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MINISTRY OF POWER GOVERNMENT OF INDIA CENTRAL ELECTRICITY AUTHORITY

India SMART UTILITY Week 2024

Session : 7

Event day 3: 14 March 2024 (Thursday)

Nuclear Renaissance and the Role of SMR in Net Zero Power Systems

Presented By

CP Tiwari, Head Technology & Process Engineering, Tata Power

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- Nuclear Reactors
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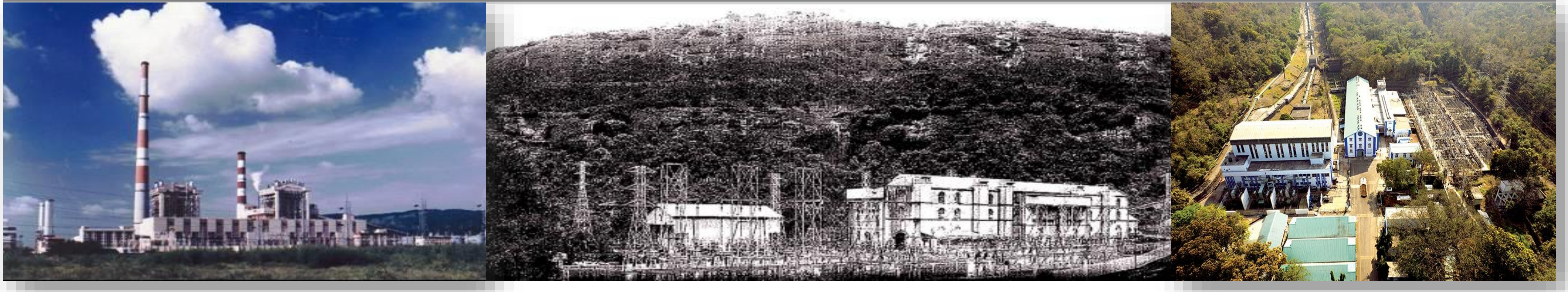
- Nuclear Value Chain - India

Vision of our founder – Mr. Jamsetji Tata

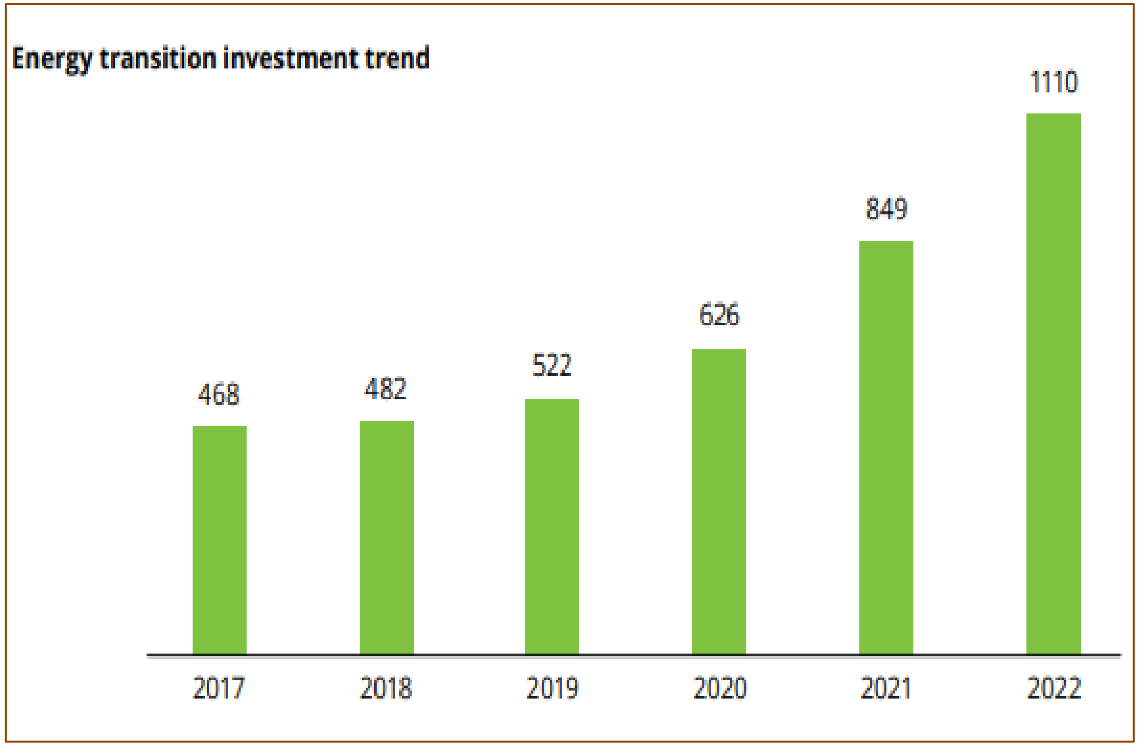


Energy Transition & Role of Nuclear Power in Decarbonization

Global Trend – Energy Transition

***Global Investment in Energy Transition in 2022:* US$ 1.1 trillion; 31% percent annual growth.**

- Investment in RE (solar and wind): **US$ 495 bn**
- Investment in Transport electrification: **US$ 466 bn**
- Other Investment includes:
    - Electrification of heat: **US$ 64 billion**
    - Nuclear Power: **US$ 40 billion**
    - Energy Storage: **US$ 16 billion**
    - CCUS: **US$ 6 billion**
    - Hydrogen: **US$ 1 billion**



* - Deloitte Report on India's energy-transition pathways A net-zero perspective September 2023

Net Zero: Role of Nuclear Energy in Global Perspective

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N Indicates pathways enabled leveraging Nuclear Power

