy expand. India's dependence on crude oil import remains extremely high (~87–88%) and natural gas also shows a similar vulnerability, with imports reaching about 46% of consumption 2023–24. This "import dependence" exposes the economy to global price shocks, geopolitical disruptions, and supply risks, exactly what a fast-growing nation wants to avoid.

Thorium-based nuclear energy is scientifically compelling due to its high natural abundance, improved resource efficiency, and potential for reduced long-lived radioactive waste compared to conventional uranium cycles. India possesses one of the world's largest thorium reserves, primarily in monazite sands along coastal and inland placer deposits, containing ~319,000 tonnes of ThO_2 , from which about 280,333 tonnes of thorium can be extracted.

As of February 2021, the Atomic Minerals Directorate (AMD) has established 3,50,438 tonnes of in situ U_3O_8 (~2,97,170 tonnes of uranium) across 44 deposits in Andhra Pradesh, Telangana, Jharkhand, Meghalaya, Rajasthan, Karnataka, Chhattisgarh, Uttar Pradesh, Uttarakhand, Himachal Pradesh, and Maharashtra. AMD has also identified 12.73 million tonnes of monazite, reinforcing India's strategic reserves of thorium and rare earth elements. Several uranium deposits are already in production, while others are progressing through techno-economic evaluation, regulatory clearances, and project development stages.

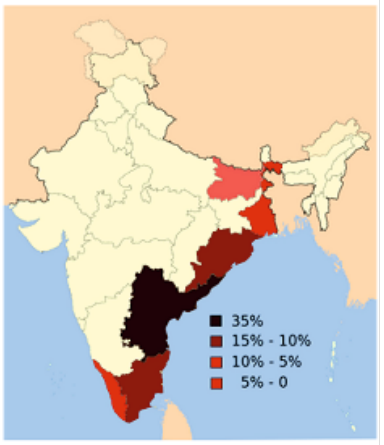


Table -2 State-wise details of the Monazite resources

State	No of Deposits	Resource (million tonne)	
		Monazite	Total Heavy Minerals
Odisha	12	3.16	332.44
Andhra Pradesh	24	3.78	333.45
Tamil Nadu	50	2.47	298.42
Kerala	35	1.84	242.88
Maharashtra	5	0.004	5.64
Gujarat	2	0.07	12.53
West Bengal	1	1.20	5.45
Jharkhand	1	0.21	1.12
Total	130	12.73	1,231.93

Fig. 6 .Map indicating Th reserves of India, present along the eastern coast with varying shades showing quantity of estimated reserves (source : http://large.stanford.edu/courses/2024/ph241/parikh1/)

However, Thorium cannot be used directly as fuel in today's mainstream reactors, but it represents a strategic, indigenous energy option for the future, potentially offering centuries of sustainable energy security when utilized through the right technology pathway. This combination of high import dependence for oil and gas, limited scope to rely on coal forever, and a large thorium endowment is one reason that nuclear energy is increasingly viewed as a necessary pillar of "Viksit Bharat".

The Strategy: India's Three-Stage Programme (A Roadmap Built for Our Resources): India's nuclear plan was designed to match India's unique resource reality. As uranium resources are relatively limited than thorium, India adopted the well-known three-stage nuclear power programme, with a clear logic.

Stage 1: Use natural uranium in Pressurised Heavy Water Reactors (PHWRs) to generate electricity and produce plutonium in spent fuel.

Stage 2: Use that plutonium in Fast Breeder Reactors (FBRs) to multiply fuel and expand fissile material availability.

Stage 3: Use reactors that enable thorium utilisation by converting thorium into uranium-233, a usable fuel, so thorium becomes a long-term energy resource.

This approach is a deliberate pathway to convert India's long-term thorium advantage into practical and scalable electricity. India's own national institutions describe this as the foundation of the country's strategy for sustainable utilisation of thorium over centuries.

