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A REPORT ON THE ROLE OF SMALL MODULAR REACTORS IN THE ENERGY TRANSITION



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NITI Aayog

A REPORT ON

THE ROLE OF SMALL MODULAR REACTORS IN THE ENERGY TRANSITION

Knowledge Partners

BARC

TATA CONSULTING ENGINEERS LIMITED

MAY 2023

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ABOUT NITI AAYOG

The National Institution for Transforming India (NITI Aayog) serves as the apex public policy think tank of the Government of India, and the nodal agency tasked with catalyzing economic development, and fostering cooperative federalism through the involvement of State Governments of India in the economic policy-making process using a bottom-up approach. NITI Aayog is developing itself as a state-of-the-art resource centre with the necessary knowledge and skills that will enable it to act with speed, promote research and innovation, provide strategic policy advice for the government, and deal with contingent issues. It is supported by an attached office, Development Monitoring and Evaluation Office (DMEO), a flagship initiative, Atal Innovation Mission (AIM), and an autonomous body, National Institute of Labour Economics Research and Development (NILERD).

ABOUT DAE

The Department of Atomic Energy (DAE) came into being on August 3, 1954 under the direct charge of the Prime Minister through a Presidential Order. According to the Resolution constituting the Atomic Energy Commission (AEC), the Secretary to the Government of India in the DAE is ex-officio Chairman of the AEC. DAE has been engaged in the development of nuclear power technology and application of radiation technologies in the fields of agriculture, medicine, industry and basic research. DAE comprises five research centers, three industrial organizations, five public sector undertakings and three service organizations. It has under its aegis two boards for promoting and funding extra-mural research in nuclear and allied fields, mathematics and a national institute (deemed university). It also supports eight institutes of international repute engaged in research in basic sciences, astronomy, astrophysics, cancer research and education.

ABOUT TCE

Tata Consulting Engineers Limited (TCE) is India's Leading Integrated Engineering Consultant providing Concept to Commissioning services. With 10,000+ projects delivered in more than 55 countries, the company has a double-digit five-year CAGR. TCE is amongst the top two consultants in its core sectors - Power, Infra and Resources. It is a well-diversified firm with equal distribution between domestic and international projects. TCE continues to be a part of India's strategic projects across infra, transportation, nuclear, power, defence, space and urbanization. Services offered by TCE include Design & Engineering, Project Management & Safety, Digital & Advanced Technology, Procurement Management, etc.

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence
ARDP	Advanced Reactor Demonstration Program, USA
ARIS	Advanced Reactor Information System, IAEA
BWR	Boiling Water Reactor
CAREM	Central Argentina de Elementos Modulares
CfD	Contract for Differences
CNSC	Canadian Nuclear Safety Commission
CO_2	Carbon Dioxide
COP	Conference of Parties (UNFCCC)
CRDM	Control Rod Drive Mechanism
CRP	Coordinated Research Project, IAEA
CSA	Comprehensive Safeguards Agreement
D&D	Decommissioning & Decontamination
DOE	Department of Energy, USA
EDF	Electricité de France Company
EIA	Environmental Impact Assessment
EPC	Engineering, Procurement and Construction
EPZ	Emergency Planning Zone
FOAK	First of a Kind
FR	Fast Reactor
GDA	Generic Design Assessment, ONR, UK
GEH	GE Hitachi Nuclear Energy
GEN IV	Generation IV
GFR	Gas Cooled Fast Reactor
GHG	Green House Gas
Gt	Giga-tonnes

GWe	Gigawatt electric
HTGR	High Temperature Gas Cooled Reactor
IAEA	International Atomic Energy Agency
ICCC	Integrated Command and Control Centre
IEA	International Energy Agency
IIoT	Industrial Internet of Things
IPCC	Intergovernmental Panel on Climate Change, UN
IPWR	Integrated Pressurized Water Reactor
ISED	Innovation, Science and Economic Development, Canada
LCOE	Levelized Cost of Electricity
LFR	Lead Cooled Fast Reactor
LMFR	Liquid Metal Cooled Fast Reactor
LR	Large Reactor
LWR	Light Water Reactor
MDEP	Multinational Design Evaluation Programme
ML	Machine Learning
MR	Microreactor
MoC	Memorandum of Cooperation
MoU	Memorandum of Understanding
MSR	Molten Salt Reactor
MWe	Megawatt electric
NDT	Non Destructive Testing
NEA	Nuclear Energy Agency
NHSI	Nuclear Harmonization and Standardization Initiative
NM	Nuclear Material
NOAK	Nth of a Kind
NPP	Nuclear Power Plant
NPT	The Treaty on the Non-Proliferation of Nuclear Weapons
NRC	Nuclear Regulatory Commission, US
NSSS	Nuclear Steam Supply Systems
NZE	Net Zero Emissions
NWFZ	Nuclear-Weapon-Free Zone
ONR	Office for Nuclear Regulation, UK

PHWR	Pressurized Heavy Water Reactor
PPA	Power Purchase Agreement
PRIS	Power Reactor Information System, IAEA
PSR	Periodic Safety Review
PWR	Pressurized Water Reactor
QA/QC	Quality Assurance and Quality Control
R&D	Research and Development
RE	Renewable Energy
RPV	Reactor Pressure Vessel
SBD	Safeguards by Design
SDG	Sustainable Development Goal
SFR	Sodium Cooled Fast Reactor
SG	Steam Generator
SIF	Strategic Innovation Fund, Canada
SME	Small and Medium Enterprises
SMR	Small Modular Reactor
SOP	Standard Operating Procedure
SSC	Systems, Structures and Components
TEA	Techno Economic Assessment
TRL	Technology Readiness Level
TWG	Technical Working Group, IAEA
UN	United Nations
UNFCCC	UN Framework Convention on Climate Change
UO_2	Uranium Oxide
USD	US Dollar
USNRC	United States Nuclear Regulatory Commission
VOA	Voluntary Offer Agreement
VC	Venture Capital

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Message

The developing world is at the cusp of an unprecedented experiment, wherein it is pioneering a development paradigm of industrialization and decarbonization simultaneously. Historically, industrial development has been synonymous with fossil fuel consumption and dependency. Green industrial development poses the challenging trilemma of energy security, energy equity and sustainability. Increasing penetration of renewables in the energy mix has also led to the realization that energy security is intertwined with critical minerals security. We need affordable, reliable, plentiful and clean energy to power the engines of a new green world economic order.

Amongst the low- carbon sources of electricity, nuclear power has been especially endowed with low lifecycle GHG emissions and low material intensity per unit of electricity generation. Hence, it makes pragmatic sense to consider the potential role that this abundant energy source can play in decarbonising the world economy. Besides electricity, advanced nuclear reactors such as Small Modular Reactors (SMRs) also expand the prospects of the application of nuclear energy for providing clean water, thermal comfort, hydrogen and heat for industrial processes. Thus, nuclear energy augments the synergy between climate action and sustainable development goals.

But harnessing nuclear energy is a capital- intensive process, and public investments alone will likely fall woefully short of the requirements. There is a broad consensus that decarbonization, which is a multi-trillion dollar process, needs to be steered by private investments. The same proposition, when applied to the nuclear industry, would imply the development of a coherent ecosystem for advanced technologies like SMRs. Public policy and regulations are the cornerstone for the establishment of an industrial ecosystem. Hence, it is imperative that the harmonization of regulations, codes and standards for emerging technologies that have global value chains is taken up on a fast-track mode.

The study report examines the critical question of how to leverage an industrial ecosystem, backed by regulatory harmonization and private investment, to achieve the goal of energy transition at an accelerated pace through the medium of SMRs.

I thank the teams at NITI Aayog, Department of Atomic Energy, Bhabha Atomic Research Centre and Tata Consulting Engineers Limited for preparing this publication in a record time frame.

(Suman Bery)

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Foreword

The challenge posed to welfare of the planet by the climate change has necessitated increasing global efforts to limit temperature increase to 1.5°C above pre-industrial levels as enunciated in the Paris Agreement. Ambitious climate action commitments have been made by nations across the world in the form of Nationally Determined Contributions (NDCs) and long term low carbon development strategies. India's G20 presidency with the theme of 'One Earth, One Family, One Future 'has the spirit of coming together for achieving common and concrete objective. The Energy transition requires rigorous discussions on the transition pathways and clean technologies for its adoption.

The energy transition strategy clearly identifies the role of Nuclear Power in basket of energy mix, basically to meet the variations in energy demand and interrupted supply from Renewables. Small-Scale Modular Nuclear Reactors has been identified as the emerging low cost, low carbon technology to meet such scenarios of fluctuating demand and supply.

The report focuses on various aspects of Small Modular Reactors (SMRs) which can provide greater flexibility in the use of nuclear energy and offer the benefit of having a low carbon footprint. SMRs typically have a power capacity ranging from less than 30 MW(e) to 300 MW(e). Their components, systems, and structures can be manufactured in a factory before being transported as modules to sites for installation to reduce the length of the building schedule – thereby economizing on resources. SMRs may also be suited to countries which have smaller grids and for whom the construction of large nuclear plants is not feasible. Given the increasing penetration of variable renewable energy and decentralized electricity generation, SMRs is being explored to provide grid flexibility along with base load power.

For harnessing the above benefits of SMRs, its cost-effectiveness and safety will have to be demonstrated. A robust policy framework addressing issues such as safeguards, techno-commercial viability, regulation, safety and research & development (R&D) is required so that the foundations for an SMR ecosystem

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are laid. A framework for large nuclear reactors is already in place in several countries which can be leveraged while ensuring that any concerns specific to SMRs are fully addressed.

One of the primary obstacles to the rapid development and deployment of SMRs continues to be financing. There is limited investment in the sector as a result of the high degree of cost uncertainty in SMR, which is typical of new technologies in the early stages of development and deployment. Both the public and the private sector have a key role to play in this sector. An enabling framework in the form of seed capital for innovation, reliable supply chain, successful 'proof of concept 'demonstrations, demand creation and conducive policy environment can channelize global investor interest.

This report is an effort towards initiating a discussion on the issues highlighted above under India's G20 Presidency. It is hoped that the report will lead to a wider dissemination of key issues with respect to SMRs among government, industry and other stakeholders. I congratulate all who have contributed in the preparation of this report.

VKSaraswat

(Dr. V K SARASWAT)

New Delhi
27.04.2023

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Message from the CEO, NITI Aayog

G20 SMR report: The Role of Small Modular Reactors in Energy Transition

It's an established fact that global warming is a function of cumulative global anthropogenic emissions and a near-linear relationship exists between cumulative CO_2 emissions and the increase in global surface temperature. Thus, it is essential for global CO_2 emissions to reach net- zero to arrest the temperature increase.

As, over 70% of the greenhouse gas emissions are contributed by the energy sector globally—through consumption of fossil fuels in industry, transport, buildings, cooking and agriculture—it is essential to decarbonize these sectors. While decarbonization can happen in many ways, electrification of demand side sectors is one of the cheapest and easily scalable options to attain this goal. But the conundrum lies in the fact that over 60% of the electricity generation worldwide is itself dependent on fossil fuels. To meet the climate objective, it is essential to consistently increase the share of low carbon energy in the system. Solar and wind power are associated with variability and need storage solutions to make them more evenly available. Nuclear power can provide a stable and base load power in the event of reduced coal thermal power.

Nuclear energy contributes about one-tenth in the global electricity mix. New technological advancements in the nuclear industry like Generation IV Reactors and Small Modular Reactors (SMRs) offer the next level of possibilities for scaling up the adoption of nuclear energy. SMRs, for instance, can be a better option not just for electricity generation, but also for non-electrical applications like desalination of water, low carbon hydrogen production, space heating and industrial processes. In addition to base-load power, they can also be used for providing flexibility to power systems that helps in grid integration of renewables.

The study report on "The Role of SMRs in Energy Transition" highlights how SMRs can effectively complement the significant contribution of large reactors in accelerating the process of energy transition for achieving climate goals. I congratulate the teams from NITI Aayog, Department of Atomic Energy, Bhabha Atomic Research Centre and Tata Consulting Engineers Limited for coming out with this timely publication. I hope that the report would serve as a useful resource for all the relevant stakeholders.

B.V.R. Subrahmanyam
(CEO, NITI Aayog)

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Message

Nations across the globe have announced their net-zero targets and several other climate action commitments. Each country is pursuing its own pathway to achieve its net zero goal depending upon its energy sources endowments, energy demand for legitimate development aspirations and available technological options. Energy security has to be ensured while progressing towards energy transition. Keeping this in view, the Ministry of Power fully recognises the importance of SMR technologies for the energy transition as it may offer flexible operations. This report offers an overview of licensing frameworks for SMRs and insights towards a harmonized regulatory approach, while underscoring the importance of standards & safety, safeguards and harmonization of licensing and regulatory practices. I congratulate NITI Aayog, TCE and DAE for this report. We need to quickly consider and implement its recommendations suitably.

Alok

(Alok Kumar)

RIGHT TO INFORMATION

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व
सचिव, परमाणु ऊर्जा विभाग
Chairman, Atomic Energy Commission
&
Secretary, Department of Atomic Energy

Preface

The overarching goal of the Paris Agreement is "to hold the increase in the global average temperature to well below 2°C" and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels". Various economics are working towards reaching the net zero emissions by 2050. Mitigating climate change necessitates a global revamp in energy generation technologies and means of energy consumption in terms of increasing the share of low-carbon technologies, enhanced energy efficiency and electrification of end-use demand. Under G20 Presidency, climate change is a key priority for India with a particular focus on climate, finance, technology, and ensuring just energy transitions for developing nations across the globe.

As a source of base load power generation, the rapid scale-up of nuclear energy can be one of the best strategies for energy transition, given its low carbon footprint. Several countries have had given reconsideration of nuclear considering the current geopolitics and the energy security concerns. However, the share of nuclear energy in global energy mix is minimal and its growth rate hinge on factors like degree and speed of innovation in the advanced reactor designs and nuclear waste management technologies and project financing. Advancements in nuclear reactor technologies in the current form of large reactors and its concurrent miniaturization in the form of Small Modular Reactors (SMRs), provided with robust passive safety features, may pick up momentum to achieve sustainable growth of nuclear industry. SMRs are expected to make a meaningful contribution during the energy transition phase.

The driving forces in the development of SMRs are their specific characteristics such as modularization, factory-build capability, scalability to match incremental power demand, flexibility and non-electrical applications. Governments, regulators, industry groups, academic institutions and both public and private companies have to actively participate for developing SMR technology for its early deployment. However, SMR industry needs to find its way through early challenges of technology demonstration, availability of special material and manufacturing techniques, project funding and harmonization of regulatory frameworks and licensing processes. Given such challenges and the need to sustain the growth of SMR industry for the achievement of long-term climate goals, it is essential to establish ecosystems for SMR.

The study report highlights the importance of energy transition and atleast propagate debate for the development of nuclear.

I hope this report will serve as a crucial resource for Regulators, Government, Technology vendor and other concerned stakeholders for realizing the full potential of SMRs in energy transition, duly factoring in concerned opportunities and challenges.

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MESSAGE

“As the world transitions towards sustainable energy, harnessing potential of nuclear power through Small Modular Reactors (SMRs) can pave the way for a cleaner and brighter future. By prioritizing research and development in this sector, the global community can help address vital issues such as climate change and energy security. SMRs offer a flexible solution for meeting energy needs. Release of this report during India’s G20 presidency can enable fruitful dialogue on SMRs and contribute towards global effort to build a sustainable and resilient energy system for all with greater participation of private players”.

Mr. Amitabh Kant

G20 Sherpa, G20 Presidency, India

"Though it is widely recognized that nuclear power will be an integral portion of the world’s energy mix, there is still a need to exploit its full potential through research and innovations in advanced reactor technologies such as SMRs while maintaining the highest standards in safety and security. This report clearly highlights the role of nuclear energy in energy transition by exploring SMR technologies and outlining their challenges and benefits. This report talks about harmonization of regulatory and licensing processes, waste management and exploring low cost finance for developing manufacturing ecosystem, and bringing in public as well as private capital to accelerate the development and deployment of SMRs. I am delighted to welcome this report on behalf of BARC".

Dr. Ajit Kumar Mohanty

Director, BARC

“The report provides an excellent overview of various designs and technology types of SMRs under different stages of development globally as well as challenges and opportunities for exploring SMR as an option for clean energy transition. Sharing technological breakthroughs, lessons learnt, best practices and joint implementation through public and private collaborations will help in developing a vibrant SMR ecosystem. It gives me great pleasure to welcome and commend this report on the role of SMRs for the energy transition around the globe”.

Mr. B. C. Pathak

Chairman, NPCIL

"NTPC recognizes nuclear energy as one of the most important components of the Clean Energy Transition and believes it will play a significant role in the future energy mix. Adoption of nuclear energy can be accelerated with Small Modular Nuclear Reactors due to their inherent advantages of safety, flexibility, cost-effectiveness, and modularity.

The report prepared by NITI Aayog, DAE and TCE describes applications of SMRs for green-field and brown-field power projects at both grid and off-grid locations. Taking advantage of existing rail connectivity, power evacuation infrastructure and availability of land and water, SMRs could be a cost-optimal clean energy solution through the retrofit of old fossil-fuel-fired power stations.

With modularization and factory-built concepts, SMRs offer a significant complementary role over large reactors. The report provides actionable items for all stakeholders with strategies for the early deployment of SMRs.

I compliment NITI Aayog, DAE and TCE for bringing out an excellent report".

Mr. Gurdeep Singh

CMD, NTPC

The fourth industrial revolution has two key facets, the Internet and Energy. Both are fundamental to how nations, industries, value chains, and economies evolve. As we commit ourselves to clean, continuous, and green energy, pathways for energy transition will evolve, and nuclear has a promising potential amidst this. Towards accelerating nuclear energy adoption, Small Modular Reactors (SMRs) are viable energy multipliers and have the potential to decarbonize industries, retrofit old fossil-fuel fired plants and provide continuous and reliable power to the smart grid. While traditional large-sized nuclear reactors are a must, we need to evaluate the potential of SMRs. This report covers technology development, policy, challenges, and potential SMR roadmap.

Tata Consulting Engineers (TCE) has been associated with the Department of Atomic Energy (DAE) for the last five decades. Under the leadership and vision of Niti Aayog, TCE is proud to contribute towards this report, "The Role of Small Modular Reactors in the Energy Transition", during the 3rd ETWG Meeting under India's G20 Presidency.

Mr. Amit Sharma

Managing Director & CEO, TCE

EXECUTIVE SUMMARY

With the advent of clean energy transition, there has been a great thrust towards adopting cleaner energy options to move towards the net zero emissions scenario by the respective countries. Many nations have already declared their net zero emissions targets. Apart from Renewable Energy (RE), nuclear is also being explored as a clean energy option to help the nations in achieving their decarbonization goals.

The International Energy Agency (IEA) has projected the global nuclear installed power capacity to rise from 413 GW in 2021 to 871 GW by 2050, more than doubling the capacity, in its Net Zero Emissions 2050 Scenario. In this scenario, with the likely reduction in the capacity of fossil-fuel based electricity generation and increasing share of variable renewable energy, nuclear power can make a major contribution in terms of providing base load power and grid balancing. Several countries have had a rethink considering current geopolitics, consequent volatility in energy prices and energy security concerns, which has resulted in revival of positive sentiments on nuclear energy across the globe.