Global GHG emissions 2020*

Power

14.7 (42%) Gt CO_2 N

Transportation

8.05 (23%) Gt CO2 N

Industry

9.1 (26%) Gt CO_2 N

Buildings

3.15 (9%) Gt CO_2 N

Decarbonization Pathways

Power
- Renewable Energy
- Nuclear Energy
- Carbon Capture Usage & Storage
- Demand Management
- H_2 based power applications and power storage

Transportation
- Zero Emission Vehicles (BEV, FCEV)
- Bio/ Low Carbon fuels
- Synfuels
- Efficiency Improvement

Industry
- Green H_2 based steel making, Nuclear Power for Hydrogen Production
- Carbon Capture Usage & Storage
- Low carbon steel making
- Material & energy efficiency

Buildings
- High efficiency Combined Heat & Power Electrification
- Energy Efficiency & Smart Buildings
- H_2 based heating

* - Deloitte Report on India's energy-transition pathways A net-zero perspective September 2023

INDIA’s Energy Transition

INDIA’s Energy Transition	Current 2023	Plans 2030	Plans 2047
Electricity in TWh Installed Capacity in GW (% RE Installed Capacity including large hydro)	1314 429 (42%)	2232 790 (67%)	5058 1955 (92%)
Industrial (TWh)	3004	4293	7601
Transportation (TWh)	1618	2258	2809
India Total Energy Need (TWh) (% Green)	7149 (<4%)	9607 (13%)	14778 (36%)

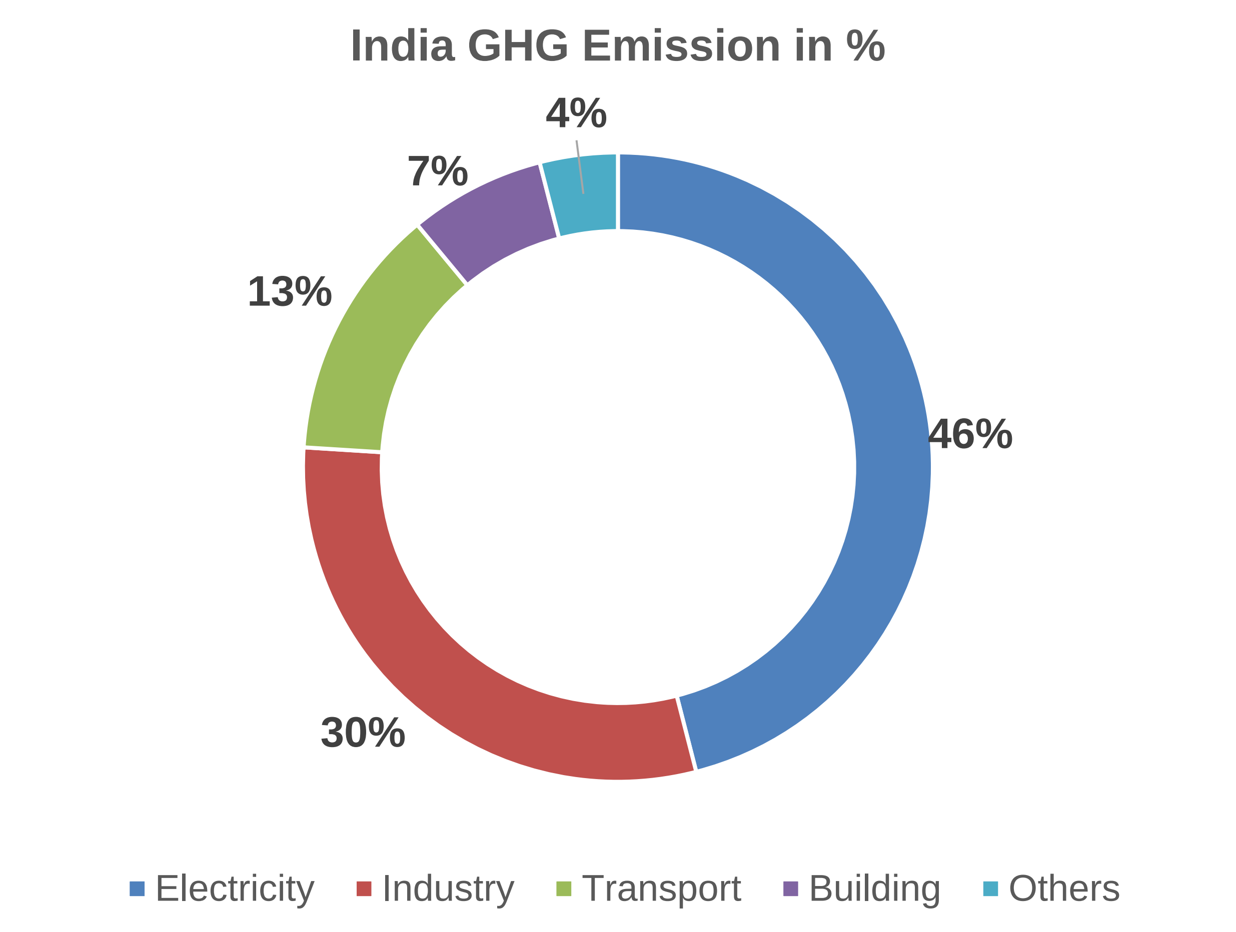
Electricity is <20% of the total energy being used in India. Out of total electricity generation in 2023, only 20% was from clean sources i.e., Renewable, Large Hydro and Nuclear.