The Target - 100 GW by 2047 (A Mission to Deliver It): India has now put a clear marker on the table. i.e. 100 GW of nuclear power capacity by 2047. The Department of Atomic Energy has described the launch of a "Nuclear Energy Mission for Viksit Bharat" with this target. In parallel, government and sector discussions have emphasized that reaching 100 GW is important for India's energy transition and long-term reliability needs.

A key point for students to note is that "100 GW" is not just a number. It represents a vision of electricity that is: Clean (very low life-cycle carbon), Reliable (available day and night), Land-efficient and Fuel-secure over the long term.

How the Blueprint is Being Built: Three Complementary Pillars

Pillar A: "Fleet Mode" — Standardised Large Reactors for Scale: To reach quickly, the programme is shifting from building one-off projects to standardised reactors in batches. Therefore, designs, supply chains, skills, and construction methods can be repeated and improved each time.

A major step in this direction was the Government's approval and financial sanction (June 2017) for ten indigenous 700 MWe PHWR units, with sites including Kaiga (Karnataka), Gorakhpur (Haryana), Chutka (Madhya Pradesh) and Mahi Banswara (Rajasthan). Once industry and regulators have mastered a standard design, repeat builds can become faster, more predictable, and cost-efficient than custom one-off projects. At the same time, India continues to expand capacity through other proven reactor lines, including additional units at Kudankulam, where Russian VVER reactors are already in operation, strengthening near-term nuclear generation while indigenous capacity ramps up.

Pillar B: Bharat Small Reactors — Clean Captive Power for Industry India's decarbonisation challenge is not only about lighting homes; it is also about cleaning up heavy industry such as steel, cement, refineries, and chemicals—sectors that need dependable power and heat.

Due to this, India has advanced the idea of Bharat Small Reactors (BSR), based on the proven 220 MWe PHWR technology originally designed and developed by the Bhabha Atomic Research Centre (BARC). While NPCIL has issued a Request for Proposal to deploy these units as captive plants "under the existing legal framework," BARC continues to provide the critical R&D support, safety validation, and design adaptations required to optimize these reactors for industrial applications.

In plain terms, the plan leverages a robust, indigenous design—engineered by BARC and commercialized by NPCIL—to offer a compact, standardized nuclear option. This allows industries to cut emissions without depending entirely on variable renewables or imported gas.

Pillar C: Breeders — The Key to Unlocking Thorium's Full Value: If PHWRs help India start and scale nuclear electricity, fast breeder technology is the bridge to the long-term thorium future.

India's confidence in breeders is rooted in experience. The Fast Breeder Test Reactor (FBTR) at Kalpakkam has provided 4 decades of operational learning and has demonstrated strong performance of India's mixed carbide fuel, including irradiation experience up to 165 GWd/t burn-up in a lead subassembly. This is not just a technical achievement, it is the "test track" that builds confidence for commercial-scale breeders.

The next milestone is the Prototype Fast Breeder Reactor (PFBR), 500 MWe, also at Kalpakkam. PFBR is a major step in Stage-II, using MOX fuel initially, breeding new fuel from uranium-238 blankets, and envisaging thorium blankets for future conversion to uranium-233. In simple language, breeders are the machines that turn limited fissile material into more usable fuel and prepare the pathway for thorium utilisation.

Future Technologies – The Molten Salt Revolution

While the Pressurised Heavy Water Reactor (PHWR) is the workhorse of today, and the Fast Breeder Reactor (FBR) is the bridge to the future, the Molten Salt Breeder Reactor (MSBR) is also a possible pathway in addition for unlocking the full potential of India's vast thorium reserves in the Third Stage of the nuclear programme.

A Liquid Fuel Game-Changer: Unlike conventional reactors that use solid uranium pellets, an MSR dissolves its fuel (thorium and uranium) into a hot, liquid fluoride salt mixture that circulates through the reactor core. This liquid state offers a unique advantage: it allows for "online reprocessing," where fission products can be continuously removed and fresh U-233 (bred from thorium) can

be managed without shutting down the reactor. This capability is essential for maintaining the neutron economy required to breed fuel from thorium effectively.