Innovation in nuclear reactor technologies, both in Large Reactors (LRs) and in the newer concept of Small Modular Reactors (SMRs) will be important for nuclear to remain a competitive option and to give access to more countries to clean and plentiful energy. Nuclear is considered among the lowest Green House Gas (GHG) emitters in life-cycle analysis. Cogeneration SMR systems, apart from providing for both electricity and process heat requirements, have potential to complement variable renewables through flexible operations. SMRs can also be installed in remote off-grid locations. Thus, they can play a crucial role in achieving energy transition goals effectively.

SMRs are conceptualized in such a way that their Systems, Structures and Components (SSCs) are manufactured in controlled factory environment and then transported to project site and installed with a view to optimize the time and cost of SMR project. They have potential deployment advantages like reduced size of Emergency Planning Zone (EPZ) and passive safety system. SMRs may be considered for repurposing of de-commissioned fossil-fuel fired power stations. While some SMR designs indicate refueling requirement every three to seven years, a few have a 30-year refueling-free operating life expectancy. Other advantages offered include smaller plant area, possibility to locate SMR plants at places which are not feasible for constructing large size reactors and feasibility to gradually increase capacity of a power plant by adding more modules later. In the case of SMRs, capital investment per reactor is less, but to start with capital investment per MW may be high compared to LRs. It might improve after N units have been constructed.

SMALL MODULAR REACTORS (SMRs)

As per the International Atomic Energy Agency (IAEA), the SMRs are advanced nuclear reactors with a power generation capacity ranging from less than 30 MWe to 300+ MWe. SMRs are:

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 for electricity production or direct application.

SMRs cover small and medium-sized modular reactors, depending on the countries' context whose SSCs are designed for factory production and transportation to project site for installation to shorten the construction schedule – aiming for the economy of serial production, e.g., adding power modules as demand arises.

GLOBAL STATUS OF SMR TECHNOLOGY DEVELOPMENT AND DEPLOYMENT

Governments, regulators, industry groups, academic institutions and companies have taken various initiatives for early deployment of SMR technology. As a result, many SMR designs are being developed. These designs span across a range of power outputs and aim to cater for various end uses. At present, nearly 80 SMR designs are under development and licensing stages, and a few of them are at deployment and operational stages globally. Following is a summary of them:

Land based water cooled SMRs

SMRs in this category include the water cooled SMR designs having different configurations of Light Water Reactor (LWR) and Pressurized Heavy Water Reactor (PHWR) technologies (integral Pressurized Water Reactors (PWRs) and PHWR, compact PWR, loop-type PWR, Boiling Water Reactors (BWRs) as well as pool type PWR) for on-land applications. These designs take advantage of mature technology used in most of the LRs in operation.

Marine based water cooled SMRs

SMRs in this category include the water-cooled SMR designs for deployment in a marine environment. This can be achieved in the form of floating units installed on barges or ships.

High-temperature gas-cooled SMRs (HTGRs)

SMRs from this category can provide very high temperature heat of more than 750 degrees Celsius and thereby higher efficiency in electricity generation. These SMRs can also be employed in several industrial applications as well as cogeneration.

Liquid metal-cooled fast neutron spectrum SMRs (LMFRs)

SMRs in this category include designs based on fast neutron technology with different coolant options including helium gas and liquid metal coolants like sodium, lead and lead-bismuth.

Molten salt reactor SMRs (MSRs)

SMRs in this category are based on molten fluoride or chloride salt in the role of coolant. MSR designs for both thermal neutron and fast neutron spectrums are under development. These technologies can sustain long fuel cycles of several years, and have option for online refueling in which fresh fuel can be introduced in molten form and cleaning of fission products can also be performed online.

Microreactors (MRs)

MRs are very small SMRs designed to generate electrical power typically up to 10 MW(e). Different types of coolant, including light water, helium, molten salt and liquid metal are adopted by microreactors.

Major Milestones Achieved

A few SMR designs have achieved some milestones like preliminary regulatory approvals, construction, operation and grid connection. As of now, two SMR projects have reached at operational stage globally: (i) The SMR named Akademik Lomonosov floating power unit in the Russian Federation has two-modules of 35 MW(e) KLT-40S that were grid-connected in December 2019 and started commercial operation in May 2020. (ii) The SMR named as HTR-PM demonstration SMR in China was grid-connected in December 2021, and is aiming for full 210 MW(e) power operation in 2023.

HARMONIZATION OF LICENSING PROCESS AND REGULATORY REQUIREMENTS

The international harmonization of licensing process and regulatory requirements of SMR will be crucial for speedy maturity of the designs, reducing time of construction & installation and optimize overall costs. SMR manufacturing on a large scale requires enabling frameworks such as policy, regulatory readiness, legal, safety, security and safeguards. The IAEA is playing a crucial role in enabling the creation of these frameworks through initiatives such as the Nuclear Harmonization and Standardization Initiative (NHSI), SMR Regulators' Forum, Coordinated Research Projects (CRPs), etc.

MODULARIZATION APPROACH IN SMR REALIZATION

Modularization is an important overarching and essential concept behind development of SMRs for cost-effective nuclear energy. Modularization techniques are well-established in industries like aerospace and shipbuilding. These techniques aim to leverage combined benefits of quality control in a controlled factory environment, efficiency and learning gained through serial production and faster installation at site owing to standardization. Under modularization, the SMR components and entire SMR module need to be standardized for controlled factory production and easy onsite installation. This will help in developing various module packages of SMRs.

CHALLENGES FOR SMR INDUSTRY

Since SMRs have a very wide range of capacity sizes ranging from less than 30 MW(e) to 300+ MW(e), therefore, a large number of SMR technology alternatives are evolving at present, which are too many for sustained growth of SMR industry. A large number of technologies, if adopted for deployment at the same time, could not only create regulatory challenges for the nuclear industry but also take away some degree of cost optimization. The choices must narrow down to a few SMR designs. In addition, Technology Readiness Levels (TRLs) of available SMR designs must improve for them to be considered by utilities, investors and governments for deployment. The SMR industry is yet to realize fully developed operational fabrication facility for large scale serial manufacturing of SMR components. Such facility may necessitate a very large investment. Technology developers have challenges in mobilizing finance for technology development, licensing and construction of prototype plants. Also, private capital only marginally gets invested in the SMR industry and not to the level of the needed requirement. There is also a need to have a robust safeguards approach in place for novel technology, at the time of receipt of Nuclear Material (NM).

THE WAY FORWARD

The central theme driving development of SMRs is to envision, design, detail and realize a standardized small sized reactor with the possibility of repetitive manufacturing in a better quality-controlled environment of a factory with efficient use of tools and techniques of modern-day Industry 4.0 paradigm. After achieving this on a sufficiently long-term basis, the learning curve value and economics of serial production can set in to drive down the cost of production. Currently, the SMR industry is in an evolution stage which consists of activities such as SMR technology development, prototyping of SMR modules, cost optimization and regulatory clearances. SMR industry needs to find its way through early challenges of technology demonstration, special material availability, special manufacturing techniques, project funding requirements and regulatory harmonization. Given such challenges and the need to grow SMR industry for achieving long-term Net-zero goals, it is essential to establish SMR ecosystem.

Standardization of designs of components and modules will facilitate adoption of SMRs at large scale. The existing safety assessment methodology should be updated for the concept of multi-module designs and emergency planning zones of SMRs. Availability of low-cost finance, inclusion in green taxonomy and utilization of innovative financing instruments such as blended finance, green bonds, etc. are required to catalyze private investment. Greater focus should also be given to ensure availability of required skilled personnel across the value chain of engineering, design, testing, inspection, construction, erection and commissioning for multi-module plants.

Strategic partnerships will be the key to successful technology development and deployment of SMRs on a large scale. Collaboration among national laboratories & research institutions, academic institutions, private companies and government departments is necessary for successful research, technology development & demonstration, safety assessments, Safeguards by Design (SBD) and harmonization of regulatory process. These collaborative efforts would be required to be extended at the IAEA level to coordinate with respective countries for developing an ecosystem for greater benefits.

SMR may complement large-size reactors in many countries to increase the nuclear share in their energy mix and achieve Net Zero Emissions goals. The respective governments and local authorities have to play a major role in consensus building towards nuclear energy by engaging relevant stakeholders.

INTRODUCTION

1

1.1 BACKGROUND

On 12 December 2015, 196 parties at the United Nations Climate Change Conference (COP21) accepted a legally binding international treaty on climate change, known as the Paris Agreement or the Paris Climate Accords. This agreement entered into force on 4 November 2016. The overarching goal of this agreement is “to hold the increase in the global average temperature to well below 2°C” and pursue efforts “to limit the temperature increase to 1.5°C” above pre-industrial levels. Achievement of these goals has necessitated a rapid revamp in the global energy supply technologies in terms of increasing the share of low-carbon energy technologies and reducing the use of fossil-fuel based energy sources.

The world’s energy systems are now being reimagined to tackle two of the foremost challenges facing humankind today: 1) Climate Change and 2) Energy Security. Being a source of low-emission electricity, nuclear energy can significantly contribute in dealing with both of these challenges. Currently, nuclear energy contributes to about 10% of global electricity generation. As per the IEA, with 413 GW of installed power capacity operating in 32 countries, nuclear power is avoiding 1.5 Gt of emissions and 180 bcm of gas demand globally in a year[1]. The International Atomic Energy Agency in its report states that “to achieve carbon neutrality and limit global warming to 1.5°C, energy sector investment must be scaled up and directed towards cleaner and more sustainable technologies that support climate change mitigation and adaptation”[2]. As per the IAEA, investment in nuclear power can not only support climate change mitigation but also help to reinvigorate energy sector to address energy security vulnerabilities.

1.2 GLOBAL ENERGY MIX, PRIMARY ENERGY SOURCES

Fossil-based energy sources contributed about 82% of the primary energy supplied in 2021, as shown in Table 1.1[3]. However, the share of renewables is steadily increasing in the primary energy mix, as shown in Figure 1.1[3].

Table 1.1: Primary Energy Mix in 2021

Fuel	Consumption (EJ)	Percentage	Combined Percentage
Oil	184.21	30.95	82.28
Natural Gas	145.35	24.42	
Coal	160.10	26.90	
Nuclear Energy	25.31	4.25	17.72
Hydroelectricity	40.26	6.76	
Renewables	39.91	6.71	
Total	**595.14**	**100.00**	**100.00**

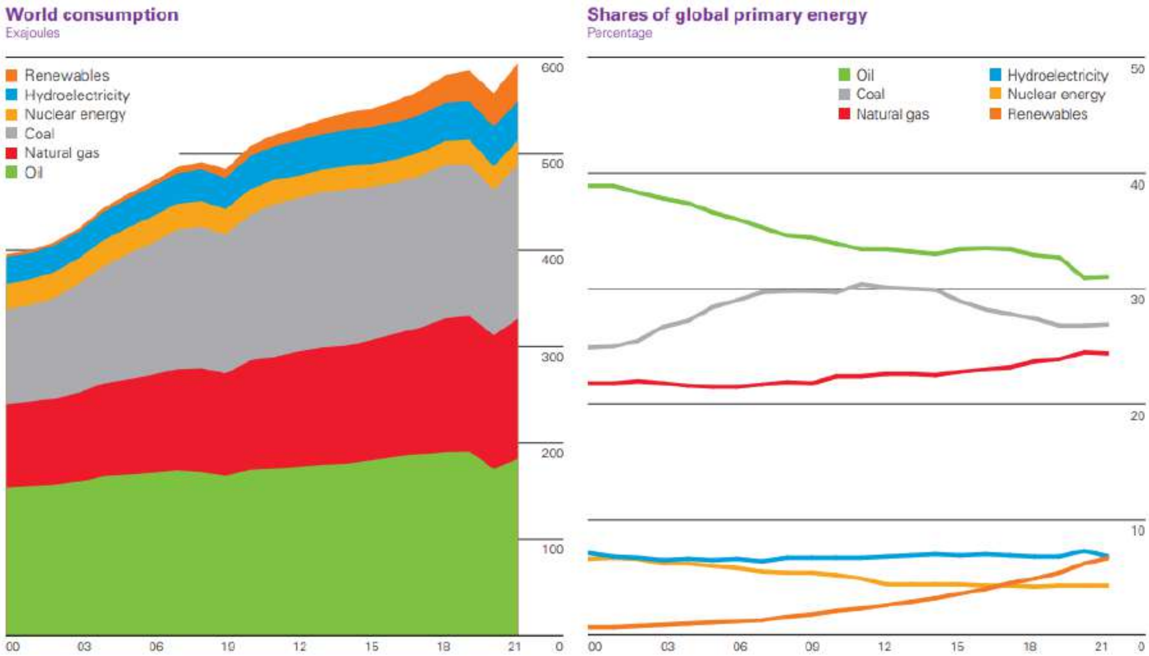


Figure 1.1: *Global Primary Energy Mix (2000-2021)*

The power sector can achieve faster decarbonization. Electrification of end use sectors is crucial for economy-wide emissions reduction. Most of economies have announced Net Zero emission targets by 2050 and IEA study shows that electricity demand could more than double to achieve net-zero by 2050. The power sector accounts for 40% of global energy related emissions and needs a complete revamp in achieving net-zero goals. Considerable investment is required for rapid expansion of low-carbon generation fleet and grid infrastructure along with integration of storage and other flexibility measures for ensuring grid stability. Transition from unabated fossil fuels towards integration of variable RE is associated with many technical, social, and political challenges.

In this scenario of reduced capacity of fossil-based electricity and rapidly growing variable renewable energy, the presence of nuclear generation ensures energy supply security and grid stability. Nuclear power can play an important role in the energy transition by providing base load capacity, 24/7 continuous availability and ability to operate flexibly to complement variable renewable generation. Key approaches to achieve flexible operation of a nuclear plant include ramping core power via control maneuvers, reduced flow through the turbine (either via steam venting or redirection to alternate users in integrated systems), and energy storage providing options for demand response [4].

As per the IEA Report on Net-Zero by 2050, nuclear power is an essential foundation for energy transition. Energy supply from nuclear is projected to rise by 40% in 2030 which almost more than doubles in 2050 as compared to 2020's level, as shown in Figure 1.2 [5].

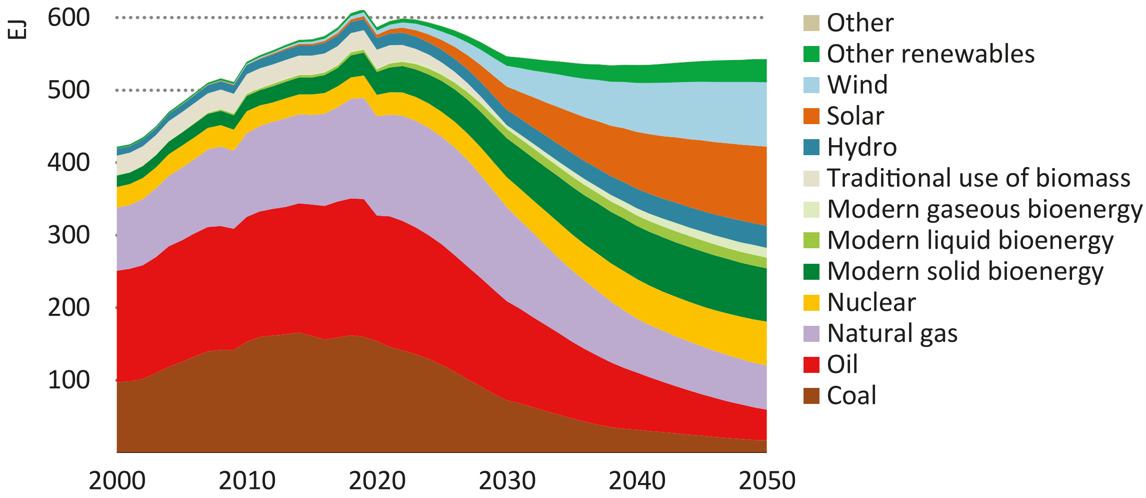


Figure 1.2: *Total Energy Supply in Net-zero by 2050 Scenario of IEA*

At present, the nuclear power has a contribution of above 25% in the total low carbon electricity generation[6]. Nuclear power can also serve non-electric applications like hydrogen production, desalination and district heating. Globally, nuclear power plants are producing almost 2.3 TWh of electrical equivalent heat for processes, desalination and district heating, which is equivalent to even less than 1% of their total electrical output[2]. This provides an option for nuclear power to expand utilization for non-electrical applications in future decarbonization efforts.

1.3 OPPORTUNITIES AND RISKS IN BUILDING NUCLEAR POWER PLANTS

All kinds of energy infrastructure including nuclear installations face an increasing threat due to climate hazards such as the rise in sea levels, windstorms and tropical cyclones resulting in disruptions of vital services, impacts on well-being and economic losses. Even though the nuclear power plants are designed for mitigation of the production loss risk and refueling outages, still the nuclear plant owners and operators need to take necessary adaptation measures to face climate related hazards. The IAEA has initiated a technical project for assessment of site hazards and safety related issues for the existing and new nuclear sites. Contribution of nuclear power technologies in achieving the decarbonization targets may get hampered if the climate mitigation measures are not adapted in future regulations, designs of nuclear power plants and operational practices. Therefore, climate constraints must be included in the strategic environmental assessment and subsequently should be the part of infrastructure and energy supply planning.

Though the contribution of nuclear energy is gaining recognition in climate change mitigation, it may be difficult to mobilize the necessary nuclear investment required for achieving net-zero goals in the current market structure. According to the IEA study on net-zero, annual global investment required for nuclear power expansion is around USD 100 billion by 2030. Financial frameworks for promoting adoption of green projects and sustainable taxonomies can address the challenges of investment. The inclusion of nuclear in sustainable taxonomy may attract green finance/climate finance towards nuclear investment. Effective policymaking, public sector financing, infrastructure readiness and a level playing field for all the low carbon technologies can further support unlocking the financial markets, provide additional incentives and mitigate various project risks. Climate change mitigation and energy transition goals can be achieved effectively when governing bodies and private sector work together. Advantages of learning curve will help to bring down the projected costs of new nuclear power plants when a number of nuclear reactors are constructed in fleet mode.

The IAEA in its latest projections for nuclear energy reflects support for a long term operation of conventional LRs, new construction of generation III and III+ reactors and the development and deployment of SMRs. Land assets in retiring fossil-fuel based power plants may be repurposed to establish SMR. Further, viability of SMR units is expected to increase continuously, driven by economy of scale and learning curve improvements, leading to deployment in large numbers.

The present international experience in regulation, safeguards and licensing of SMRs is very limited. Considering the benefits of SMRs, increasing interest is being shown by technology developers and governments in their development and deployment. With many countries having active national programmes dedicated to SMR design and technology evolution, more than 80 SMR designs are at different stages of development and licensing with a few designs at deployment and operational stages globally.

1.4 OBJECTIVES

The primary objective of this publication is to study the role of SMRs in energy transition, the status of SMR technology development, readiness of nuclear supply chains for their deployment, initiatives being undertaken to harmonize SMR regulation and international licensing process, preparation for international safeguards, etc. The need to de-risk SMR projects for attracting investment from private players has also been discussed. Finally, the report concludes with the way forward for the industry and stakeholders.

1.5 SCOPE

The study draws the information from publicly available documents, technical reports and publications from the International Atomic Energy Agency (IAEA), the Nuclear Energy Agency (NEA) and the International Energy Agency (IEA), media reports and expertise of knowledge partners in this field. The emphasis of this publication is on activities, viewpoints and choices of power asset owners, technology vendors, regulators, and governments. This publication provides insights on the way forward for realizing the full potential of SMRs in energy transition, duly factoring in concerned opportunities and challenges.