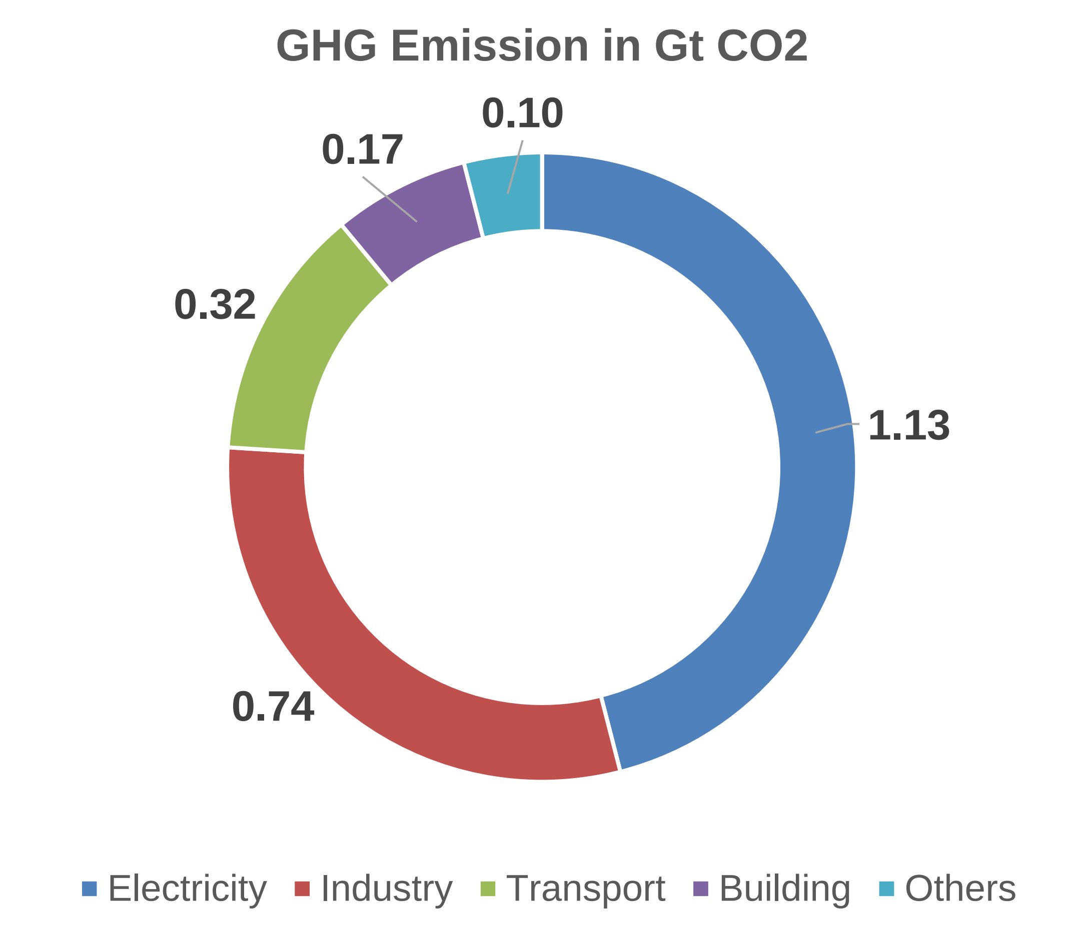
Energy from clean sources was <4% of the total energy used in 2022. It is expected clean energy proportion in total energy mix will reach to 13% by 2030 and 36% by 2047.

In 2030 & 2047, part of clean energy will be used as Electricity, and some part will be in form Green Hydrogen, Green Ammonia and Green Methanol, Green Ethanol, SAF etc. as electricity may not be able to decarbonize industrial and mobility sectors especially marine, long-haul transport and aviation.

Methanol will also be used as Energy Carrier like Hydrogen and Ammonia

India's Energy Mix & Emission Landscape





Industry needs clean electricity for Decarbonization

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INDIA Select Commodities	Total Energy for Green product, TWh/ million ton of product	Total connected load for green product, GW / Mt PA	INDIA Demand -2030 MTPA	Total Energy for Green Product TWh	In GW Electricity Production
Steel	7.98	0.96	300	2395	289
Aluminium	63.78	7.68	6	383	46
Copper	29.43	3.55	3	88	11
Cement	1.59	0.19	660	1048	126
Silicon	336.78	40.58	1	337	41
Aluminimum	14.85	1.79	12	178	21
Green Hydrogen	60	7.23	3	180	22
Grey Hydrogen (SMR Route)	34.08	4.11	3	102	12
Total Clean Electricity Demand for Decarbonization					**568**

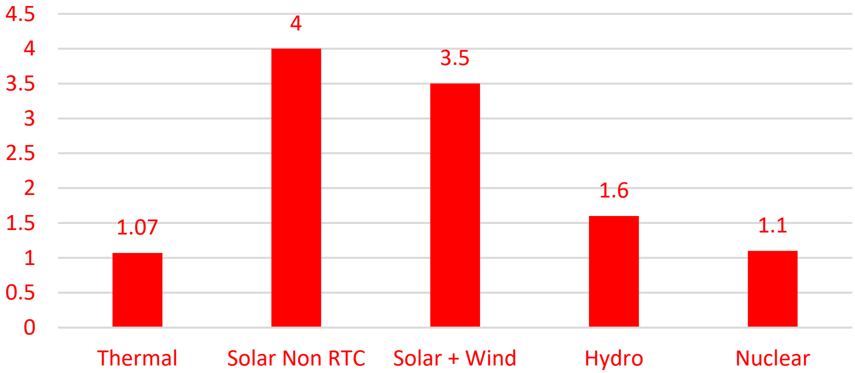
These numbers only include CO_2 capture but not for transport sequestration or reuse – for which energy needed would be additional.