BARC's Indigenous Innovations (IMSBR): Recognizing this strategic necessity, the Bhabha Atomic Research Centre (BARC) is actively working on the design and development of the Indian Molten Salt Breeder Reactor (IMSBR).

- **The 5 MWth Demonstration:** BARC has initiated the design of a 5 MW (thermal) demonstration reactor to validate these advanced technologies before scaling up.
- **Custom Chemistry:** The proposed fuel salt is a specific mixture of Lithium, Calcium, Thorium, and Uranium fluorides, while the coolant is a separate fluoride salt mix (LiF-NaF-KF) known as FLiNaK.
- **New Materials:** Molten salts are corrosive at high temperatures. To solve this, BARC scientists have indigenously developed a special Ni-Mo-Cr-Ti alloy (Nickel-Molybdenum-Chromium-Titanium) that has shown excellent resistance to salt corrosion, ensuring the reactor components can withstand the harsh operating environment.
- **Passive Safety:** The design includes inherent safety features such as a "freeze valve." If the reactor gets too hot or loses power, a plug of frozen salt melts, and gravity automatically drains the liquid fuel into sub-critical dump tanks, stopping the reaction instantly without human intervention.

By mastering these complex technologies—from liquid fuel chemistry to specialized alloys—India is laying the groundwork for a sustainable, centuries-long energy future powered by thorium.

To prepare 100 GW by 2047 is practical, the Department of Atomic Energy (DAE) and Government of India have taken proactive steps to mobilise national capability and reduce delays. With the SHANTI Bill, 2025 providing an updated policy framework, structured public-private partnership models have been initiated (with regulatory oversight) to bring in Indian industry's scale, especially for timely manufacture, supply chains, and project execution.so that nuclear capacity addition can be accelerated in line with Viksit Bharat @ 2047.

The Ecosystem: "Team India" for Net Zero: Reaching 100 GW is not only about building plants. It is about using clean electricity to decarbonise everything else including transport, fuels, industry, and defence infrastructure. That is where the wider national Science and Technology ecosystem matters. Major R & D organisations such as CSIR, DRDO and others have teamed up in this national mission. A glimpse in this direction is provided for completeness's sake. Each is a topic for separate monograph.

CSIR and clean fuels: Government releases highlight how indigenous bio-jet fuel technology developed through national R&D has been demonstrated in both military and civilian aviation contexts, including a SpiceJet demonstration flight (2018) and trials linked to defence aviation, showing how indigenous technology contributes to decarbonising hard sectors.

Hydrogen and industrial decarbonisation: CSIR-CECRI has developed and commercialised a PEM-based hydrogen generator, and national collaborations continue to strengthen India's hydrogen technology base which is important because hydrogen can decarbonise certain industrial processes where direct electrification is difficult.

DRDO and practical sustainability: DRDO's bio-digester technology has scaled widely. Government information notes over 2.5 lakh bio-digesters installed in Indian Railways coaches, improving sanitation and reducing environmental discharge along tracks. DRDO has also partnered with SECI for 300 MW of solar projects across DRDO establishments, with the stated aim of creating net-zero energy campuses by 2027, a signal that clean-energy transitions are also happening inside strategic national infrastructure.

Summary: Why the 100 GW Vision Matters: India's Vision-2047 nuclear blueprint is not a stand-alone project. It is a strategy shaped by three realities:

Energy security: high dependence on imported oil and growing gas imports create vulnerability.

Clean reliability: a modern grid needs clean power that works at night, in monsoons, and during renewable lulls.

Long-term fuel advantage: India has large thorium-bearing resources and a staged programme designed to utilise them sustainably.