1.6 STRUCTURE

Chapter 2 discusses the concept and importance of Energy Transition. It covers historic perspective on nuclear power, its development, current status and policy regime including regulatory, safety & liability aspects and finally leads to a discussion on the emergence of SMRs.

Chapter 3 presents global developments in SMRs including an overview of SMR technologies, types, benefits, challenges, and status of deployment.

Chapter 4 analyses available options for SMR development and comments on possible roadmaps for its deployment. It also delves into the techno-economic feasibility of SMRs, concept of modular design and construction, development of SMR ecosystem, and SMR industry's infrastructure requirements.

Chapter 5 covers SMR regulatory roadmap, international licensing process harmonization for SMRs, regulatory approach, safety in design, safeguard and security framework, and environmental impact assessment.

Chapter 6 analyses key enablers to promote private sector investment in SMR industry.

Chapter 7 presents the suggested Way Forward.

ENERGY TRANSITION, ROLE OF NUCLEAR POWER AND EMERGENCE OF SMALL MODULAR REACTORS (SMRs)

2

2.1 ENERGY TRANSITION

Energy transition is the process of revamping global energy systems through rapid introduction of low-emission energy supply technologies, and aggressive penetration of non-fossil based energy sources in the primary energy mix. Energy transition also entails efficient consumption and decarbonization of hard to abate sectors. Energy Transition involves recasting of existing energy systems in terms of overall architecture, size, constituents, economics and end-use patterns along with reorientation of energy policy. It also involves responsible energy consumption through adoption and mainstreaming of circular economy and sustainable lifestyles.

To quote from the UN Theme Report on Energy Transition[7], transformational opportunities can be created by energy and the energy transition which can unlock important benefits like poverty reduction, providing education, healthcare and green jobs. A substantial reduction in CO_2 emissions by energy transition can help to control conditions of extreme weather like heat waves, floods and droughts. The role of private sector, governments, communities as well as research institutions in energy transition would be critical.

It is evident from the current market trends that there is a complete buy-in and support for energy transition from investors, shareholders and consumers. This trend is manifested in inclusion of energy transition imperatives into investment decisions of large asset managers in terms of their trim-down investments in fossil fuels. Energy transition has led to increase of renewable sector workers' percentage worldwide, and it has also thrown up multitude of economic opportunities for companies to benefit from.

2.2 CASE FOR NUCLEAR & ITS POTENTIAL

As per IAEA Power Reactor Information System (PRIS), as of April 2023, 413 nuclear power reactors with a total net installed power generating capacity of 368 GW(e) are in operation globally with 56 new build reactors having 59 GW(e) capacity under construction as demonstrated in Figure 2.1 and Table 2.1 [8]. The share of nuclear power generation is nearly 10% of the global electricity mix. As per IEA, the nuclear power installed capacity is projected to rise to 871 GW by 2050, more than doubling the current capacity, in its Net Zero Emissions 2050[9]. As per IAEA, the nuclear power has avoided the CO_2 emissions of 70 Gt over the past five decades and it continues to avoid CO_2 emissions of about 1 Gt annually[6]. In the current energy system, with rapidly growing renewables, presence of nuclear power capacity ensures energy supply, security and grid stability. The United Nations Intergovernmental Panel on Climate Change (IPCC) clearly identifies nuclear energy's role in addressing the climate crisis. The IEA acknowledges the role of nuclear energy in energy transition. The UN Economic Commission for Europe (UNECE) has stated that nuclear power is an "indispensable tool" for achieving the Sustainable Development Goals (SDGs).

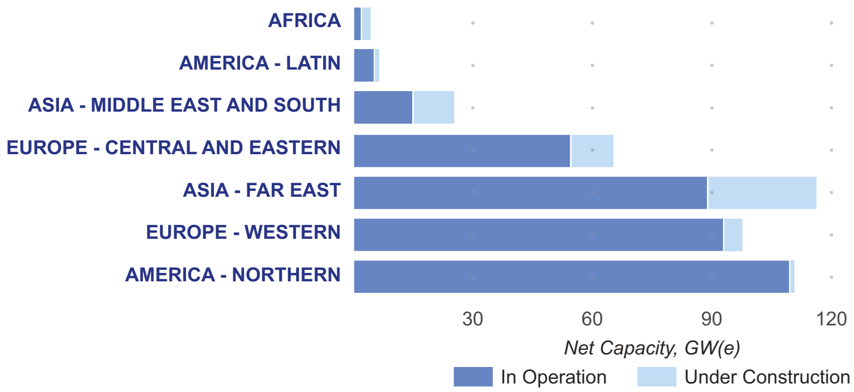


***Figure 2.1:** Regional Distribution of Nuclear Power Capacity as on April 2023 (IAEA, PRIS)*

Table 2.1: Nuclear Power Plant Status Changes, as on April 2023 (IAEA, PRIS)

New Connections to the Grid					
S. No.	Reactor Tag	Capacity (MWe)	Reactor Type	Country	Date
1	FANGCHENGGANG-3	1000	PWR	China	10 Jan 2023
2	MOCHOVCE-3	440	PWR	Slovakia	31 Jan 2023
3	VOGTLE-3	1117	PWR	USA	31 Mar 2023
Plant Shutdown					
1	EMSLAND	1335	PWR	Germany	15 Apr 2023
2	ISAR-2	1410	PWR	Germany	15 Apr 2023
3	KUOSHENG-2	985	BWR	Taiwan, China	15 Mar 2023
4	NECKARWESTHEIM-2	1310	PWR	Germany	15 Apr 2023
5	TIHANGE-2	1008	PWR	Belgium	1 Feb 2023
Construction Starts					
1	SANMEN-4	1163	PWR	China	22 Mar 2023
2	HAIYANG-4	1161	PWR	China	22 Apr 2023

Out of total CO_2 emissions of energy sector, electricity generation contributes to 40% and balance 60% comes from the use of fossil fuels in industrial process heat, heating in buildings, cooking and transport. Nuclear energy can be a source for generating heat and hydrogen along with electricity. It is suitable for both providing base-load power as well as flexible operations. It complements the growth of renewable energy sources and also provides benefits of reliability, high capacity factor, low operating expenses, low emissions, direct employment and ensures economic activity throughout the life-cycle of power plants.

The deployment of nuclear energy across all sectors of energy and economy can help to decrease the reliance on fossil fuels. A study conducted by UNECE concludes that the environmental impact of nuclear energy (modeling only PWRs, being representative of the global nuclear capacity) during entire life cycle is the lowest among all electricity generation technologies, as shown in Figure 2.2. Further, the figure also demonstrates material use per kWh for different electricity generation technologies which is amongst the lowest in case of nuclear energy. This composite benefit of nuclear energy in terms of low material use and low emissions intensity illustrates their potent role in the climate change mitigation and the energy security.

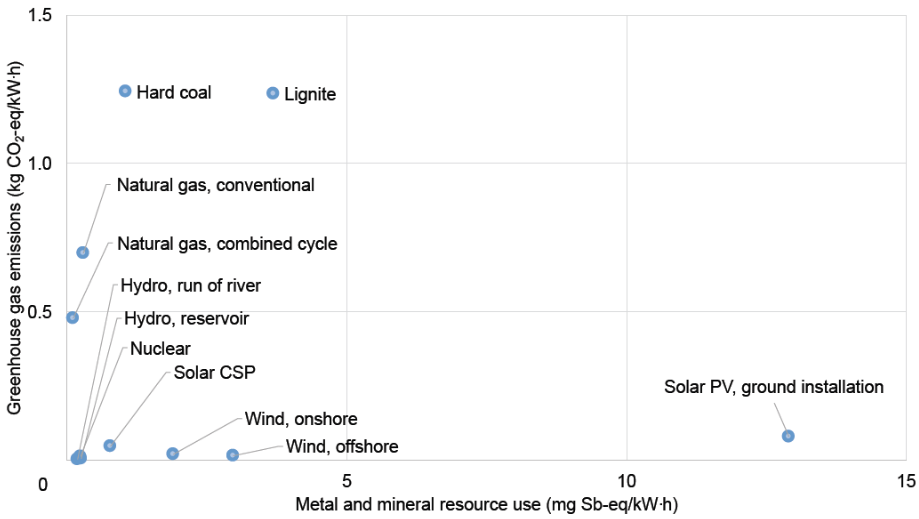


***Figure 2.2:** Lifecycle Greenhouse Gas Emissions and Resource Use per kWh for Different Electricity Generation Technologies*

Nuclear fission power is considered as an important low emissions technology in Net Zero Emissions pathway. Advanced designs, such as SMRs, are considered to be deployed in significant number in the IEA's Net Zero Emissions (NZE) projections for electricity generation, particularly in advanced economies [1]. Due to the learning curve, cost of nuclear power reactors reduces when they are constructed in series. Further, SMRs, especially the High Temperature Gas Cooled Reactors (HTGRs) could be used for non-electrical purposes such as production of hydrogen and process heat. The Low Nuclear Case of the NZE not only requires integration of higher proportion of renewables into electricity systems but also leads to higher overall costs and additional strain on clean energy supply chain. Considering uncertainty in technology development, feasibility and economics of nuclear fusion power, energy from nuclear fusion is not considered in the NZE scenario of the IEA.

2.3 CURRENT NUCLEAR POLICY REGIME- REGULATORY, SAFETY, LIABILITY AND WASTE MANAGEMENT

General

Nuclear installations can be defined as the facilities associated with nuclear fuel cycle, for example: uranium ore mines, milling plants, uranium enrichment and fuel fabrication plants, storage facilities for spent fuel, reprocessing facilities, nuclear power plants, test reactors and research reactors. Primary responsibility for the safety of such nuclear installations lies with the organizations which operate the facilities. Under certain abnormal conditions, the inventory of radioactive substances in such facilities can lead to release of radioactivity into biosphere creating risk of exposure to radiation for plant operators, staff, general public and environment. Risk management in such facilities is addressed in nuclear regulation.

Normal legal hierarchy applicable in Nuclear States incorporates many different levels—starting from constitutional level for establishing basic legal and institutional setup, second the statutory level to enact specific laws through parliament, third level comprising of regulations consisting of in-depth provision of technical rules for control or regulation of activities as specified by statutory instruments. Expert groups and regulatory bodies have been entrusted with the work to frame such rules because of their special character, and these are finally authenticated under the national legal framework. The fourth level consists of optional guidelines to facilitate implementation of the above rules and guidelines.

Regulatory Structure

Regulatory bodies play a central role in ensuring the overall safety of nuclear installations. Regulatory involvement can happen in any of the following modes[10]:

1. **Reactive approach-** Operating organization prepares plans and proposals for operation of a nuclear facility; regulatory body reviews them and decides whether they are acceptable

2. **Step-by-step licensing-** For large nuclear installations like power reactors, for technical and economic reasons, the licensing process is divided into different stages viz. site selection, design, manufacturing, construction, commissioning, operation and decommissioning.

3. **License renewal-** Operating license is given for a certain period and renewed periodically after review and necessary upgrades. Some countries grant operating license without a fixed term (Periodic Safety Review (PSR) is still carried out every ten years) and some countries grant licenses for a fixed term (the length of the license period may vary in different countries but typically most countries include PSR in the license renewal). Continuous oversight is always additional to the licensing process. Continuous oversight includes inspections ensuring the compliance with the safety requirements and license conditions at all times. Some States may prefer yearly appraisal of the facility and extension of license.

4. **Suspension, revocation or modification of license-** Legislation pertaining to nuclear installations must have provision that enables regulatory body to modify, suspend or revoke an operating license. This right of regulatory bodies needs to be clearly defined in legislation and subject to review by the State to ensure security of investment.

Safety

Nuclear safety involves protecting the population as well as the environment from the risks of radiation and also the safe operation of nuclear facilities. This includes- (a) safety of nuclear installations, (b) protection from radiation exposure, (c) safety in transportation and handling of nuclear fuel, (d) safety in nuclear waste management and (e) safety during nuclear plant decommissioning.

Safety of nuclear installation also involves emergency preparedness, prevention and mitigation for both on-site and off-site plant conditions. Preparedness against off-site and on-site emergencies needs to be given great importance in the licensing process. On-site emergency preparedness involves a reliable and in-time detection of adverse incidents at a facility likely to lead to an emergency, control over progression of such incidents and ability to stop them with lowest possible impact on the facility. For power reactors, it is important to prevent core damage, restore and maintain cooling of core and bring it back to a safe state. Facilities must have necessary preparedness to effectively manage such emergencies. Off-site emergency management involves taking necessary measures to prevent radiological exposure to public and environment through effective communication, exchange of information, prompt decision making and swift action.

Liability

Even for nuclear installations which have been designed and realized under strict safety regulations and high safety standards, occurrence of nuclear and radiological incidences cannot be totally ruled out. Moreover, the impact of a nuclear accident may not be limited within State borders, and damage may be suffered by communities, properties, and environmental ecosystems in several States. Such impact may be partly immediate and partly over a longer time period. Hence, it is imperative for State legislators to create avenues to establish and enforce nuclear accident liability so as to adequately compensate the people, and the concerned stakeholders, affected by nuclear accidents.

Parties involved in harnessing nuclear energy accept that general tort law is not sufficient to handle nuclear risks and a special nuclear liability regime is necessary, with provisions to address impact across the boundaries. International nuclear liability conventions are important ways towards timely, just and useful actions as well as speedy implementation of judgements given by legal entities in various countries.

International Nuclear Liability Conventions

These can be categorized as global or regional.

Global international nuclear liability conventions-

- Vienna Convention on Civil Liability for Nuclear Damage, 1963
- Convention on Supplementary Compensation for Nuclear Damage, 1997

- Joint Protocol Relating to the Application of the Vienna Convention and the Paris Convention, 1988

Regional Nuclear Liability Conventions

- Paris Convention on Third Party Liability in the Field of Nuclear Energy, 1960
- Brussels Supplementary Convention to the Paris Convention, 1963

Establishing comprehensive regimes for civil liability is the aim of the Vienna Convention as well as the Paris Convention. The Brussels Supplementary Convention aims to make further compensation available, when compensation from other Conventions falls short of the requirement. States need to study and streamline nuclear liability conventions with their respective country specific legislation. States may either amend domestic laws to include requirements and specifications of the International Conventions, or may enforce International Conventions in totality as self-standing legal instruments. Provisions of the International Conventions as well as similar country specific legislation get triggered in case of an accident. In such cases, final liability is attributed to the operator irrespective of responsibility for fault except under special conditions like wars.

Spent Fuel and Waste Management

Nuclear waste management refers to the safe and secure handling, storage, transportation, and disposal of spent fuel and radioactive waste. It is a critical aspect as radioactive waste poses significant risks to human health and the environment.

Countries with established nuclear power programmes have been managing their spent fuel for decades. For these countries, management of spent fuel arising from new nuclear plant installations shouldn't pose a challenge if they opt to deploy new plants based on current technologies. Countries that are new to nuclear power should carefully consider spent fuel management and establish relevant capabilities and infrastructure as they work on introducing nuclear energy [11].

A few advanced reactor designs such as MSR, and SFR may increase the volume of nuclear waste in need of management and disposal [12]. The excess waste volume is attributed to the use of neutron reflectors and/or chemically reactive fuels and coolants in advanced reactor designs.

2.4 HISTORICAL PERSPECTIVE

The nuclear industry has been developing LWRs and PHWRs since 1960s with progressive increase in reactor capacity and improvement in safety features, performance, and economics. At present, nuclear power reactors of various types are in operation like PWRs, BWRs, PHWRs, FBRs, HTGRs etc. Among the various reactor types, PWRs are at the top with more than 300 operating reactors in the world at present.

Though the basics of reactor technology remain the same for different reactor types, the differentiating features pertain to how each reactor type approaches the safety function, overall simplicity and cost of the plants. Passive systems for engineered safety are getting importance in the modern days' designs, for example, using gravity flow of water in place of active safety systems like water flow actuated by pumps. Such designs also provide for safety based on lessons learned from past nuclear accidents. New designs also bring in economy in realization of power reactors.

While some utilities and States are less favourable towards new nuclear plants, others are showing interest in various options available for nuclear power generation. Improved and advanced nuclear reactor designs are already being implemented, some are under finalization and some are under improvement for better overall safety and economy of nuclear power generation. New options like SMRs are on the horizon, and a few SMRs are already operational.

2.5 EMERGENCE OF SMRs

Roots of SMRs can be traced back to 1940s-1950s when small capacity nuclear reactors of various designs were used for military purposes. Globally, increasing interest is being shown by technology developers and prospective customers. Many countries have active national programmes dedicated to SMR design and technology development with a view to deploy them by 2035 with extensive global cooperation.

It is conceptualized that systems, structures, and components of SMR will be manufactured in factory, transported to site and installed, which can help in reduction of installation time as well as cost optimization. Technology developers are working on various SMR designs which are either based on established nuclear power reactor technologies like PWR and BWR or based on advanced technologies like HTGR, LMFR, and MSR. SMR designs primarily aim to generate emission free electricity. Also, they aim to supply other clean energy products like hydrogen. SMRs can be used in applications such as industrial heat, desalination, and transport. SMR designs also aim to achieve flexibility in operation for grid stability with renewables of variable nature. They are also being positioned and designed for countries having requirement of small electrical grids. SMRs can be useful in remote off-grid locations as well. They have potential deployment advantages like reduced size of EPZ or a few operators monitoring several modules. Rise of SMR technology in nuclear power generation industry can not only strengthen nuclear sector itself but also can make marked contribution to energy transition as well as resilient infrastructure.

2.6 SUMMARY

Nuclear energy is emerging as an important theme in global energy transition scenario. SMRs—with multitude of applications including electricity generation, grid integration of renewables, process heat, desalination and hydrogen production are opening up new avenues for deeper and accelerated adoption of nuclear technology.

GLOBAL DEVELOPMENTS IN SMRs

3

3.1 OVERVIEW OF SMR TECHNOLOGY AND TYPES

Global interest in SMRs has been increasing due to their ability to provide both flexible power generation as well as base-load power for a wide range of applications. They can also be deployed for repurposing ageing/de-commissioned fossil fuel-fired power plants. They also display an enhanced safety performance through inherent and passive safety features. They are suitable for cogeneration and non-electric applications in addition to installation in remote regions with less developed infrastructure. There is also the possibility for synergetic hybrid energy systems that combine nuclear and alternate energy sources, including renewables.

Production of SMR and its components & systems is being envisioned in a controlled factory environment in modular fashion with transportation to site and integration to take advantage of economies of scale and learning curve advancements. Many SMR reactor technologies and designs are being developed at present in various countries, two are in operation and four are under construction.

SMR designs can be categorised into six types based on the basic nuclear technology employed in the design:

1. Land-based water-cooled SMRs (PWRs)
2. Marine based water cooled SMRs (PWRs)
3. High temperature gas-cooled SMRs (HTGRs)
4. Liquid metal-cooled fast neutron spectrum SMRs (LMFRs)
5. Molten Salt Reactor SMRs (MSRs)
6. Microreactors (MRs)

Technical details of all the SMR technologies under development and deployment are summarized below[13]:

1. Land-based water-cooled SMRs (PWRs)

These include water-cooled SMR designs of various configurations of LWR and PHWR technologies. The designs take advantage of mature technology used in most of the LRs in operation. There are 25 water-cooled SMR designs. These designs include integral PWR, PHWR, compact PWR, loop-type PWR, BWRs and pool type PWR. Central Argentina de Elementos Modulares (CAREM) is an integral PWR having natural coolant circulation and is under construction in Argentina with first criticality target of 2026. Another integral PWR with design simplification, ACP100, whose construction started in 2021 in China, is targeting commercial operation in 2026. More designs are under preparation for early deployment in their own country or for export such as NuScale VOYGR and GEH BWRX-300 in the USA, Rolls-Royce SMR in the UK and Electricité de France Company (EDF) NUWARD in France. A pilot project of land-based SMR Nuclear Power Plants (NPPs) based on the RITM-200N is being implemented with its first criticality scheduled for 2027.