Challenges in energy transition

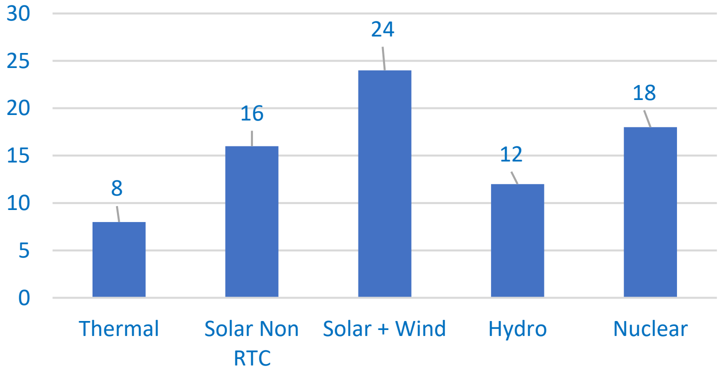
- Facilitating low-cost financing
- Developing manufacturing ecosystem
- Capacity increase
- Relaxation of trade barriers
- Create a framework to enable private-sector participation in the nuclear power sector.
- Promote new technologies, such as Small Modular Reactor (SMR).
- Facilitate faster land acquisition and clearances

Nuclear can provide an alternative with competitive LCOE

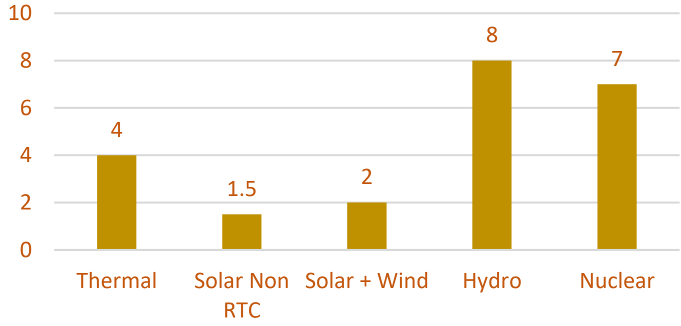
Installed Capacity to provide 1 MW Net Power



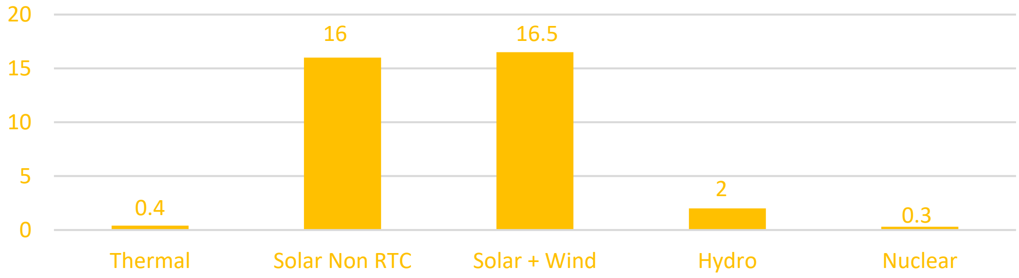
Capex in Rs Cr for 1 MW



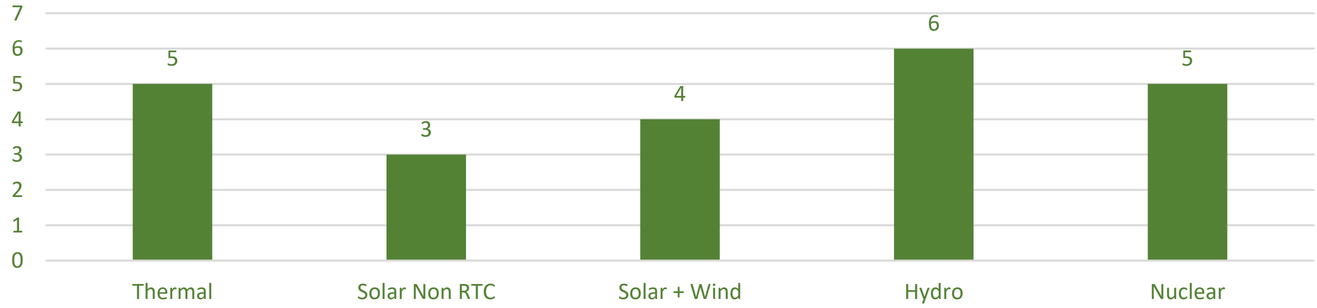
Construction Time in Year



Land Requirement for 1 MW Installed Capacity



LCOE in Rs / KWH



- **Nuclear similar to thermal in terms of land requirement, but is significantly lower than thermal including land use for mining**
- **Cost per MW of nuclear is ~2x of thermal power, but LCOE is comparable with thermal.**
- **LCOE of Nuclear is higher than solar or solar + wind combination, Nuclear Power is dispatchable.**
- **IAEA reports lifecycle emissions of only 5.1-6.4 g/kWh of nuclear power, which is ~1% of thermal and less than 50% of Wind & Solar emissions**

Nuclear Reactors

Type of Nuclear Reactors

Based on Nuclear Reaction

1. **Fission** – all commercial power nuclear reactors are Fission reactors. Fuel used as Uranium or Plutonium. Thorium Cycle is also possible. These can be further sub-divided into:
    - Thermal Neutron Reactors and
    - Fast Neutron Reactors
2. **Fusion -** fusion power produced by nuclear fusion of elements such as the deuterium isotope of hydrogen. Not in much use