By combining fleet-mode PHWR construction, industry-oriented Bharat Small Reactors, and the breeder pathway that unlocks thorium, the 100 GW mission aims to provide India with clean, firm, indigenous electricity, a foundation for a carbon-constrained world and a developed India. The 100 GW vision is not just a target, it is a strategy for indigenous survival. By combining the force of nuclear power with the innovation of CSIR, the resilience of DRDO and the industrial capabilities, India is building an energy ecosystem that is robust, indigenous, and truly sustainable.

7. Conclusion — The Perfect Partnership

The climate and energy debate is often reduced to an unnecessary choice between Renewables and Nuclear, distracting us from the actual goal.

A nation depends on reliable electricity available in all hours in every season. This power keeps hospitals running, transport moving, factories productive, homes comfortable, and digital systems functioning. When the challenge is as large as climate change, the sensible question is not "either-or" but how to combine the best technologies to build a clean, secure and dependable system.

Renewables are expanding rapidly and are essential for decarbonisation. As solar and wind depend on sunlight and wind patterns, they need reliable partners that can deliver electricity when the sun sets, the wind slows, or demand suddenly rises. That is where firm, clean power becomes critical.

Every Technology Has a Role: India's clean-energy transition requires a balanced approach where each energy source contributes strategically. Coal will remain part of the mix until low carbon alternatives are widely available, making it essential to improve efficiency and control emissions in the interim.

Solar and wind - the fast builders: These are quick to deploy, increasingly affordable, capture India's abundant natural resources and reduce emissions whenever the sun shines and the wind blow, especially by cutting daytime fossil generation and lowering local pollution.

Hydro and storage - the flexible balancers: Hydropower, pumped storage, and batteries help the grid respond to changing demand and variable renewable output. They smooth the ups and downs and provide valuable flexibility, particularly during short-duration peaks.

Nuclear - the steady foundation: Nuclear plants operate steadily, day and night, through monsoons and heatwaves. They provide firm, low-carbon electricity that supports the entire system, keeping essential services and industries powered even when renewables are low.

Coal - the dependable bridge, made cleaner and more efficient: Coal-based generation will continue to support grid reliability and industrial growth in the near-to-medium term. The focus must be on modern, high-efficiency thermal technologies such as Advanced Ultra Supercritical (AUSC) plants that generate more electricity from the same fuel, leading to lower emissions per unit of power, alongside stringent pollution-control systems and better operating practices.

In short: renewables bring speed and scale, hydro and storage provide flexibility, nuclear provides round-the-clock reliability, and coal, where needed, should progressively shift to cleaner, higher-efficiency operation. A realistic clean future needs all of them, blended wisely.

The Symphony of Net Zero: Imagine India's electricity grid of 2047 not as a single system, but as a coordinated network of diverse energy sources, working in harmony to reliably meet demand. Solar and wind capture nature's variability while hydro and batteries buffer fluctuations and respond quickly to changes. Nuclear provides a steady baseline that keep the grid stable when variable sources are dropped. By combining these technologies, high renewable electricity systems can be both practical and dependable, minimizing reliance on fossil fuels

A Vision for 2047: "Team India Net Zero": India's vision for a developed, carbon-conscious nation, Viksit Bharat @ 2047 requires more than one institution or one technology. The national roadmap is increasingly shaped by the idea of a balanced system, massive renewable expansion plus firm clean power. The Department of Atomic Energy's ambition to reach 100 GW of nuclear capacity by 2047, alongside rapid renewable growth, reflects this combined approach.

But achieving this is not a solo mission. It is **Team India Net Zero**, involving:

Public institutions building large, standardised reactor fleets and strengthening the nuclear ecosystem.

Indian industry supporting manufacturing, supply chains, and potentially deploying smaller reactors for industrial decarbonisation.

Scientific and engineering organisations developing supporting technologies including materials, hydrogen, clean fuels, safety systems, and advanced manufacturing.

Citizens and communities engaging with facts, demanding transparency, supporting responsible development, and participating in a cleaner way of life.

Decarbonisation is not just a power-sector shift. It is a national transformation.