2. Marine based water cooled SMRs (PWRs)

These include SMR designs for deployment in marine environment. This can be achieved in the form of floating units installed on barge or ships. Many flexible SMR deployment options are available in this category. Some marine based water-cooled SMR designs are deployed for nuclear ice-breaker ships. SMR KLT-40S which is deployed as floating SMR in Russia is from this sub-category and is the first SMR design connected to the grid. Floating small-scale NPPs based on RITM-200M and RITM-200S are under construction.

3. High temperature gas-cooled SMRs (HTGRs)

SMRs in this category can provide very high temperature heat of more than 750°C. High temperature heat makes it possible to generate electricity at high efficiency factors. These SMRs can also be employed in many industrial applications and cogeneration. IAEA publication has described 14 SMRs using HTGR technology which includes HTR-PM in China, connected to the grid in December 2021. This category also includes three test reactors. Two are in testing operations for more than twenty years in Japan and China respectively.

4. Liquid metal-cooled fast neutron spectrum SMRs (LMFRs)

These include eight designs that adopt fast neutron technology and liquid metal coolants, including sodium, pure lead and lead-bismuth eutectic. Substantial progress has been made in technology development as well as deployment on these SMRs. Lead-cooled fast reactor BREST OD 300, which is under construction in Russia, has a target of 2026 as a demonstration project. SVBR-100 is an innovative lead-bismuth fast modular reactor for multi-purpose applications with natural safety features.

5. Molten Salt Reactor SMRs (MSRs)

This category includes 13 SMR designs that belong to Generation IV (GEN IV) of nuclear reactors. These designs have advantages such as inherent safety due to specific properties of molten salt, low coolant pressure eliminating the need of large containments, system with high temperatures which leads to high power generation efficiency and a flexible fuel cycle. Many MSR designs have initiated preliminary licensing activity in Canada, Denmark, the Netherlands, the UK and the USA.

6. Microreactors (MRs)

These include 12 micro-reactor designs. Many emerging designs are under development in this category of very small reactors that generate power up to 10 MW(e). Various options for coolant like light water, helium, molten salt and liquid metal, are adopted by microreactors. Heat pipes are another proposed cooling system option. Many designs under this category have initiated work to get license in the USA and Canada. In Canada, Global First Power (GFP) submitted an initial site application to the Canadian Nuclear

Safety Commission (CNSC) for MR with USNC's Micro Modular Reactor technology. Microreactors can serve niche electricity as well as heat applications of future such as powering micro grids and remote off grid areas, quickly restoring power in areas affected by natural disasters and also for seawater desalination.

3.2 SMR DEVELOPMENT AND DEPLOYMENT STATUS

SMR development and deployment status for some designs is summarised in Table 3.1. For further details on SMR models, reference can be made to the IAEA publication "Advances in SMR Technology Developments, a supplement to Advanced Reactor Information System (ARIS) 2022 Edition"[13].

Table 3.1: Examples of SMR Designs and their Development Status from Major Technology Types

Technology	Output MWe	SMR Type	Developer	Country	Features	Status
WATER COOLED						
KLT-40S	2 × 35	PWR in floating NPP	JSC Afrikantov OKBM	Russian Federation	Floating SMR for cogenerating heat as well as electricity	In operation
ACP100	125	PWR	CNNC	China	Integrated PWR, tube-in-tube and once through Steam Generator (SG), underground nuclear island	Under construction
CAREM	30	PWR	CNEA	Argentina	Natural circulation for core heat removal, containment with pressure suppression	Under construction
VOYGR	6 * 77	PWR	NuScale power corporation	USA	Has extended time available for cooling of core, does not need AC / DC power, water addition or operator action	Received standard design approval for 50 MWe

Technology	Output MWe	SMR Type	Developer	Country	Features	Status
NUWARD	2 × 170	PWR	EDF, CEA, TA, Naval Group	France	Integral PWR, Main components of Nuclear Steam Supply Systems (NSSS) contained within Reactor Pressure Vessel (RPV), Submerged Containment	Basic design stage
SMART	107	PWR	KAERI and K.A.CARE	Republic of Korea	Coupling with desalination and process heat application, integrated primary system	Standard design approval received
RITM-200N	2 × 55	PWR	JSC Afrikantov OKBM	Russian Federation	For floating and land-based NPPs, integral design, inherent safety features	Detailed design
UK SMR	470	PWR	Rolls Royce and Partners	UK	Modularization facilitates speedy and economical construction	Conceptual design
SMR -160	160	PWR	HOLTEC International	USA	Defence-in-Depth with passive safety cooling systems and active non-safety systems; critical components below grade.	Preliminary design completed
BWRX-300	272 to 290	BWR	GE-Hitachi Nuclear Energy and Hitachi GE Nuclear Energy	USA and Japan, Canada	Natural circulation BWR, integral RPV isolation valves, isolation condenser	Pre-licensing
HIGH TEMPERATURE GAS COOLED						
HTR-PM	210	HTGR	INET, Tsinghua University	China	Inherent safety features, offsite emergency measures not required	In operation

Technology	Output MWe	SMR Type	Developer	Country	Features	Status
GTHTR 300	100 to 300	HTGR	JAEA	Japan	Multiple applications of power generation, cogeneration of hydrogen, process heat, steelmaking, desalination, district heating	Pre-licensing
Xe-100	82.5	HTGR	X-Energy LLC	USA	Online refueling, core cannot melt and fuel damage minimized by design, independent radionuclide barriers, potential for advanced fuel cycles	Basic design
EM^2	265	GFR	General Atomics	USA	Silicon carbide composite cladding and fission gas collection system	Conceptual design
FAST NEUTRON SPECTRUM						
SVBR	100	SFR	JSC AKME engineering	Russian Federation	Integral monoblock primary circuit where reactor, steam generators and pumps are installed in one vessel	Conceptual design
BREST OD 300	300	LFR	NIKIET	Russian Federation	Natural properties of lead, fuel & core and cooling process design lend inherent safety to design	Under construction

Technology	Output MWe	SMR Type	Developer	Country	Features	Status
MOLTEN SALT						
Integral MSR	195	MSR	Terrestrial Energy Inc	Canada	Core-unit is replaced completely as a single unit every seven years	Conceptual design
KP-FHR	140	Pebble bed salt cooled reactor	KAIROS Power, LLC	USA	Longer than 72-hour coping time for core cooling without AC or DC power, or operator action	Conceptual design
MICROREACTORS						
U-battery	4	HTGR	Urenco	United Kingdom	Simplicity, established technology basis, demonstrated fuel	Conceptual design
MMR	5-10	HTGR	Ultra Safe Nuclear Corporation	USA, Canada	No core meltdown; adjacent non-nuclear power conversion plant; no EPZ required; load following / fully dispatchable; nuclear reactor isolated from load via molten salt loop; <6 months assembly at site	Conceptual design
Aurora	1.5	FR	OKLO Inc	USA	Low decay heat term, removed by inherent and passive means, Water not required for safety-related cooling	Conceptual design
SHELF-M	10	PWR	NIKIET	Russian Federation	Power source for users in remote and hard-to-reach locations; both floating and submerged nuclear power plants	Conceptual design

SMR Power Range

Power range for SMR designs span from less than 30 MWe up to 300+ MWe. Figure 3.1 summarises the power range of SMR designs.

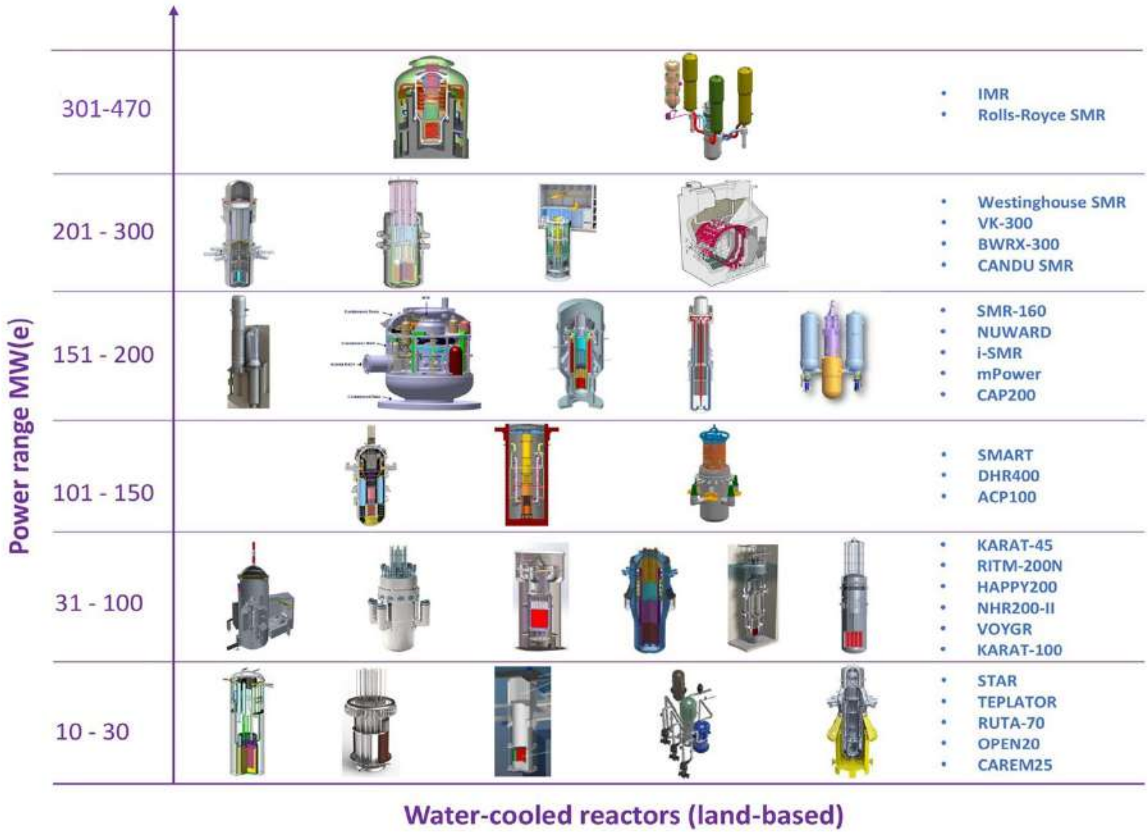


Figure 3.1: *Power Range of SMR Designs (Source: IAEA)*

SMR Temperature Range and SMR's Non-Electric Applications

The temperature range and nonelectric applications of SMR are illustrated in Figure 3.2[13]. Some SMR technologies such as HTGR lie on the higher side of the temperature range. Some of these designs are in the prototype stage since many years but are now getting renewed impetus because of global interest in SMR development.

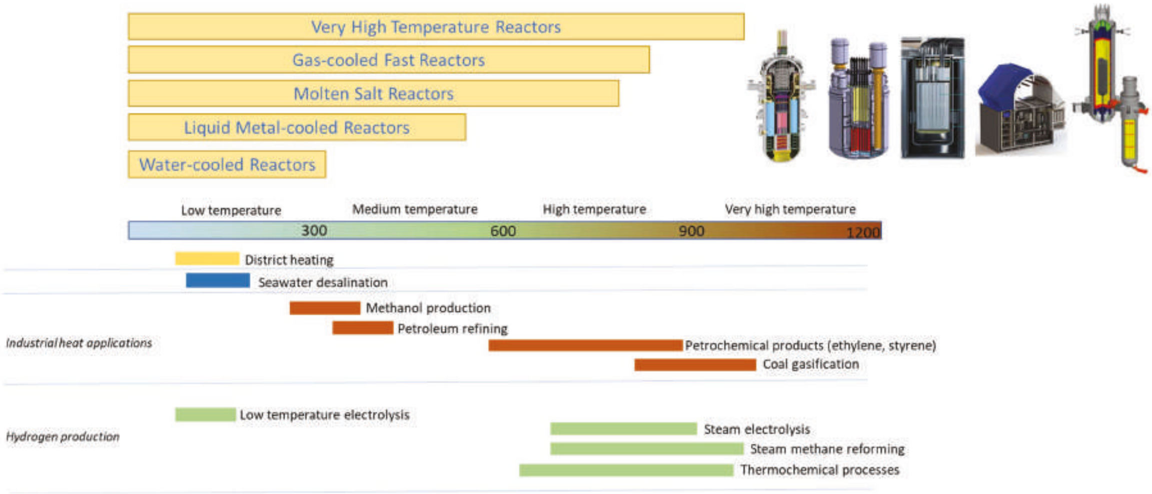


Figure 3.2: *Temperature Range and Non-electric Applications of SMR Designs (from IAEA)*

SMR Technology Distribution Across the World

SMR technology distribution across the world is illustrated in Figure 3.3[13]. This is dominated by countries with established nuclear power industry.

Figure 3.3: *SMR Technology Distribution across the World Regions (source: IAEA)*

SMR Technology – Some Special Features

The maximum power level of a nuclear reactor in SMR design and dimensions of SSC are based on the factors such as radioactive inventory, nuclear safety of reactor, capabilities in fabrication, handling and transportation, serial production, etc.

SMR modules are conceptualized to be factory built and standardized with respect to process, mechanical, electrical and instrumentation aspects. The modularity is expected to bring cost optimization, quality improvement, reduction in complexity at the site, reduction in construction time and bring down schedule risk in deployment of SMR projects.

3.3 BENEFITS & CHALLENGES OF SMRs

SMRs present opportunities to improve and expand nuclear power generation, however, they can experience certain challenges[14], including perceived risk in investment, availability of finance, competition from cheaper electricity generation technologies, constraints from licensing and regulatory sides, public perception of risk, constraints of supply chain, inadequate operational experience, non-availability of suitable sites, nuclear waste related challenges, safeguards challenges, etc. Table 3.2 summarises the benefits and challenges of SMR technology.

Table 3.2: Benefits and Challenges of SMRs

Benefits of SMR	Challenges Associated with SMR
SMRs are adaptable and scalable SMRs are adaptable and can be scaled up or down to supply more or less power. It can also be used to supplement existing power plants with zero-emission fuel or to help repurpose ageing thermal power stations.	**Technology choice issue** Many SMR technology alternatives are available at present with varying requirements of supply chains, regulation, operations, etc. For large scale commercial deployment of SMRs, the technology choice needs prioritization. Technology Readiness Levels (TRLs) of available SMR designs need to improve for consideration by utilities, investors and governments for deployment. There is need for extensive additional research and experimental facilities for new technological solutions. Further, development of analysis tools is crucial.
Refueling interval SMR-based power plants might only need to refuel every three to seven years, as opposed to every one to two years for traditional plants. It is stated that some SMRs have a 30-year without refueling operating life expectancy[11].	**Supply chain issues** As with big LWRs, the supply chain is an important factor in SMR competitiveness. Recent major construction projects are helping to establish global supply chains. Therefore, more effort would be required to establish resilient Global supply chains. Supply chains for the SMR industry may need consolidation in order to capitalise on economies of scale, as witnessed in the aviation industry.
Compact design Land implications in the case of SMRs are less as compared to land requirements for large reactors and renewable energy sources. SMRs are anticipated to reutilize parts of ageing/ decommissioned fossil fuel based power plants and can also act as an alternative to decarbonize industrial processes.	**Licensing challenges** Newly developed SMR technologies may find it difficult to accommodate in the existing licensing process. The lack of experience with innovative designs within the nuclear safety regulatory organisations presents a substantial problem in examining and approving the safety standards.

Benefits of SMR	Challenges Associated with SMR
Safety features Extensive use of passive safety features in SMR designs, which rely on the laws of physics to shut down and cool the reactor under abnormal circumstances, provide inherent safety. In most cases, these technologies don't need a power supply and can handle accidents without the assistance of a person or a computer. A molten salt reactor with a freeze stopper is an example of a passive safety mechanism.	**Safeguards challenges** In most countries, novel SMR technologies will require the application of international safeguards, potentially requiring the development of novel or customized technical measures that demand time and resources, typically in collaboration with the relevant governments and industry.
Economical SMRs could provide a pathway for developing economies to promote sustainable growth by adopting SMRs with a low capital outlay and/ or a phased capital expenditure[15, 16]. They have the adaptability to allow co-generation, supply heat for desalination and manufacturing etc.	**Potential disadvantages** SMRs also produce radioactive waste from spent fuel and require spent fuel storage & disposal facilities. Apart from the technological and cost aspects of such a requirement, this requirement can also lead to socio-political resistance. Additionally SMRs, because of their unique nature, may entail extra technological aspects that are not necessarily present in existing massive LWR designs. LWR-based SMRs, for example, include non-conventional components like helical coil SGs, internal Control Rod Drive Mechanism (CRDM), or novel types of in-vessel instrumentation with minimal operating expertise. SMRs in GEN IV will contain characteristics that have never been tested before.
SMRs are flexible SMRs can be integrated with RE to fulfill the need for flexibility, producing energy services, and low-carbon co-products. These can include electricity, hydrogen, synthetic fuels, hot process gases or steam. When coupled with variable energy sources SMRs can mitigate fluctuations on a daily and seasonal basis [4].	**Public perception and engagement** Nuclear power has faced traditional opposition due to the potential consequences of a nuclear disaster, notwithstanding the low likelihood of such events. Creating awareness and integrating the large masses with mainstream of this industry is a challenge.

More than 80 SMR designs, and concepts are currently under development and have varying degrees of readiness levels. For each of these projects, development costs need to be understood, as well as construction and operation expenses, which still need to be appropriately estimated, analyzed, and optimized. Specific revenue models are also needed for demonstrating the business case and secure access to funding, financing, and low cost of capital for the promoters of the technology. Finally, the macroeconomic impact associated with SMR design development, manufacturing, construction and operation (including periodic maintenance) has to be quantified and communicated to gain the support of the government and society at large.

Figure 3.4 provides an overview of the economic challenges facing SMR during project execution with a focus on costs and cost drivers, funding and financing issues, and economic impact.