Based on Type of Coolant

1. **Water Cooled Reactors:**
    - Light water cooled Reactors – used in Western Countries e.g.
        - ✓ Pressurised Water Reactor (PWR)
        - ✓ Boiling Water Reactors (BWR)
        - ✓ Supercritical Water Reactor
    - Heavy water cooled Reactors used in India, Argentina, China, South Korea e.g.
        - ✓ Pressurised Heavy Water Reactor
2. **Liquid Metal Cooled Reactors**
3. **Gas Cooled Reactors**
4. **Molten Salt Reactors**
5. **Organic nuclear reactors**

Based on Generation

1. **Generation I** - early prototypes design
2. **Generation II** - most current nuclear power plants, 1965–1996)
3. **Generation III** - evolutionary improvements of existing designs, 1996–2016
4. **Generation III+** - evolutionary development of Gen III reactors, offering improvements in safety over Gen III reactor designs, 2017–2021
5. **Generation IV** - technologies still under development; unknown start date, possibly 2030

Key concerns with large-scale nuclear plants

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Nuclear safety risk mitigation measures limit locations

- **Large exclusion zones (1 km from center of reactor)**
- **Emergency Planning Zone (16 km from center of reactor)**
- **Large-scale water source needed**
- **Acceptability to public / local communities**

Long construction timelines (min 6-7 years), especially due to regulatory requirements and surprises during construction (e.g., seismic protection)

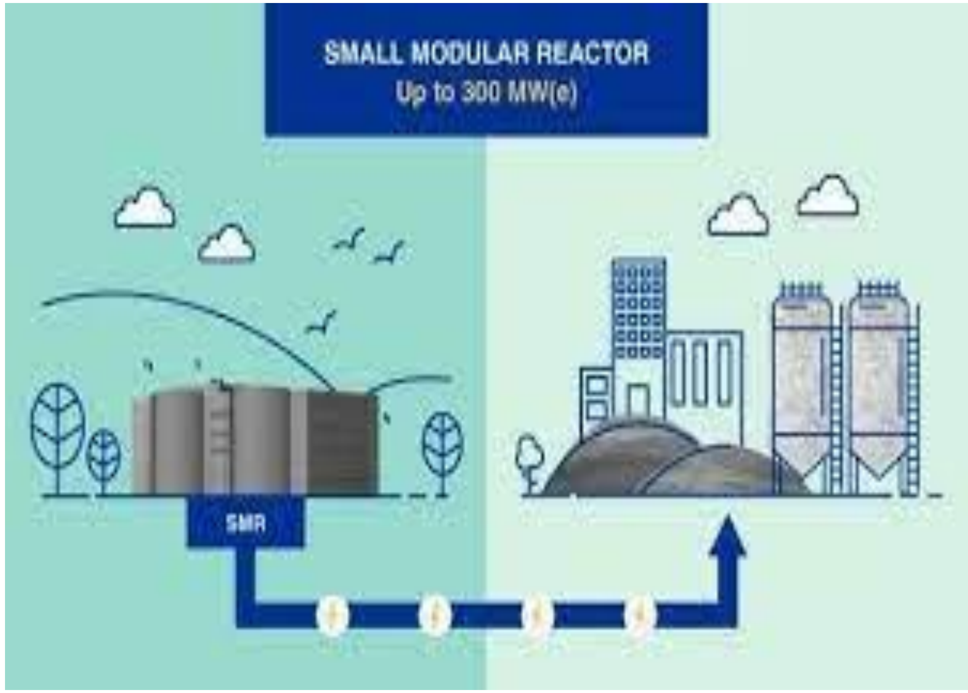
High capex cost – typically INR 10,000+ Cr for 700 MW

Primarily only for **grid-scale applications**

Acceptability to public/ local communities

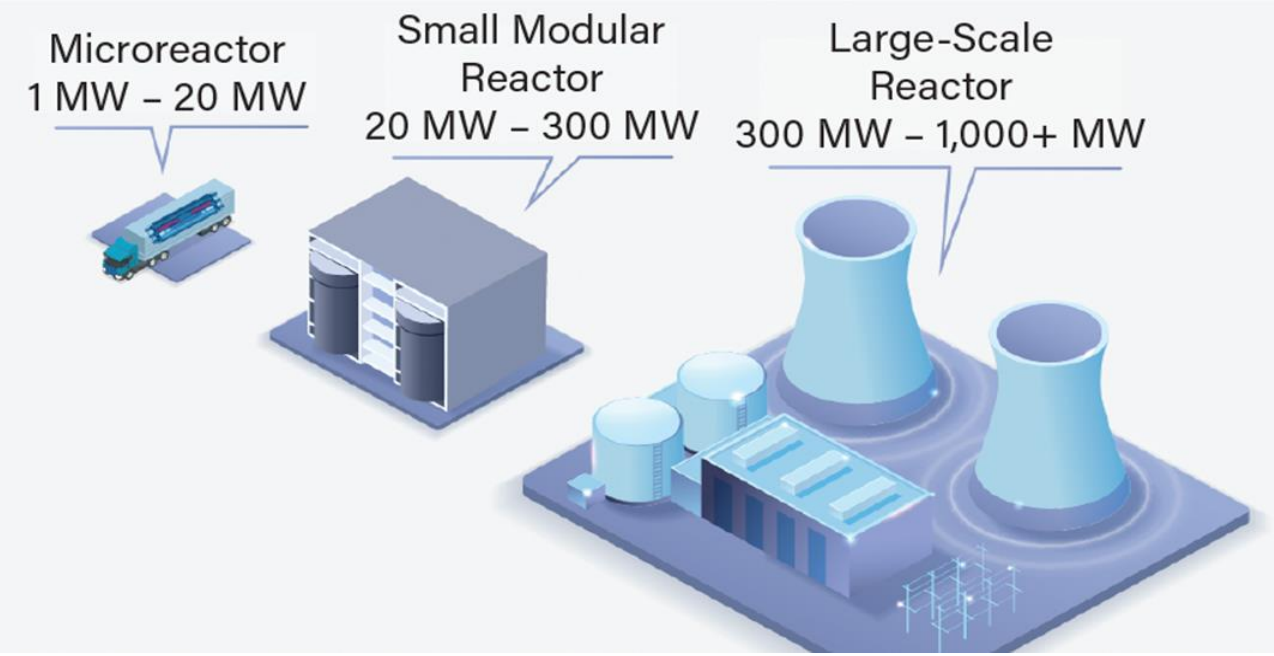
Potential security/ safety failures due to presence of large amount of fuel/ waste