What This Partnership Delivers: A Better Life on Earth: A successful clean-energy mix is not only about climate targets. It improves daily life in visible, meaningful ways:

Cleaner air and healthier cities: Reducing coal and oil use leads to less particulate

pollution, low smog, and fewer respiratory illnesses especially for children and the elders.

Stronger energy security: The more India relies on indigenous resources such as renewables, domestic nuclear capability, and long-term thorium potential, the less vulnerable we become to imported fuel shocks and global disruptions.

Reliable power for development: Continuous, reliable electricity is essential for a modern economy. Firm clean power sustains critical sectors and infrastructure, enabling growth and raising living standards across the country.

The Choice Is Ours - From Fear to Facts: The technology exists, the roadmap is clear, and safety systems have continuously improved. The real barrier is not physics, but hesitation driven by outdated fears and incomplete information.

This booklet aims to replace fear with facts and refocus the discussion on what matters, a clean, reliable, and affordable future for the next generation. Nuclear energy is not a "mysterious threat." It is a carefully engineered tool that has powered India's safety for decades and can serve even more strongly along with renewables.

Final Thought

Solar and wind and Nuclear, working together with hydro, coal, storage, and smarter grids, offer India a clear path to clean, reliable and prosperous energy. Energy choices are not a battle, but climate change is a challenge. To win, we need the whole team working together.

Acknowledgement

This booklet reflects a shared aspiration to demystify nuclear energy and place it in the broader context of climate action and India's clean-energy transition.

We express our sincere gratitude to the scientists, engineers, technicians, and regulatory professionals of the Department of Atomic Energy (DAE) and its constituent organisations, whose dedication over the past seven decades has built India's indigenous nuclear capability with a strong emphasis on safety, self-reliance, and public responsibility. We also acknowledge the valuable contributions of the Council of Scientific and Industrial Research (CSIR) and the Defence Research and Development Organisation (DRDO), whose complementary research and technology efforts strengthen India's pathway towards a low-carbon future.

We pay respectful tribute to Dr. Homi Jehangir Bhabha, whose vision of the Three-Stage Nuclear Power Programme continues to guide India's long-term energy security, and to the many unsung workers who operate, maintain, and safeguard nuclear facilities round the clock with professionalism and discipline.

Finally, we thank the readers—students, teachers, and citizens—for engaging with the science, asking thoughtful questions, and keeping an open mind. A clean and secure energy future will be built not only by technology, but also by informed public participation and scientific temper.

Disclaimer

Educational Purpose: This booklet is prepared solely for educational and public-awareness purposes. It simplifies complex scientific and policy concepts related to nuclear energy, climate change, electricity systems, and radiation safety for a general audience. It should not be treated as a technical manual, regulatory guidance, or an academic reference document.

Accuracy and Updating of Data: Every effort has been made to ensure that statistics, targets (for example, the 100 GW vision by 2047), and technical descriptions are accurate and responsibly presented. However, scientific datasets, operational parameters, and government policies evolve over time. Numerical values and references are based on publicly available information as of February 03, 2026 and may be updated by the relevant authorities.

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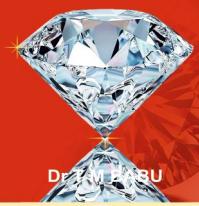


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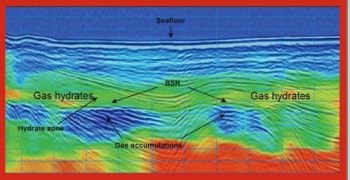
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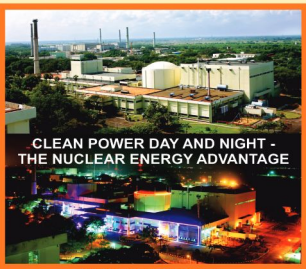
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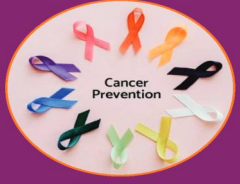


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