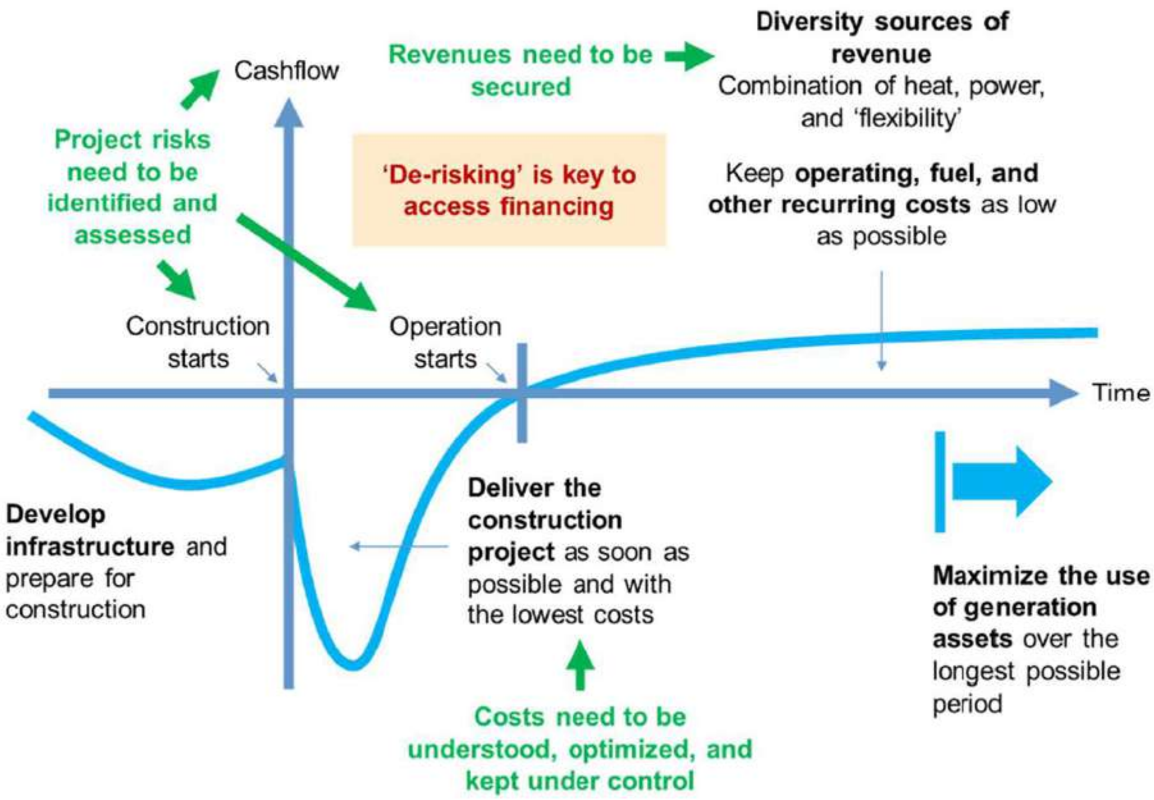


Figure 3.4: *Economic Challenges Facing SMRs*[13]

Specific Benefits of SMRs Against Large Nuclear Power Reactors

Table 3.3 compares SMRs and Large Nuclear Power reactors with respect to underlying economics of scale approach adopted to drive down costs with a view to bring out technological benefits and challenges of SMRs.

Table 3.3: Comparison of SMRs and Large Reactors (LRs)

Criterion	LR (Large Reactors)	SMRs (Small Modular Reactors)
Mode of execution	Project mode (stick built) with partial modularity	Product mode (completely modularized and standardized)
Benefits of Learning curve	One unit can be built every five to seven years on average	Modularization can help in increasing the number of units.
Mobilization of Workforce	Mobilization based on project life cycle, highly variable, tied with stages of construction and commissioning	Mobilization is permanent in factory. Skilled workforce for installation deployed for short duration on site
Supply Chain Management	Discrete and Project based	Continuous ongoing commercial relationships for ecosystem of multiple SMR units
Engineering and Component Production	Very large size equipment	Standard components with high TRL in supply chains

Criterion	LR (Large Reactors)	SMRs (Small Modular Reactors)
Civil Design	Large reactor size; Aspects of geology, geography and environment may lead to site specific variations in design.	Developed as standard designs, with seismic isolation, use seismic design parameters for multiple possible sites
Manufacturing	Partly modularised, stick-built and large-scale on-site construction	Fully modularized, more than 90% of components are prefabricated in controlled factory environment and SMRs are assembled on site
Investment	Requires large scale national infrastructure investment and long gestation periods (on average 5 to 10 years) before realization of revenue generation streams.	Requires relatively smaller investment per reactor; relatively short period to revenue generation (on average 5 years or lesser) with possibility to reduce this time by means of learning by doing and factory standardization
In-situ Work Component	Large projects often with large site specificity requiring project execution in design and build mode driven by project location. In-situ work component is higher in LRs.	Potentially a very high degree of replicability due to streamlined quality control in factory environment and standardized on site assembly. In-situ work component is relatively lower in SMRs.

3.4 COMPARATIVE ANALYSIS OF SMR DEPLOYMENT AND POLICY FRAMEWORK

As per IAEA statistics, various SMR designs are under development and are being considered by countries and technology developers for advanced applications of nuclear energy production. The market for nuclear energy products is expected to grow significantly given the potential for power and other applications, relatively lower capital investment requirement per reactor, etc.[17].

Analysis Based on Stage of SMR Realization

Operational SMRs

The Akademik Lomonosov floating NPP with 2 x 35 MWe of KLT-40S was connected to the grid in December 2019 followed by commercial operation since May 2020. China followed by advancing into the first criticality of the 210 MWe HTR-PM SMR in December 2021 which is now in operation. These are the only two SMRs (going by standard definition of SMRs) currently in operation.

SMRs Under Construction -

Argentina's 30 MWe CAREM25 SMR is under construction with the first criticality target in 2026. China commenced construction of 125 MWe ACP100 SMR in July 2021 with commercial operation target of December 2026. Russia has launched construction of 300 MWe BREST LFR SMR in June 2021 with construction completion target of 2026.

SMRs in Development

Mature SMR designs include 77 MWe VOYGR by NuScale in USA which is stated to be at the equipment manufacturing stage, 470 MWe Rolls-Royce SMR by Rolls-Royce in UK and 290 MWe BWXR-300 by GEH in USA. Table 3.1 enumerates examples of SMR designs from major types of technology.

Country wise Analysis of Technology Development

Technology development for SMR Designs is underway in many countries with the global market size of SMRs being projected to approach US $300 billion by 2040. An analysis of progress in SMR technology development in various countries that have made initial inroads is presented below:

SMR Development in Argentina

Argentina is building a 30 MW(e) CAREM25 SMR which is an integral PWR with commissioning and first fuel loading target of 2023. A stage-wise licensing approach is taken by the regulators based on the specific safety milestones.

SMR Development in Canada

Canada has continued its commitment to nuclear power technologies and has allocated funding support to SMR development and deployment. The CNSC and US Nuclear Regulatory Commission (USNRC) signed a Memorandum of Cooperation (MoC) in 2019 covering technical reviews of advanced reactor and SMR technologies. The Canadian government launched an SMR national action plan with its partners in 2020 for deploying SMR technology, updating regulations and leveraging foreign market opportunities. This plan followed the 2018 SMR roadmap. A study undertaken under a Memorandum of Understanding (MoU) by four provincial governments identified SMR development on three fronts: 1) On-grid SMRs as base load generation source; 2) off-grid SMRs to serve remote communities by replacing diesel; and 3) On and off-grid SMRs of GEN IV for further development and deployment. A CAD $20 million investment in the Canadian Molten Salt Reactor (MSR) developer Terrestrial Energy was made in 2020. At present, the CNSC is conducting review of Terrestrial Energy's MSR, Ultra Safe Nuclear Corporation's MR, ARC's ARC-100, NuScale's Integrated Pressurised Water Reactor (IPWR) based SMR and a few more SMR designs.

SMR Development in China

China became the world's first country with a land based SMR going into operation in December 2021 when its industrial demonstration plant HTR-PM SMR, an HTGR two-unit design, was grid-connected. HTR-PM with two units together has an overall installed capacity of 210 MW(e). SMR ACP100, a 125 MW(e) PWR, is under construction in Changjiang.

SMR Development in Russia

Russia's Akademik Lomonosov floating power unit was grid connected in 2019 and started commercial operation in 2020 and it is being used to supply heat and electricity to communities. NPP projects based on: RITM-200N, SVBR-100, Shelf-M, RITM-200M, BREST-OD-300, RITM-200S are under construction.

SMR Development in UK

U.K. earmarked a package of £215 million in 2020 (to be matched by private investment) for UK SMR which is an industry consortium targeting to develop 16 Rolls-Royce SMRs by 2030 with further potential for export markets. Rolls-Royce intends to build a 470 MWe SMR with availability to the UK electricity grids by the early 2030s. The 470 MWe Rolls-Royce SMR is under Generic Design Assessment (GDA) review process of the UK Office for Nuclear Regulation (ONR). Additionally, the UK Government's Department for Business, Energy & Industrial Strategy is currently assessing the GDA Entry application(s) of Cavendish Nuclear/X-Energy, GE-Hitachi Nuclear Energy, GMET Nuclear Limited, Holtec Britain Limited, Newcleo Limited and UK Atomics Limited.

SMR Development in USA

Subsequent to Licensing Technical Support program for SMRs, the program for Advanced SMR Research and Development (R&D) support was launched in year 2019. Department of Energy (DOE) has worked with NuScale and UAMPS for demonstration of a First of a Kind (FOAK) technology at the Idaho National Laboratory by 2030 and on a broader level, plans to support domestic SMR developers to resolve generic issues in technical and licensing areas.

Under the DOE's Advanced Reactor Demonstration Program (ARDP), having a $600 million funding package, the DOE awarded in 2020 an initial $30 million as funding for risk reduction for five SMR designs viz. BWXT Advanced Technologies, Holtec, Kairos Power, TerraPower partner Southern Company Services and Westinghouse Electric Company for technology development. USNRC certified NuScale Power's 50 MWe power module with the NRC final rule taking effect on February 21, 2023 to permit utilities to reference this design in their licensing applications to build and operate SMRs.

USNRC has under its review, at various stages, the SMR designs of NuScale, Holtec, GEH and mPower.

Table 3.4 summarizes developments in SMRs in countries which currently do not have nuclear power reactors. Further, Table 3.5 summarizes countries with operating NPPs which are developing or deploying SMRs.

Table 3.4: Examples of Initiatives in SMR Technology Development by Countries without Nuclear Power (List is Non-exhaustive) (Source: IAEA)

S. No.	IAEA Member State without Nuclear Power	Rationale of interest in SMRs
1	Denmark	Developing Molten Salt Reactor type SMRs (a private industry endeavor)
2	Estonia	Conducting feasibility studies on SMRs, are positive about demand and potential for SMRs; Estonia's Fermi Energia selected GEH's BWRX-300 SMR for potential deployment by early 2030s
3	Ghana	Small electricity grid; Use IAEA Reactor Technology Assessment Method for SMR studies
4	Indonesia	National nuclear lab performing basic R&D in HTGR; SMR regulatory framework being developed
5	Israel	NPP site selected after site studies; plan to deploy SMR by 2030
6	Italy	National labs and universities actively supporting international SMR development; particularly thermohydraulic testing
7	Jordan	Assessing infrastructure and SMR technology, plan of deployment by 2030s
8	Kenya	Participated in IAEA activities on SMRs; technology assessment underway
9	Morocco	National utility is developing techno-economic studies for SMRs
10	Philippines	Strong interest in NPP and SMRs, conducted feasibility study on SMRs
11	Poland	Few agreements in place for development and deployment of SMRs
12	Singapore	Identified SMR as possible future option through IAEA Technical Cooperation National Project

Table 3.5: SMR Support in Countries Having NPPs (Non-exhaustive) (Source: IAEA)

S. No.	IAEA Member State with Nuclear Power	Rationale of interest in SMRs and key projects
1	Argentina	SMR CAREM is under construction
2	Brazil	Signed arrangement with IAEA for NPP and SMR technology cooperation
3	Bulgaria	Signed MOU with NuScale to discuss possible deployment of SMR
4	Canada	Implementing Canada SMR Roadmap; active regulatory review in progress for SMR designs; utilities collaborating on SMR deployment, SMR site selected
5	Czech Republic	SMR technology development is in progress
6	China	R&D on SMR designs and regulatory framework is underway, one SMR is grid connected, another under construction
7	Finland	SMR R&D in progress, focus on SMRs for district heating
8	France	Developing NUWARD with the objective of starting construction by the end of this decade and hosting a number of start-ups which benefit from the government support programme France 2030
9	Japan	Operating high temperature test reactor at JAEA; developing BWR-type and HTGR-type SMRs
10	Korea, Republic of	National labs and universities supporting international SMR technology development
11	Russian Federation	Technology developer of many SMRs, active SMR regulatory body, Floating Akademik Lomonosov SMR in operation, NPPs based on: RITM-200N, SVBR-100, Shelf-M, RITM-200M, BREST-OD-300 and RITM-200S under construction and planning to start land based SMR construction in 2024
12	Sweden	Pilot study is in progress for the construction of 2 units of SMR; sites have been identified.
13	United Kingdom	Active regulatory body, Technology developer of SMR, Regulatory review in progress
14	United States of America	Active regulatory body, Developer of many SMR designs, NuScale received final design certification from Nuclear Regulatory Commission (NRC)

3.5 SUMMARY

SMR has emerged as one of the most promising technologies in nuclear power. A number of SMR technologies are under development in various countries. A few SMRs are in operation with a few more under construction. Governments, institutions, and industry are supporting development in R&D, funding and deployment.

ROADMAP FOR SMR DEVELOPMENT

4

4.1 TECHNO-ECONOMIC FEASIBILITY OF SMRs

SMRs fulfil criteria for being an emission free energy source and can also be used to produce hydrogen which supports decarbonization of hard-to-abate sectors of the economy. SMRs have the potential to be competitive from an economic standpoint. Volatility in prices of fossil fuels and consequent concerns about energy security have a big impact on prospective viability. An ideal power capacity mix needs to factor-in the aspects related to base-load power and reliability of electricity supply, as countries reduce their reliance on fossil fuels for power generation. The capability of SMRs to operate flexibly and thus, integrate cohesively with renewables of variable nature also has benefits for grid security. Both these options, wherein SMRs can be deployed for providing base-load power as well as integration of renewables into the grid, offer a potentially larger role for nuclear energy. The cost of deployment is likely to be significantly influenced by the SMR technology used and the rate of commercialization. For off-grid applications in isolated locations and towns, with electricity capacity needs between 10 MW and 20 MW, SMRs may be competitive with diesel especially in cases where the cost of transportation of fuel is excessive.

SMR Project Specific Feasibility

The intent of project specific techno-economic feasibility study is to verify whether the claimed potential benefits of SMRs are feasible and also to identify risks, if any. The feasibility study must be conscious of the TRL of the SMR technology being considered with respect to its design development and regulatory certification. Summarized below are the generic points which support project-specific feasibility studies of SMRs-

1. SMR technology vendors are pitching for reduction in cost for Nth of a Kind (NOAK) SMR application. This cost reduction is expected to come mainly from shorter construction and installation time, less complex design, inherent safety of reactors and economics of serial production of SMR modules.
2. Some countries have plans for fleet mode deployment of SMRs backed-up by assurance from governments on certainty of volumes for particular SMR design, which can reduce effective cost of deployment through modularization and learning curve benefits.
3. There have already been several initiatives for international harmonization of SMR licensing processes and regulatory requirements. This could help in standardizing the designs for exports and bring down costs by reducing deployment time.
4. SMRs are perceived to have low technology risk, which has helped to attract investors who are planning to finance new nuclear capacity as an emission free energy source.
5. In a nutshell, SMR economy is influenced by three main aspects: (1) shifting of the construction of the nuclear reactor from on-site mode to factory mode;

(2) leveraging the economics of scale in the factory manufacturing and (3) savings in cost by means of benefits of learning curves[16].

Project specific Techno-Economic Assessment (TEA) needs to be performed against a set of pre-defined criteria. Key assessment points in a typical feasibility study for SMR Technology are indicated below-

1. Potential of the SMR technology towards emission free generation of electricity
2. Operational flexibility in electricity generation
3. Potential to deliver heat for district heating and industrial applications
4. Technology readiness level and validation of its manufacturability
5. Outstanding technical challenges in design
6. Requirement of further R&D investment before commercial deployment
7. Status of review and certification of designs by regulatory bodies
8. Timescales and costs for licensing
9. Intrinsic safety in design
10. Simplicity in design (less complexity)
11. Competitiveness of the estimated Levelized Cost of Electricity (LCOE) of SMR
12. Cost advantages due to learning curve
13. Cost competitiveness of the technology relative to other technologies
14. Fleet deployment possibilities
15. Export potential of SMR technology
16. Challenges in international harmonization of SMR licensing processes for growth in global markets
17. Supply chain constraints
18. Changes required to existing nuclear infrastructure like fuel fabrication and waste disposal facilities

Operational Flexibility of Nuclear LRs and SMRs

As per IAEA study report on "Technology Roadmap for SMR Deployment", most NPPs have operated/are operating in the flexible load-following mode[18]. Such NPPs achieved this with good safety performance. The flexible operation was either envisaged in the original design or was mandated under operational adjustments or license amendments. Key approaches to flexible operation of a nuclear power plant include ramping core power via control maneuvers and reduced flow through the turbine (either via steam venting or redirection to alternate users in integrated systems)[4].

SMRs can perform flexible operation and they are expected to achieve relatively superior load-following capability as compared to LRs due to small core size and other favorable reactor characteristics along with simpler and robust reactor design and the latest digital instrumentation and control. Integrating SMRs and RE into a single energy system, enables SMRs to provide flexibility of electricity generation, ancillary services and other low-carbon products such as hydrogen, synthetic fuels, hot process gases or steam[4].

Leveraging the above intrinsic advantages of SMRs in fulfilling flexibility requirements, it can be possible to incorporate the feature of operational flexibility as an integral part of standard SMR designs. Caution is required to mitigate a possible degradation of efficiency or fuel utilization and a possible rise in maintenance costs by adjusting the reactor designs[4].

4.2 MODULAR DESIGN AND CONSTRUCTION OF SMRs

The Concept of Modularization

Modularization is seen as an essential component of the SMR idea. Modularization technique has been widely used in some of the established industries like aviation and shipbuilding. Modularization implies re-arranging the work in the form of smaller work packages and moving such work packages off-site and off from critical path. These work packages can then be executed independently in a fabrication shop, an assembly area or factory. Detailed planning of such modularization can result in saving of cost and reduction in overall time required to complete the work because of controlled environment, experience and skills gained from repeated execution, optimum equipment utilization and learning curve. When used for a design activity, the term modular means a strategy to design a component by subdividing it into different modules that are easy to build and replace over time resulting in ease of installation and maintenance. The strategy combines the stated benefits in terms of quality and efficiency obtained from serial production, standardization and ease in onsite installation of modules[19].

Steps involved in Module Design Process for SMR Projects

1. It starts with assessment of critical path in the overall schedule for realisation of an SMR Project, amenability to modularization of various systems, structures and components (SSCs) in the project (reactor itself being already conceptualized as modular) and various options available to shift maximum possible work off-site with a target of about 90%, which is crucial to materialize SMR cost advantages.
2. Having identified overall scheme of modularization for the project as per step-1 above, the next stage involves conceptual design of individual modules giving due consideration to installation sequences, weights, dimensions, time duration, equipment required like cranes and positioning equipment, working

clearances in congested areas at site, stability during installation, structural design for installation stages, temporary supporting structures etc.

3. Interface management including readiness of adjacent SSCs, time lag, construction tolerances etc.
4. Feasibility check on mode of transporting the modules from factory to site, width and height clearances, load carrying capacity of roads if required, cost of transportation by alternate routes and requirement of temporary storage facilities.
5. A final check on cost competitiveness of the selected option of modularization considering all costs involved, time required, risks involved and ease of installation.

Adequate funding and time must be allocated for detailed analysis of modularization of the project, on the lines of the process explained above, to harness cost advantages through modularization.

4.3 NUCLEAR POWER INFRASTRUCTURE

The IAEA states that "A nuclear power programme requires a sustainable infrastructure that provides governmental, legal, regulatory, managerial, technological, human resource, industrial and stakeholder support throughout the programme's life cycle"[20]. The infrastructure for nuclear power programme in a country requires planning based on specific goals and interests of the country with regard to energy security, available resources and suitable technology options for generation of nuclear energy. This must be followed by identification of stakeholders, creation of country specific framework of institutions for governance, regulation and financing of nuclear power projects and a long-term vision & commitment up to 100 years.