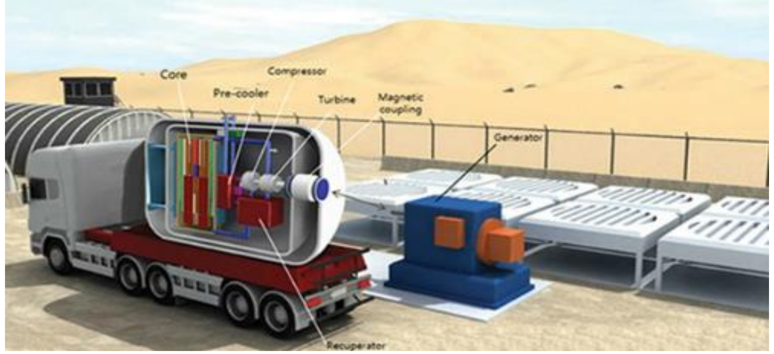
Dependence on imported Uranium – potential for embargo/ trade actions



Small Modular Reactors

Small Modular Reactors (SMRs)





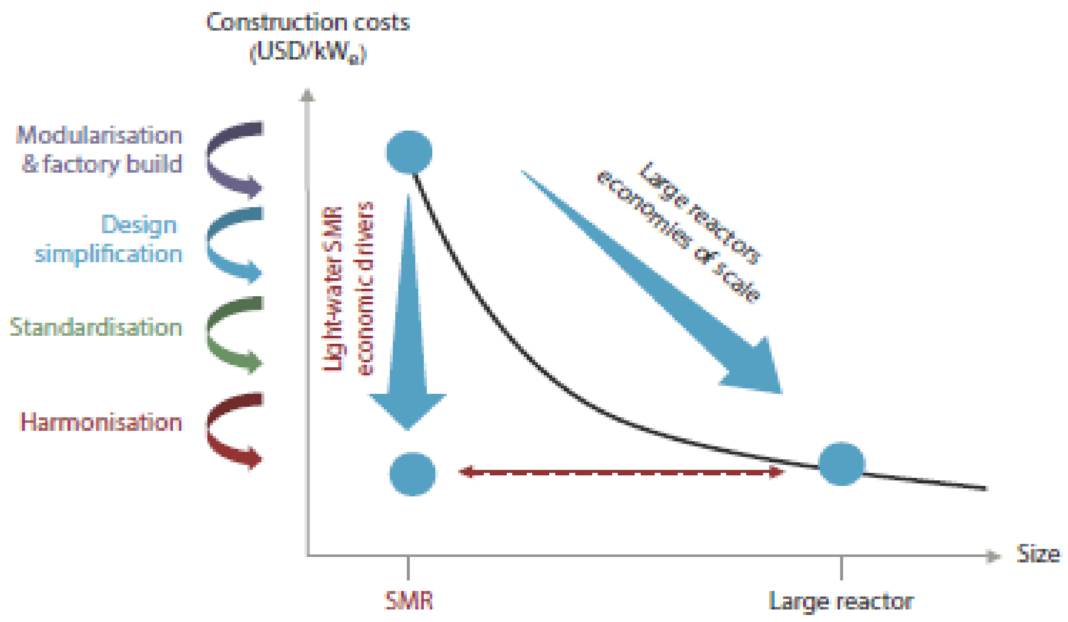
- **Small Modular Reactors** are reactors with up to 300 MWe of output with a standard design
- SMRs are typically **built in factories, and assembled on site** (*vs full-scale nuclear reactors which are constructed in-situ*)
- Small Modular Reactors have been in operation in **naval applications for decades** *(e.g., US aircraft carriers & Russian nuclear submarines)*

Large Nuclear Reactor Vs SMRs

	700 MW Reactor	100 MW SMR
Potential use cases	Grid-scale power generation	• Captive use (power, heat) • Off-grid/ island power generation • Seawater desalination • Hydrogen production
Exclusion zone	1 km radius; 16 km Emergency Planning Zone	To be firmed by DAE/AERB (indications are it could be limited to facility boundary)
Water requirement	100,800 m^3/ day	14,400 m$^{3/}$day
Nature of manufacturing	Construction-on-site	On-site assembly of pre-fabricated components
Extent of bespoke machinery	Very high	Low – due to standardization of design
Project timeline	6-7 years	• 4-5 years for initial reactors till stabilization of design & delivery process • <3 years (in series production)
Investment/ Unit (INR Cr)	>11,500	<2,000
Fuel options	Uranium (Imported & Domestic)	**Uranium (Imported & Domestic)**
Amount of fuel on-site (including spent fuel)	50-70 T of Uranium (Basis VVER 1000 MW reactor)	**10-15 T of Uranium (basis SMART reactor)**

Key Economic Drivers of SMR

1. **Simplification** – Passive mechanism improvements, greater design integration, reduced number of components
2. **Standardization** – Lower output means lesser site dependency and more standardization
3. **Modularization** – techniques tailored to logistics and transportation standards; 60~80% factory fabrication; advanced manufacturing techniques including additive manufacturing
4. **Harmonization** – regulatory and industrial harmonization provides access to global markets



Source: NEA (2020).