The IAEA has developed the Milestones Approach for implementation of nuclear power programmes, which is a phased and comprehensive method involving many organizations such as government, regulators, utilities, operators, institutes, universities and public. It has been assessed that the infrastructure required for SMRs is generally like that required for big nuclear power plants (NPPs) with some degree of modification in certain components[18].

4.4 SAFETY AND SAFEGUARDS – APPLICATION TO SMR INSTALLATIONS

Nuclear Safety of SMR Installations

SMRs may differ from large reactors due to their specific characteristics such as remote refueling requirement, transportation of the fuelled reactor to the site, substantial commissioning work getting shifted to the factory, SMR's remote and autonomous operation concepts in surveillance, control & testing, and long refueling time intervals of SMRs. For innovative SMR variants, the knowledge about their physical phenomena is limited leading to uncertainty in absence of comprehensive experimental investigation data. Current nuclear reactor safety standards may not be adequate to address safety aspects of innovative SMR designs. Thus, there is a need for capability building in safety analysis of SMRs by designers, operators and regulators for their speedy development and deployment. Efforts are already underway by the SMR industry, the larger conventional nuclear power industry and regulatory bodies for identifying unique SMR licensing issues and collaborative efforts are being taken for development of alternative approaches to address the issues under available and evolving regulatory paradigm. The IAEA and other international organizations are already taking initiatives for facilitating these efforts and harmonization of regulatory approaches. A detailed account of IAEA initiatives is given in Section 5.6 of this Report.

Safety Standards

Blanket application of LR Standards to SMRs may not be possible. Safety Standards for SMR will have to cater for the modularity concept which is the main theme for SMR development and its sustainability as an industry. Specific features of SMRs need their addressal in SMR specific Standards especially for non-LWR type innovative SMR designs. Also, global growth of SMRs will need harmonization of regulatory requirements of various countries.

The IAEA has launched major initiatives towards addressing the needs of Standards applicable for SMRs. IAEA has started revising SSG12 (Licensing Process for Nuclear Installations) to ensure it is applicable for SMRs, and is soon going to start developing a new standard on 'safety demonstration of innovative technology in power reactor designs'. IAEA has launched a very significant review of applicability of IAEA safety standards to non-water cooled reactors and SMRs conducted in 2021/22 and compiled a safety report available in pre-print as mentioned in Section 5.6.

Safeguards by Design

The IAEA safeguards, being the technical measures intended to facilitate independent verification of a State's use of radioactive material as well as technology only for peaceful purposes, need to be extended to SMRs by addressing SMR specific safeguard challenges such as new fuel types in SMRs, transportation of modules, remote locations, and other needs in terms of manufacturing, material handling, operations, and decommissioning. Thus, extension of the concept of Safeguards by Design (SBD) to different stages of SMR development and deployment will need active involvement of various stakeholders like governments, regulators, vendors, operators and the IAEA[21]. Currently the IAEA is engaged in SBD discussions with several SMR vendors through its Member State Support Programme, as well as internal inter-departmental coordination on '3S' interfaces (safety, security, safeguards).

4.5 SMR ECOSYSTEM DEVELOPMENT

SMR industry is at evolution stage which involves technology development, prototyping and optimization. Early deployment options include green field as well as brownfield applications. Countries adopting SMRs are either already the nuclear power nations or yet to build their first nuclear power plant. Like any nascent industry, SMR industry also needs to find its way through early challenges of technology demonstration, special material availability, special manufacturing technique feasibility, project funding requirements and regulatory harmonization issues.

To overcome such challenges and to ensure sustainable growth for SMR industry, it is essential to establish SMR ecosystems at national as well as global scale. An industrial ecosystem is an analytical notion which is conceptualized to include everything from Small and Medium Enterprises (SMEs) to large manufacturing companies to academic institutions and may also include departments and facilities of governments. Ecosystem concept considers interfaces and dependencies among various players. The objectives or favourable outcomes of an industrial ecosystem can be measured in terms of efficiencies and cost optimization at project development stage, supply chain effectiveness, operational cost benefits and industry growth.

An important ecosystem element recommended for the SMR industry is modularization of SMR components to such an extent that components can be used across different SMR technologies and also across various SMR projects. SMR designs are getting standardized by respective technology vendors. However, for faster deployment and scale-up of SMR industry globally, it is imperative that highly sophisticated product architecture development, platform approach and modularization are widely adopted by global SMR industry. A fully matured SMR ecosystem shall have a platform based and product architecture driven module development system which will be able to design standard SMR modules and components considering local conditions of customer requirements, transport constraints like turning radii, road widths, height clearances, road strength, rail freight weight restrictions etc in the shortest possible time and in an optimized manner for SMRs belonging to different technology domains such as PWR, HTGR, LMFR etc. SMR technology development and deployment shall take the course as depicted in Figure 4.1. The product shall pass through various steps of modular engineering, module standardization, configuration and production with learning curve leading to reduction in time to market, improved efficiency and increased flexibility, optimized procurement, manufacturing ecosystem and plant build ecosystem. SMR needs to be included under green taxonomy. This will also ensure Climate/ Green financing to this sector. Long tenure facility of lending may help the investors to come forward and mitigate financing risk.

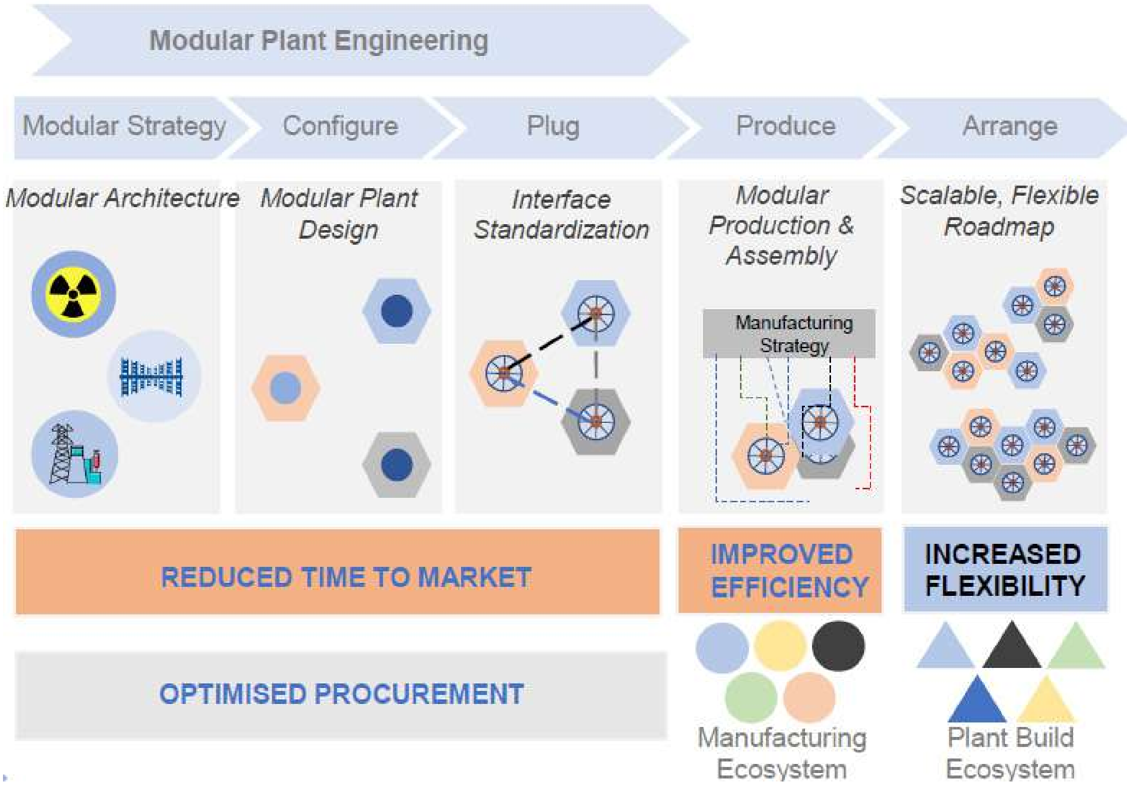


Figure 4.1: *SMR Engineering & Realization*

Developing an Integrated Ecosystem for Realization of SMRs

Following actions are essential to develop an integrated ecosystem for realization of SMRs-

1. Robust strategy to define Modular approach decoupling SMR from site specific works
2. Develop a dedicated design and manufacturing hub ecosystem-
    a. Design agencies and approving agencies co-located with manufacturing entities for scaling up
    b. Ensure manufacturing safety, security, quality, and productivity (avoids supply chain nightmares)
3. Establish vendor selection, appraisal and certification process
4. Develop independent third-party Quality Assurance and Quality Control (QA/QC) vendor for inspections and site certifications through alternate vendor development and benchmarked quality metrics
5. Develop key manufacturing capabilities (Figure 4.2)-
    a. Pressure Vessels and Pumps
    b. Heavy Forgings, Castings, Machining

   c. High pressure/ temperature parts, tubings
   d. Material/Welding technologies
   e. Non Destructive Testing (NDT) facilities

6. Develop special material facilities (Figure 4.3)
7. Leverage 3 Dimensional (3D) Metal Printing for scalability and speed
8. SMRs can be transported by rail/ barge/ road from manufacturing hub to the site of SMR based power plant
9. R&D thrust for continuous improvement
10. Closer collaboration between industry, academia and research bodies
11. Development of qualified contractors, engineering firms and training & certification organization
12. Creation of testbeds

- Heaving Forging Press
- Casting
- Welding Technologies
- Alloys / Superalloys Forgings
- Pre-Stressed Containment Structures
- High Temperature Piping
- Modular Building, Prefab
- Fuel rod sub-assemblies
- fuel transfer arms, fuelling machine carriages and trolleys
- steam separators / mist eliminators
- Control Rod Drive Mechanisms
- Reactor Pressure Vessels
- Calandrias
- End-shields
- Steam generators
- Primary heat transport system
- Heat exchangers
- Valves
- Electrical & Instrumentation
- Fabrication of Structural, Piping and related Modules
- Turbine & Generators
- Sensors, Electronics, Controls

Figure 4.2: *SMR Manufacturing Equipment and Critical Components*

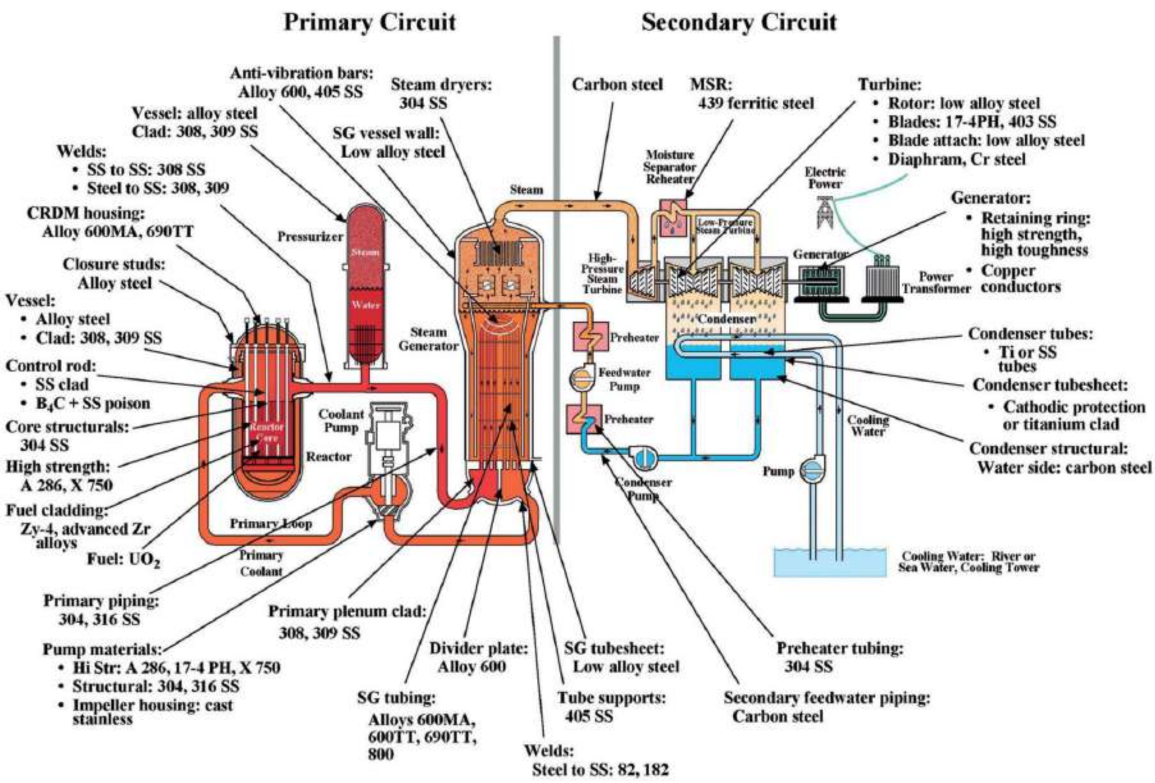


Figure 4.3: *Indicative List of SMR Material Requirement (Typical PWR)[22]*

Industry 4.0, Monitoring, Controls, Security, Safety Management

Manufacturing of SMR modules in controlled factory environment is the main lever identified for cost optimization of SMR technology. State of the art techniques of industrial manufacturing, which have limitations in their use at construction sites, could be deployed effectively in such controlled factory environment.

Globally, Industry 4.0 has brought in a sea change in modern day factory manufacture in terms of process automation, process control, optimization, quality control, feedback and process improvement mainly through integration of new manufacturing technologies, Cloud, Industrial Internet of Things (IIoT), Artificial Intelligence (AI) and Machine Learning (ML) into production facilities.

Towards enhancing the benefits of advanced manufacturing techniques in factory environment for SMR production, principles of Industry 4.0 need to be deployed extensively in SMR industry, with the following features-

1. Integrated Command & Control Centre (ICCC) for monitoring multiple SMR installations
2. Real Time Monitoring with Digital Dashboards and Analytics
3. AI based equipment health prognostics
4. System performance monitoring
5. Safety and Security

6. Asset Digitization and Long-Term Data Archiving and Management
7. Augmented / Virtual Reality tools for training

Talent Management

SMR ecosystem cannot thrive without a concerted effort on talent management. It can be achieved through following initiatives-

Competency Development

Competency development is key to smooth take-off and sustainability of SMR industry. International standardization of designs and close international cooperation in licensing and regulations and in regulatory oversight are prerequisites for commercial viability of SMRs. A robust competency development programme in SMR Technology supplier countries as well as receiver countries is required in the following areas-

1. Modular System Engineering
2. Design/ Engineering
3. Testing/ Manufacturing
4. Construction/ Erection
5. Operation & Maintenance
6. Life Cycle Management
7. Digital Mindset
8. Programme Management
9. Benchmarked Quality & Safety

Institutions

To develop the above competencies, institutional development and involvement are central to SMR ecosystem development, involving-

1. Academia / Laboratories
2. Skill development institutes
3. Certification agencies

Industry Academia Collaboration

Collaboration between SMR industry and academic institutions is necessary for development of technologies through-

1. Sponsored Projects
2. R&D programmes
3. Certification courses

4.6 EARLY IDEAS FOR SMR DEPLOYMENT

Greenfield/Brownfield Applications

SMRs can be deployed on new (greenfield) power plant sites or they can be deployed on existing (brownfield) power plant sites like de-commissioned fossil fuel based thermal power plant sites. Existing power plant sites may present advantages of existing rail connectivity, land availability, water availability, power evacuation infrastructure and remote location away from population. Schematic diagram of such SMR deployment is shown in Figure 4.4.

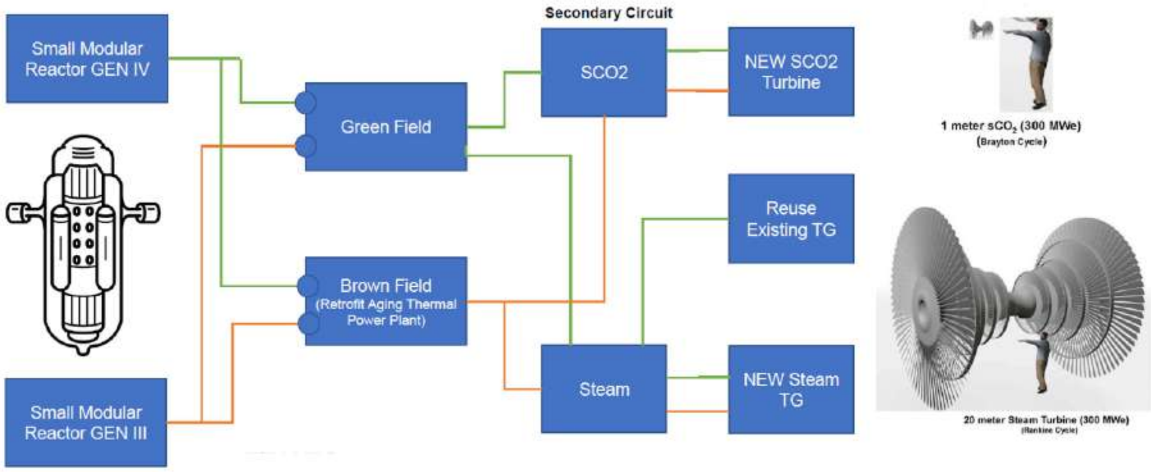


Figure 4.4: *SMR Deployment: Greenfield/ Brownfield Applications*

4.7 SUMMARY

SMRs are likely to use approaches such as product architecture frameworks, modularization, fabrication and testing in factories, and designs that may be replicated and supplied to a number of different power plant operators in various countries. To strengthen and sustain the SMR ecosystem development, a synergistic work environment in the SMR industry is essential along with focus on competency development through collaboration among industry, institutions, and academia. At the same time the sector needs to be included in green taxonomy for accessing climate/ green and low cost finance for SMR development and deployment.

REGULATORY ROADMAP FOR SMRs

5

5.1 SMR LICENSING PROCESS

Introduction

A mature licensing process and regulatory framework happens to be in place in several IAEA Member States, because of their well-established infrastructure for large nuclear power reactors, which can be used as a starting point for development of SMR regulatory framework. Such a framework encompasses the entire nuclear fuel cycle and life cycle of a nuclear power plant starting from site evaluation and extending up to decommissioning. Further, there is extensive internationalization of regulatory framework and sharing of regulatory insights. Specific requirements of SMR technology and new concepts will require additions and changes to this existing framework, which will eventually lead to an independent and compact regulatory & licensing framework for SMRs. A high degree of internationalization is expected since the SMR industry, by its nature, is more likely to expand across the boundaries of nations.

Comparison between Lifecycle Stages of Large Reactors and SMRs

The licensing process is applied at various stages of the lifecycle of a nuclear installation. The current licensing framework for LRs involving design certification, early site permit and a combined construction and operating license can be adapted for SMRs by including the concepts such as modularization, different SMR operating conditions and changes in safety requirements for innovative SMR designs[16]. Table 5.1 gives comparison between the lifecycle stages of large reactors and SMRs[15]. The IAEA SSG-12 Specific Safety Guide on "Licensing Process for Nuclear Installations" is under revision to ensure applicability for SMRs.

Table 5.1: Comparison between Life-cycle Stages of Large Reactors and SMRs[15]

LRs	SMRs
Siting and site evaluation	Siting and site evaluation
Design	Design
Construction	Construction
Commissioning	**Manufacturing of SMR Modules**
Operation	**Offsite Commissioning**
Decommissioning	**Transportation**
Release from Regulatory control	**Onsite Commissioning**
	Operation
	Onsite Decommissioning
	Offsite Decommissioning
	Release from Regulatory control

The licensing process of SMRs may also require additional considerations such as manufacturing of SMR modules, their offsite commissioning and transportation, onsite commissioning of multiple reactor types at one project site, different operating concepts of SMRs, and onsite & offsite decommissioning.

Harmonization of SMR Licensing Regimes

A key requisite for global growth of SMRs is a harmonized Licensing Protocol. Harmonization in SMR licensing regimes is important to realize economies of serial production of SMRs to ensure their competitiveness and commercial viability[23]. Global harmonization in licensing regimes for SMRs based on conventional LWR technology is needed for early deployment of such SMRs in different global markets. Harmonization can also be achieved in areas such as joint safety evaluations and SBD considerations for common technology types.

The IAEA coordinates efforts by Member States that are developing various SMR designs through a systematic approach. With several SMR designs under development and many of them being novel with innovative safety concepts and manufacturing techniques, their large-scale deployment remains a challenging task. The IAEA has undertaken several initiatives for harmonization of SMR licensing regimes by bringing together the regulators, policy makers, SMR designers and operators for developing uniform regulatory and industrial approaches. The IAEA plans to support the national regulators through development of specific guidance[24]. A more detailed account of the initiatives undertaken by the IAEA is provided in section 5.6 of this Report.

The Multinational Design Evaluation Programme (MDEP) has also shown the possibility of cooperation on licensing of a design amongst different regulatory regimes, while preserving sovereign authority of national regulators. Exploration of multilateral licensing coordination, bilateral collaborations and joint safety evaluations by the NEA under MDEP offers valuable lessons for harmonization of SMR licensing regimes[23].

5.2 REGULATORY APPROACH

SMR technology involves new and innovative concepts not implemented in the existing nuclear power projects. The new designs are likely to pose challenges to the regulatory review process because of incorporation of some previously unused materials, component forms, structural forms, equipment and configurations. Many of these features might not have been previously reviewed and evaluated by the nuclear regulatory bodies.

Some advanced concepts like Molten Salt Reactor being adopted in the SMR designs have been around in the nuclear regulatory paradigm for quite some time now, but they are not used in any operating nuclear power reactor. The vendor and license applicant need to ensure the safety of such designs. Their role is to carry out additional research, experimental tests and validate the new analytical tools. The regulator reviews these and considers whether there is any need for additional independent studies regarding the most significant safety issues.

SMR technology is already ready for implementation with PWR, HTGR, LMFR options; however, more work is required on the other advanced options like MSR. Early realization of demonstration plants can facilitate validation and testing of new concepts and will help to develop regulatory procedures for the new SMR concepts and to bring in uniformity in the licensing process. While undertaking the regulatory assessment of such SMR designs, regulatory bodies have to study the design in detail and also its safety bases and operating principles as proposed by developers. Regulatory oversight will be required for the SMR designs employing novel concepts, fuels and safety features, which will have to be proved or qualified by the developers by conducting independent R&D, analysis and testing supported by extra monitoring in early stages of deployment of such concepts[25].

5.3 SAFETY IN DESIGN OF SMRs

Safety of SMRs must be assessed considering SMR specific parameters, their robustness in terms of Defense in Depth principles and their resilience against various types of hazards. Plant specific challenges, due to multiple SMR units being present at one site and shared systems, necessitate careful identification of initiating events such as common-mode initiators. This is the foundation of the safety demonstration. SMR designs should exhibit the capability to mitigate the consequences of severe accidents[26].

SMR developers need to demonstrate the inherent safety in SMR designs. Notable inherent safety advantages claimed by the developers are- (1) a low inventory of nuclear material in the reactor leading to a low residual heat and low accidental release of radioactivity, (2) Less cooling requirement increasing flexibility in site selection, (3) integrated design for some SMR models leading to elimination of risk of large pipe breaks in coolant loops, (4) possibility of underground construction or submersion, leading to better safety against external hazards such as earthquakes and aircraft crash, and (5) Simplification of SSCs, resulting in avoidance of common mode failures[26].

5.4 SAFEGUARDS AND SECURITY FRAMEWORK FOR SMR INSTALLATIONS

Types of Safeguards Agreements

The IAEA concludes mainly three kinds of safeguards agreements with States and regional safeguards authorities: (1) Comprehensive Safeguards Agreement (CSA), (2) Item specific safeguards agreement, and (3) Voluntary Offer Agreement (VOA). In addition, a protocol may also be concluded besides the safeguards agreement[21]. Comprehensive safeguards agreement is concluded pursuant to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and/ or a nuclear-weapon-free zone (NWFZ) treaty, under which safeguards are applied on all source material or special fissionable material in all peaceful nuclear activities within the signatory's territory, under its jurisdiction or carried out under its control anywhere. CSAs are also referred to as ‘full scope’ safeguards agreements. Item-specific safeguards agreement specifies the items (e.g. nuclear material, non-nuclear material such as heavy water), facilities and/ or equipment to be safeguarded and prohibits the use of the specified items in such a way as to further any military purpose. Voluntary offer agreement is concluded between the IAEA and a nuclear-weapon State as defined in the NPT, which is not required to accept the IAEA safeguards under the NPT but has voluntarily offered to do so. The scope of VOA is limited to nuclear material and facilities in civilian activities offered by the State for the application of the IAEA safeguards[27]. Most safeguards agreements in force are CSAs[21].

Measures for Effective Implementation of Safeguards for SMRs

Requirements of safeguards must be considered by the States during implementation of SMR programmes. The best way for implementation is integration of safety, security and safeguard measures that complement each other[25]. More importantly, the Safeguards Agreements need review and adaptation to SMRs because such new reactor technologies did not exist when the agreements and the international conventions were drafted. SMRs potentially require the development of novel or customized technical measures, especially for innovative designs.

One of the major safeguards concerns for innovative SMR designs could be the requirement of a higher enrichment level for fuel. The current safeguards frameworks consider enrichment mostly below 5% for reactor fuel, the exceptions typically involving research reactors. Many LWR-based SMRs will easily meet this description; however, innovative SMR designs may face challenges in this and other areas of fuel design, movement, and storage. Due to their potentially greater deviations from the current safeguards measures, considerable R&D is needed on both the developers’ side as well as that of the State safeguards authority and the IAEA to develop efficient safeguards approaches for SMRs and build the requisite expertise. Specific SMR features like their transportability or floating nature may also create new challenges for the existing safeguards paradigms [23].

Security of SMR Installations

The IAEA in the publication “Lessons Learned in Regulating SMRs” states that the overarching goal of the nuclear security framework in a country shall be “to protect persons, property, society, and the environment from malicious acts involving nuclear material and other radioactive material”[25].

The objectives of security of nuclear material and nuclear facilities are to protect nuclear material and sensitive information against unauthorized removal; to protect nuclear material and vital safety equipment from sabotage; to detect and recover any material out of regulatory control; and to mitigate the radiological consequences of sabotage. Tools implemented towards achieving these objectives include security measures to deter unauthorized access or removals, detect such acts or attempts, or delay an adversary from completing such acts (thereby allowing more time for response forces to intervene), and the protection of sensitive information and information systems[23]. To accomplish these goals, the application of a structured framework consisting of multi-layered defensive approach for physical protection of SMR facilities is necessary.

5.5 ENVIRONMENTAL IMPACT ASSESSMENT

Environmental Impact Assessment (EIA) is a standard procedure followed by governing bodies and regulators for assessing the significant impacts of a project or development proposal on the environment. It helps decision makers in taking necessary actions to avoid, reduce or offset those impacts. Key stages in a typical EIA include screening, consideration of various alternatives, preliminary assessment, scoping, mitigation of undesirable effects, the main EIA study and the final environmental impact statement including further review and monitoring. EIA is a requirement for licensing in various regulatory regimes.

What the IAEA Licensing Process Recommends for EIA of Nuclear Installations

The IAEA licensing process recommends that a site-specific EIA shall be carried out, and also a legal relation to the licensing process shall be established. The regulatory body shall consider factors pertaining to the risks for the environment and communities including location of the communities, population density, emergency response preparedness, prevailing environmental conditions, marine conditions, and consequences of discharges from the concerned nuclear power plant[28].

Requirements for Effective EIA for SMR Sites

EIA for nuclear facilities (SMR included) shall consider the existing status of the environment, and environmental implications of building, operating, decommissioning, and abandonment of the nuclear facility; it shall also contain environmental management and monitoring strategies. Environmental aspects which need to be analyzed in an EIA considering design or type of the NPP or the SMR are categorized into ten different categories such as atmospheric environment, aquatic environment, preservation of quality of soil, wildlife preservation, impact on human health and socioeconomic considerations. Potential transboundary effects of NPP/ SMRs must also be considered.

Often, the EIA may be conducted early in the SMR licensing process when the engineering design information of the SMR may be preliminary. However, alternative techniques, such as a cautious evaluation, may compensate for the lack of detail. Getting an understanding of the public opinion about a proposed nuclear facility is an important constituent of EIA to ensure that views from various stakeholders are taken into account.

The IAEA recommends that EIA data for SMRs include all aspects of the EIA report for conventional NPPs. Modifications to this list, however, are at the discretion of each Member State, depending on special needs such as additional legislations and also consideration of SMR technology specific impacts, if any.

SMRs may possess some features which are entirely different from conventional nuclear power reactors when it comes to conducting EIA such as power rating of SMR, plant area, modular design, non-electric uses, siting locations, co-location of SMRs with industrial facilities, subterranean construction, refueling source term, and nuclear waste management.

EIA must address issues pertaining to the combined impact of several SMRs at one site or progressive impact of SMRs introduced with a time lag at a given site, with likely revisions in EIA from time to time. EIA can be implemented through a prescriptive or a risk-based methodology, or a combination of the two.

In a nutshell, EIA for SMR projects is largely in line with that for LRs. However, deviations in SMR technologies with respect to conventional nuclear plants (LRs) need careful examination, assessment and consideration in EIA for SMRs[28].

5.6 INITIATIVES FROM IAEA ON HARMONIZATION OF REGULATORY AND INDUSTRIAL ACTIONS ON SMRs

Considering the global interest in SMRs, the IAEA has launched several initiatives related to SMR development and deployment. As a result, the IAEA has prepared a number of publications and created many international forums that contribute to SMR development.

The IAEA has provided a broad-based support for enabling the process of deployment of SMRs by coordinating the SMR technology development initiatives taking place in the Member States. Some of the recent initiatives include-

- **Nuclear Harmonization and Standardization Initiative (NHSI)**– The IAEA launched this initiative in 2022 with the main purpose of harmonizing the SMR regulatory activities and standardizing the industrial approaches for realization of the advanced reactor concepts, especially the SMRs.

  NHSI work plan was developed in two separate but complementary tracks- the regulatory track and the industry track (technology holders and operators)[29].

  Under the regulatory track, focus is on- (1) building a framework for information sharing, (2) developing a framework for international pre-licensing regulatory design review and (3) developing approaches for leveraging the reviews by other regulators. The IAEA expects that the NHSI will give an impetus to the regulatory collaboration, thus avoiding the duplication in regulatory efforts, will improve efficiency of regulatory reviews and will help in reaching common regulatory positions within the requirements of nuclear safety and within the realms of national sovereignty.

Under the industry track, focus is on achieving standardization in industrial approaches followed in manufacturing, construction and operation of SMRs so as to reduce the time to licensing, project costs and time to deployment of SMRs. This is envisioned to be achieved under the four objectives of- (1) harmonizing the high level user requirements, (2) sharing of knowledge about national codes and standards, (3) software testing and validation for modeling of SMR designs and (4) nuclear infrastructure establishment for development of SMR projects.

- **SMR Regulators Forum** (since 2015): The IAEA has promulgated a platform for national regulators to discuss and collaborate on SMR technology regulation. This forum facilitates the enhancement of the nuclear safety in SMRs by resolving common nuclear safety issues challenging the SMR regulatory reviews and by helping in making robust regulatory decisions.
- **Coordinated Research Projects (CRPs)**: The IAEA facilitates the collaboration on common research themes among research institutes in its members states through the CRPs. SMR related CRPs include-
    - CRP on economic appraisal of SMR projects, launched in 2020
    - CRP on Challenges, Gaps and Opportunities for Managing Spent Fuel from SMRs, launched in 2023
- **Technical Working Group (TWG) on SMRs –** The IAEA launched a TWG on SMRs in 2018
- **Medium Term Strategy (2022-2029):** To provide support to various SMR stakeholders like operators, regulators, industry, and governments in dealing with challenges faced in SMR deployment[30]
- **The IAEA Technology Roadmap for SMRs:** A publication which gives guidance to the Member States in terms of generic roadmaps that can be used as reference[18]
- **The IAEA Platform on SMRs and their Applications:** A platform on the IAEA website to provide support to the Member States in development and deployment of SMR technology
- The 2022 IAEA publication "**Small Modular Reactors: A New Nuclear Energy Paradigm**"[17]
- The 2022 IAEA publication "**Advances in Small Modular Reactor Technology Developments**"[13]
- The 2020 IAEA publication "**Applicability of Design Safety Requirements to Small Modular Reactor Technologies Intended for Near Term Deployment (LWRs & HTGRs)**"[31]
- The 2022 IAEA publication "**Safety Report on Applicability of Safety Standards to Non-Water-Cooled Reactors and Small Modular Reactors**"[IAEA Preprint][32]

- **Member State Support Programme tasks on SBD for SMRs:** facilitating early SBD discussions with specific vendors, with the support of State safeguards authorities.

5.7 SPENT FUEL AND WASTE MANAGEMENT

For most conventional light-water PWR technology based SMR designs, Uranium Oxide (UO_2) fuel with shorter fuel assemblies can be used[33]. Existing regulatory guidance can likely be used because no substantively unique features are expected in the spent fuel and waste generated from these SMRs. Regarding radioactive waste from such LWR SMRs, in the absence of detailed data, it can be expected that the composition of low-level wastes will be similar to large LWRs and thus same or similar regulations and guidelines would apply. Approach may likely be the use of spent fuel pools followed by dry storage. This may also require redesigning casks for transportation of fuel because of differences in the size of fuel assemblies.

In the case of non-LWR SMRs, (for e.g., based on LMFR, HTGR and MSR concepts) new fuel types may need higher enrichment and different fuel forms which may lead to design and realization of totally different types of fuel fabrication facilities[33]. This may require re-design of casks for fuel handling & transportation, new research & development efforts given the expected variation in fuel properties and commensurate changes in regulatory provisions. Because of new types of spent fuel and nuclear wastes generated from non-LWR SMRs, which are different from existing nuclear power plants, they may involve new management or disposal approaches. Nuclear regulators will have to assess the regulations and guidelines to ensure that they are adequate to protect public health and safety.

In general, the current spent fuel and waste related regulatory framework is broad enough for application to the light-water SMRs. However, changes to this framework may be needed for non-LWR type SMR designs. The SMR technology developers need to consider the new forms of spent fuel and nuclear waste that may get generated during SMR operation, anticipate any new issues in their processing and provide for such requirements in their designs, plant layouts and project planning.

A study presented in the Proceedings of the National Academy of Sciences in 2022 has expressed concerns that most of the SMR designs may increase the volume of nuclear waste because of the use of neutron reflectors and specific types of fuels and coolants in SMRs[12]. The study presents some observations regarding the challenging decay heat power and the radiochemistry of SMR spent fuels. SMR fuel development and waste management processes need to address these issues in an effective and cost optimized manner.

The IAEA Bulletin of June 2019 states that the countries already having large nuclear power reactors in operation possess knowhow and infrastructure to manage spent fuel[11]. Hence, they may be in a better position to manage spent fuel from SMRs based on their experience in the existing technologies with incremental research and infrastructure development. Countries not having existing nuclear power infrastructure need to develop capabilities for SMR spent fuel management and the required infrastructure. Management of the SMR spent fuel as well as the SMR radioactive waste shall be an important consideration while selecting SMR technologies for deployment in such countries.

Some SMR power plants are envisaged to have refueling after 3 to 7 years. Some SMRs are being designed to operate for 30 years before refueling. This long refueling time will be positive in terms of reduced effort and investment in management of spent fuel [11].

Given this scenario of spent fuel and waste management, it is likely that a combination of technological and policy issues vis-à-vis spent fuel and waste management may arise especially for some FOAK SMR technologies which need to be resolved at the earliest. A Coordinated Research Project (CRP) is being undertaken by the IAEA that aims to address such challenges in managing the spent fuel of SMRs using various technologies.

5.8 SUMMARY

At present, nearly 80 SMR designs are being developed in various countries. Some of these designs are innovative and not yet licensed. Some designs employ modern manufacturing methods which are not yet prevalent in the nuclear industry. To hasten the process of SMR deployment, harmonization of SMR regulatory system is important. Initiatives are being undertaken by SMR stakeholders and international regulatory bodies to establish links among regulators, operators, SMR technology vendors, governments and policy making bodies to accelerate the efforts towards global harmonization of codes, standards, and licensing parameters.

KEY ENABLERS TO PROMOTE PRIVATE SECTOR INVESTMENT IN SMRs

6

6.1 GENERAL

SMR is a promising technology among various available options for energy transition. At present, SMR technology is in development phase with only a few SMRs deployed or under construction, and the technology is not yet available commercially on any significant scale[1]. According to IEA's NZE scenario, advanced reactors like SMRs are expected to ramp up their contribution to emission free energy supply and constitute a significant part of new nuclear capacity additions after 2030, especially in advanced economies[1]. This comes with the premise that continuous and fast progress is made in developing and demonstrating the SMR technology and bringing down cost curves.

Global awareness and priority assigned to the NZE and energy security challenge are pushing stakeholders, including governments, to support emission free technologies like SMR. With such a promising and scalable solution for energy transition expected from SMR technology, it becomes imperative for governments and other stakeholders to maximize private sector investment in SMR projects. This chapter elaborates on rationale behind important role of private sector investment in SMR sector, including analysis of factors hindering such investment and ways to de-risk investments.

6.2 IMPORTANCE OF PRIVATE SECTOR PARTICIPATION IN SMR DEVELOPMENT

Financing remains one of the critical challenges against accelerated development and deployment of SMRs. Due to high degree of uncertainty in SMR costs (which is expected of new technologies under development and initial deployment), there is limited private investment in the sector. First prototype plants are likely to see only partial benefits of modularization and standardization with limited learning curve benefits.

Private sector participation remains constrained in the sector due to high investment costs, safety issues, long construction time, nuclear waste management issues and proliferation risks. Government support for R&D along with initial funding for building and operating SMRs would be critical to instill confidence in future large-scale deployment of SMR technology.

Attracting Private Sector Financing is Hard Without Initial Government Support

The conventional nuclear power projects, thus far, have massive involvement from governments and entities promoted by governments in terms of creation of nuclear infrastructure including regulatory framework, direct investment, Power Purchase Agreements, sovereign guarantees, etc. However, constrained Government budgets necessitate the involvement of private capital to catalyze growth in the sector. Government stakeholders may analyze SMR projects on the lines of project financing models, along with de-risking of projects, so as to attract private sector funding in the SMR industry[34].