- ❑ Cost economics of SMRs is yet to be proven.
- ❑ Despite high investments into SMR development, no SMRs are yet in commercial operation.
- ❑ As world struggles with the immense challenges of transitioning away from fossil fuels, OEMs across the globe are extensively working on development of SMRs.

Small Modular Reactors (SMRs) Features

International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA) defines SMR as those nuclear reactors producing less than 300MWe per module.

- Small – physically a fraction of the size of a conventional nuclear power reactor.
- Modular – making it possible for systems and components to be factory-assembled and transported as a unit to a location for installation.
- Reactors – harnessing nuclear fission to generate heat to produce energy.

- **Small Power Output**: Multiple Units at same location with more operational flexibility
- **Modularity in Design & Compact architecture**: Modules to be produced in factory, high quality standards, less construction time, easy transport, less footprints, less cost*
- **Passive Safety Concepts**: Less reliance on active safety systems and additional pumps as well as AC power for accident mitigation.
- **Smaller Size**: Smaller radioactive inventory in a reactor
- **Potential for sub-grade (underground or underwater) Installation**: Provides more protection from natural (*e.g.*, seismic or tsunami according to the location) or man-made (*e.g.*, aircraft impact) hazards.
- **Lower requirement of cooling water**: Suitable for remote regions and for specific applications such as mining or desalination.
- **Ability to remove reactor module** or in-situ decommissioning at the end of the lifetime.
- **Less Frequent Re-fueling****

' - Though it is being claimed that cost will be less, it is yet to be proved.*

*'** - Conventional plants require refueling every 18 -24 months, Ultra Safe Nuclear Corporation claims 5MW Micro modular reactor requires no refueling in 20 years operational lifetime*

Small Modular Reactors – Type (1/2)

The IAEA 2020 edition explains six (6) SMR, arranged in the order of the different types of coolants, the neutron spectrum adopted. The sixth is dedicated for microreactors, as a new sub-category within SMR.

1. Land-based water-cooled SMRs

- This presents notable water-cooled SMR designs from various configurations of light water reactor (LWR) and heavy water reactor (HWR) technologies for on-land on-the-grid applications.
- These designs represent the mature technology considering most of the large power plants in operation today are of water-cooled reactors.

2. Marine-based water-cooled SMRs

- This presents concepts that can be deployed in a marine environment, either as barge-mounted floating power unit or immersible underwater power unit. This unique application provides many flexible deployment options.

3. High Temperature Gas Cooled SMRs

- HTGRs provide high temperature heat (≥750°C) that can be utilized for more efficient electricity generation, a variety of industrial applications as well as for cogeneration.

4. Fast Neutron Spectrum SMRs

- This part presents eleven (11) SMR designs that adopt fast neutron spectrum with all different coolant options, including sodium, heavy liquid metal (e.g. lead or lead bismuth) and helium-gas.

Small Modular Reactors (SMRs) – Types (2/2)

5. Molten Salt SMRs

- This part highlights ten (10) SMR designs from molten salt fueled and cooled advanced reactor technology (MSRs), which is also one of the six Generation IV reactor designs.
- MSRs promise many advantages including enhanced safety due to salt's inherent property, low-pressure single-phase coolant system that eliminates the need of large containment, a high temperature system that results in high efficiency, and flexible fuel cycle.

6. Micro-sized SMRs

- An unprecedented development trend emerged on very small SMRs designed to generate electrical power of typically up to 10 MW(e). The range of electrical output is between 1.5 to 5 MW(e), the adopted enrichment is between 4% up to 19.75%, with long fuel cycle between 36 months up to 20 years.
- They are from different types of coolant, including HTGRs and designs that use heat pipes for heat transport.
- Several designs are undertaking licensing activities in Canada and the United States for planned near-term deployment.
- In 2019 a site application was submitted by Global First Power for a single small modular reactor using USNC's Micro Modular Reactor (MMR) technology at the Chalk River Laboratories site.
- Microreactors serve future niche electricity and district heat markets in remote regions, mining, industries and fisheries that for decades have been served by diesel power plants.

Small Modular Reactors (SMRs) - Safety Features

Passive Safety Features: Operates without human interventions, less reliance on active safety system, No active safety injection system. Coolant systems can use natural circulation – convection – to eliminate pumps that could break down. Convection can keep removing decay heat after reactor shutdown.

Negative temperature coefficients in the moderators and the fuels keep the fission reactions under control, causing the reaction to slow as temperature increases.

Some SMRs may need an active cooling system to back up the passive system, increasing cost.

Additionally, SMR designs have less need for containment structures.

Smaller reactors would be easier to upgrade.

Multiple candidates in SMR today – No dominant design globally

- **Water Cooled**
  - Land based
  - Marine based

- **Non-Water Cooled**
  - High temperature gas cooled
  - Molten salt
  - Fast neutron spectrum

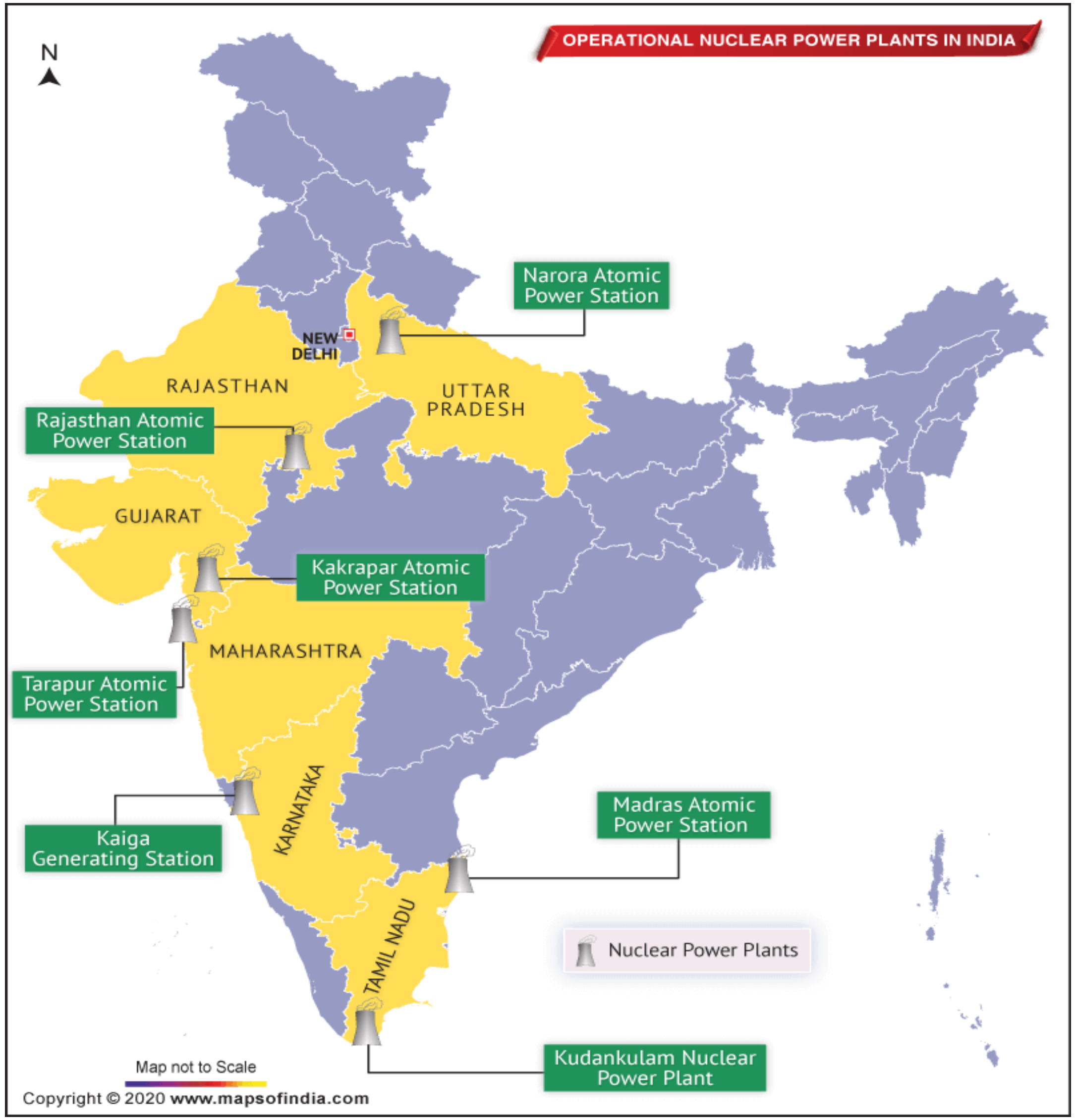
IAEA has published data on 71 SMRs of which 61% are conceptual phase, 25% are in basic or detailed design phase and rest in certification, licensing stages.

Only one marine based SMR and two HTGRs are in operation and 1 land-based water cooled SMR is in construction phase.

Source: Media reports

Illustrative list of SMRs under development

NAME	CAPACITY	TYPE	DEVELOPER
NuScale	60 MWe	Integral PWR	NuScale Power
SMR-160	160 MWe	PWR	Holtec, USA+ SNC-Lavalin, Canada
RITM 200/400	55 MWe / 105 MWe	Integral PWR	OKBM Afrikantov-Rosatom, Russia
UK SMR	470 MWe	PWR	Rolls-Royce, UK
ACP100/ Linglong One	125 MWe	Integral PWR	NPIC/ CNPE/ CNNC, China
Nuward	2 x170 MWe	PWR	EDF, France
SMART	100 MWe	Integral PWR	KAERI, South Korea
ARC-100	100 MWe	Sodium FNR	ARC with GE Hitachi, USA
Integral MSR	192 MWe	MSR	Terrestrial Energy, Canada
RITM-200M	50 MWe	Integral PWR	OKBM, Russia
BANDI-60S	60 MWe	PWR	Kepco, South Korea
Xe-10	75 MWe	HTR	X-Energy, USA
ACPR50S	60 MWe	PWR	CGN, China



Nuclear Value Chain - India

India has a mature nuclear ecosystem, primarily controlled by the govt

Central Government agency for nuclear energy policy; owner of fuel

Regulator of the nuclear industry; formulation of rules & compliance monitoring

Designer, Integrator, Manufacturer and Licensor of Nuclear Reactors
- *More cost effective than global players*

Operator of nuclear plants

Govt is actively working for private participation in Nuclear Power Generation

THANK YOU

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Links/References (If any)

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