Nuclear projects, because of their large size and high complexity, have been dependent upon government support to ensure revenues from electricity generation and to reduce risk to investors. SMR projects may attract low cost private investment as they are relatively smaller in size and less complex at site in comparison to LRs.

Venture capital funding for cleantech and energy projects has remained stagnant. For example, in the USA, Venture Capital (VC) funding in the energy sector in 2020 amounted to only 1% of total VC funding, as shown in Figure 6.1. "Hard" clean energy technologies like SMRs find it relatively difficult to attract private capital due to perceived technology development risks and long return time frame.

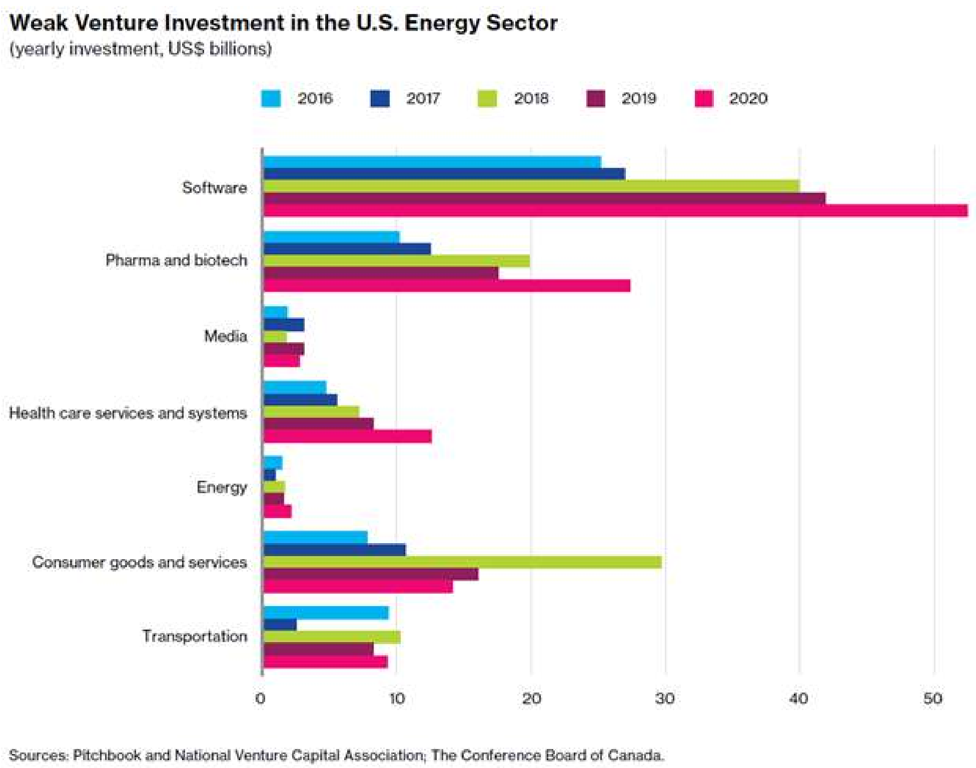


Figure 6.1: *Weak Venture Investment in the U.S. Energy Sector*[35]

Private sector participation in SMR deployment can be encouraged through the following key incentives:

1. Political support for SMR initiative
2. Conducive SMR regulatory framework led by national regulators
3. A mature nuclear supply chain
4. A successful 'Proof of Concept/demonstration can drive investor confidence/ business case
5. Unambiguous Civil Nuclear Liability Framework and supporting legal structure
6. An effective energy policy framework and incentives for low-carbon technologies

7. It is essential to provide (a) the seed capital required for innovation, (b) funding for demonstration and commercialization and (c) financing for scaling-up operations to enable the development and growth of such initiatives.

6.3 ALTERNATE AVENUES FOR PRIVATE INVESTMENTS IN SMR

Evaluation of early stage SMR development in Canada, the USA, and the UK indicated that SMR technology vendors are sourcing investment from two non-traditional sources - high-net-worth individual investors, often organized through a family office, and corporate partnerships with Engineering, Procurement and Construction (EPC) firms[35].

Family offices are a key source of early-stage finance for SMR vendors, supporting technology development and licensing. They provide patient, risk-tolerant capital in ways that traditional venture capital funds cannot. While these investors expect a commercial return, their investment decisions are value driven. As a result, the investors are willing to accept more risk and longer periods of illiquidity. However, these sources of investment are not sufficient to advance the sector.

The EPC companies could play a critical role in later stage technology development and construction of first-of-a-kind power plants when risk-mitigation frameworks are appropriately designed. In the USA and the UK, such investment comes through equity partnerships with EPC firms. Through these partnerships, EPC firms supply equity to vendors and then provide design, manufacturing and construction services for power plants. This consortium model allows vendors to access equity from the balance sheets of large firms and share risk with partners along the path to commercialization[35].

6.4 DE-RISKING SMR PROPOSALS

Governments and private players have a critical role to play in commercializing “hard” clean technologies like SMR. This support could be in the form of demand assurance for nascent technologies, financing R&D projects for accelerated technology development and fostering regulatory and market frameworks, etc. In each case, the underlying objective is to reduce uncertainty and risk to crowd in private capital.

At the technology development stage, vendors can benefit from cost-sharing to reduce risk. At the project construction stage, private sector partners can benefit from risk mitigation measures like loan guarantees or long-term price contracts.

To encourage innovative technologies that are required to confront the climate crisis, incentive and support measures would be crucial. Solar photo-voltaic technology has depended on decades of public sector support initially, including R&D investment and feed-in tariff programmes designed to scale up the market. In exchange for public investment, governments could also take equity stakes in companies or intellectual property, ensuring their risk is rewarded when a commercial venture succeeds[35].

How to De-Risk SMR Projects? A Matrix of Actionable Points

Table 6.1 summarizes actionable points towards de-risking SMR projects so that they become more attractive for private sector partnership[34].

Table 6.1: Actionable Points to De-risk SMR Projects

S. No.	Area in SMR Project	Action Required
1	Reactor Safety of SMR	Demonstrate entire safety paradigm for the SMR design, especially the reactor safety. This will require building test facilities. Natural convection based SMR designs will need experimental proof based on full scale tests before any regulator can license them. Failing in this could lead to delays during regulatory review and approvals.
2	Interfaces in Regulatory Process	Interface structure needs to be clearly defined, bringing in regulatory cooperation and harmonization in Licensing process.
3	Detailed Design of SMR	Detailed design R&D based on reference SMR plant using a reliable supply chain is required.
4	Inter-Governmental Coordination Framework	Address issues pertaining to nuclear liability, safeguards, export control measures and participation of industries.
5	Vendor Management	Prepare framework for integrated project delivery with experienced vendors and sub-contractors.
6	Owner-Vendor Partnership Framework	Prepare a legally binding contract with defined roles and responsibilities.
7	Project Management	Implement extensive project management framework in SMR projects.
8	Human Resource Development	Long-term initiatives in technical training and capability building must be undertaken.
9	Safeguards by Design	Early interaction between IAEA, countries and SMR vendors to consider safeguards requirements in designs is advisable.
10	Revenue-securing mechanisms	Providing certainty over future revenues through off-take agreements, power purchase agreements (PPA), and contracts for differences (CfD), among other revenue-securing mechanisms.

De-Risking SMR Proposals by Reducing Uncertainty in SMR Contracts

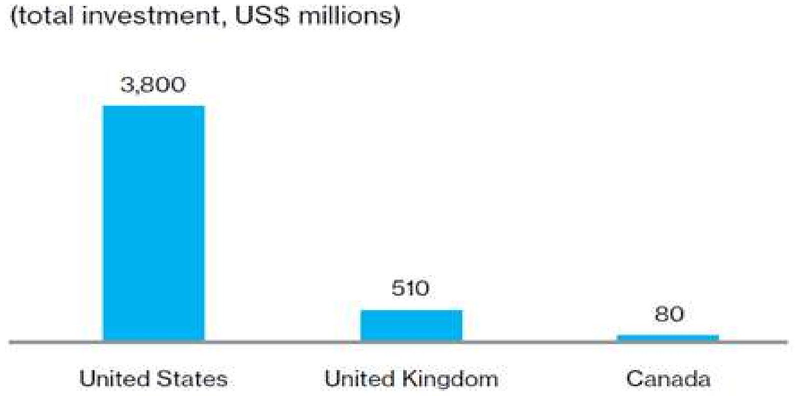
As SMRs are in nascent technology development and licensing phase, de-risking of SMR projects can be managed in two ways- funding from government and pre-qualification of limited number of potential vendors for further engagement by utilities. These two initiatives can reduce uncertainty amongst private investors because-

a. Pre-qualifications and funding awards provide a third-party evaluation and diligence to investment proposals and consequently bring down technology risk for investors. This diligence is particularly useful when performed by sector specialist utilities or government departments with sector expertise. While investors will perform their own technical due diligence, evaluations from other stakeholders mitigates the project risk.

b. Second, government grants and funding reduce political uncertainty by demonstrating "skin in the game." The political context surrounding SMR deployment introduces significant risk for investors. Public funding demonstrates that the government values the individual vendor and the broader sector's contribution to country's clean energy transition.

c. Finally, down-selection and government funding reduce investor uncertainty by clarifying a commercial pathway for SMR deployment. This funding is the most valuable when awarded as part of a commitment to both technology development and demonstration of a FOAK power plant.

Risk mitigation approach in the SMR industry has two limitations: significantly smaller funding levels and less strategic programmes. Figure 6.3 shows comparative levels of public funding for SMRs in Canada, the US and the UK.



Note: Figures for the United States and the United Kingdom represent funding issued or earmarked under the US Advanced Reactor Demonstration Program and UK Advanced Nuclear Fund, both initiated in 2020. Figures for Canada represent all funding committed by federal and provincial governments for SMRs to date.
Sources: Ahn and others; UK Department for Business, Energy & Industrial Strategy; The Conference Board of Canada.

Figure 6.2: *Public Funding for SMRs*

Canada lacks a sector-specific funding program. Unlike the USA and UK, funding for the SMR industry in Canada is allocated by Innovation, Science and Economic Development Canada (ISED) through the Strategic Innovation Fund (SIF). The SIF is one of Canada's primary innovation-oriented funding programmes providing support for large-scale projects across all sectors of the economy. Main challenge with SIF is the long evaluation timelines that create a high degree of uncertainty for applicants. Cost-share awards are an excellent way to catalyze private sector investment, but this uncertainty makes it difficult for vendors to coordinate programme and investor timelines. Both the SIF and the United States' ARDP are cost-share programmes designed to leverage private sector investment. Unlike the SIF, ARDP provides dedicated funding across three streams of SMR technologies. A dedicated approach increases the prospects for funding, makes the process more transparent, and increases the speed of administering applications.

De-Risking SMR Proposals – Break Down of Financial Risk

Analysis of various risks and their contribution to overall risk is done by organizing them into a set of factors depending upon two criteria-

- Different phases in life cycle of investment project like Licensing, Construction, Operation, Decommissioning & Decontamination (D&D)
- Breaking down risks during each of the life cycle phases into the risk factors for tracing the key sources of uncertainty

Figure 6.3 summarizes the two level breakdown of financial risk.[36]

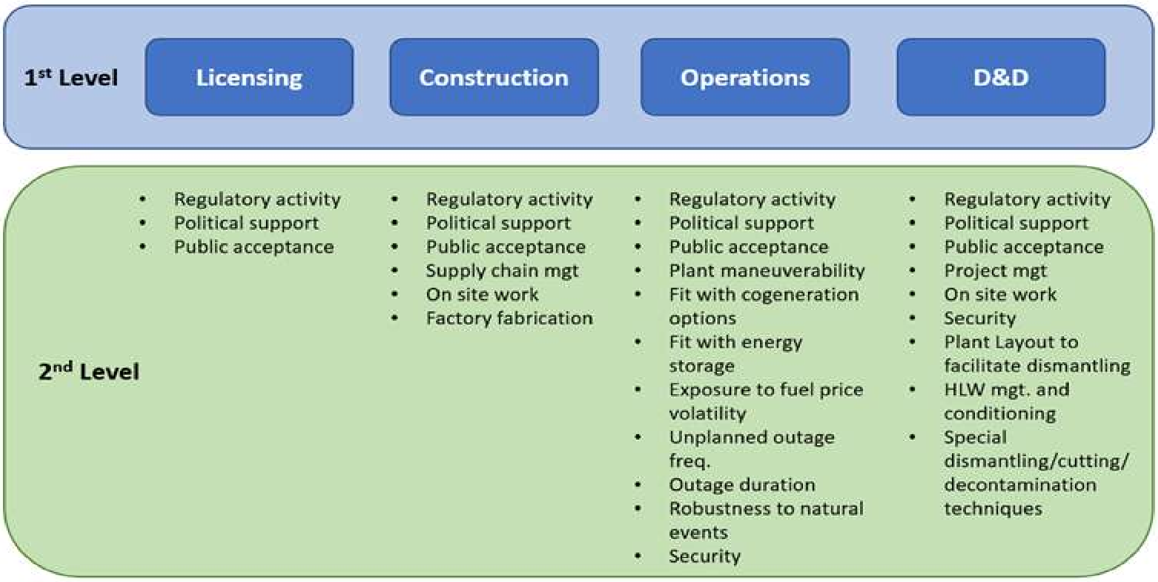


Figure 6.3: *Risk Break-down Structure at Two Levels*

6.5 SUMMARY

SMRs have potential to play a key role in Energy Transition. The SMRs are conceptualized to provide benefits of flexibility in deployment, reduced safety risks, compact design and advantages of economies of scale from standardization and modular construction. Given the nascent nature of the technology and investor perceptions of business and regulatory risk, collaborative involvement of government and private sectors is critical to de-risk projects and accelerate commercialization.

THE WAY FORWARD

7

SMRs can emerge as a technology to provide clean electricity, hydrogen and process heat. SMRs can provide stable baseload electricity and have the capability to operate flexibly to support integration of variable RE into the grid. They can also serve non-electric applications such as desalination and district heating. Micro SMRs can be used to supply electricity as well as heat for communities in remote locations.

SMRs, currently under development stage, have reached a fair degree of maturity for PWR and PHWR type technologies; whereas other technologies such as HTGR, LMFR and MSR are in R&D stage with potential to crystallize workable SMR designs in near term. So far, the safety standards and legal frameworks for the nuclear energy have been developed and established in context of PWRs, BWRs, and PHWRs. For other reactor types namely HTGR, MSR, etc.—they have to be developed. Regarding SFRs, some countries like India, Russia and France have developed regulatory frameworks, while others have to develop them. During deployment of SMRs with innovative design features, novel technology and state-of-the-art models, it is expected that several new challenges may be faced leading to changes in the legal, regulatory and safeguards frameworks.

Early realization of a few demonstration plants for SMR designs can reduce the intensity of risk perception which can give impetus to supply chain formation and bring investment and stability to the industry. Adaption and streamlining of licensing and regulatory frameworks by taking key SMR attributes into account are also important to develop a global SMR market. With government support and harmonization in licensing and regulatory approaches, SMRs can see growth under the NZE initiatives. In nutshell, if SMRs are going to play a meaningful role in the climate change mitigation, the FOAK SMR units must be under deployment by early 2030's (or even earlier) for them to achieve sufficient market penetration and make a difference[37].

Successful deployment of SMR technology must leverage private sector investment. A robust and technology-neutral policy framework is required for securing private investment including factors currently having growing influence on investment flows such as taxonomies and environmental, social and governance factors[1].

Some of the key points have been highlighted in the table below as the way forward for development and deployment of SMR:

Table 7.1: Way Forward for SMR Development and Deployment

S. No.	Key Points	Way Forward
1	Prototype/ Demonstration Projects	• Reactor's prototypes need to be constructed to validate the design, manufacturing, installation and operational aspects as well as verification of SSC´s reliability. • Flow of private investment at demonstration stage may be encouraged.
2	Early Deployment	• For SMR to play a meaningful role in energy transition scenario, the FOAK units of SMRs need to be deployed by the early 2030s.
3	Updating Existing Nuclear Regulatory Frameworks	• Regulations and guidelines need to be reviewed and revised to keep them up to date in context with innovative designs and features of SMRs. • The existing nuclear safety regulations are mostly designed for land-based plants and unit concept of large reactors. For the concept of multi-module and flexible operation of SMRs, these regulations and guidelines need to be modified. • The nuclear regulatory framework should be comprehensive to allow various kinds of SMR technologies and designs.
4	Collaborative Framework for SMR Projects and Harmonization of Licensing Policy and Nuclear Liability	• Stakeholders need to share technological breakthroughs, lessons learnt, best practices and regulatory insights at early stage of technology development. • IAEA standards may be considered for adoption by respective countries, in case of absence of national guidelines. • Regulatory framework, project development model, risk sharing frameworks and guidelines pertaining to licensing, project completion, and nuclear liability need to be developed. • A pre-licensing vendor design review can facilitate early identification and resolution of potential technical or regulatory issues in design process. • Streamlining of international nuclear liability conventions with the country specific legislation is required. States may either amend domestic laws to include requirements and specifications of the International Conventions, or may enforce International Conventions in totality as self-standing legal instruments.

S. No.	Key Points	Way Forward
5	Comprehensive Safety	• A comprehensive safety assessment methodology is required to ensure that the Systems, Structures and Components (SSCs) of SMRs are designed, manufactured, constructed, installed, commissioned, operated, tested, inspected and maintained according to appropriate safety standards. • Existing safety assessment methodology should be updated to define emergency planning zone for SMRs. • Standard Operating Procedures (SOPs) for safe handling of spent-fuel and reprocessing need to be followed.
6	Innovative Financing Frameworks	• Availability of low-cost finance, green finance and incorporation of nuclear into green taxonomy can improve the economics of SMR projects. • De-risking SMR projects and establishing attractive financing frameworks such as blending finance, green bonds, etc. is pivotal for incentivizing private investors. • It has been observed that venture capital is a poor fit for the "hard" SMR sector. Hence, the public and private sectors must work together to identify alternative sources of early-stage finance.
7	Human Resource, Skills & Awareness	• Developing human resources, identification of skill gaps for multi-module and remote operation of SMRs, design of training programmes & simulators, capacity building for readiness level assessment and local community awareness are critical for sustainability and socio-political acceptance of the SMR industry.
8	SMR Manufacturing Facilities	• When SMRs reach the NOAK stage and economic benefits from serial production become important for business sustenance, large manufacturing facilities would need to be established by vendors/suppliers. • Early start for development of such facilities with involvement of interested stakeholders will be the key to get timely supplies.
9	Modularization and Design Standardization	• SOPs, guidelines and frameworks need to be developed for standardization and modularization to encourage the adoption of best practices and ensure that SMRs meet the highest standards of safety and performance. • Components need be standardized for usage across multi-module SMR designs leading to speeding up of manufacturing process.

S. No.	Key Points	Way Forward
10	R&D Programme	• Formulation of R&D programme and knowledge sharing platform by bringing together nuclear power utilities, regulators, government agencies, industries, universities, and research organizations is crucial for accelerating the development of a vibrant SMR ecosystem.
11	Nuclear Supply Chain Resilience	• Development of a concerted strategy for retooling and expanding the existing nuclear supply chains to meet growing demand for SMRs and further expansion of nuclear industry.
12	Safeguards by Design (SBD)	• Consideration of Safeguards requirements during early stages of SMR designs in close interaction with IAEA, such that the implementation of Safeguards can be effective throughout the life cycle of SMR plant.

SUMMARY

For achieving climate goals, nuclear power can contribute substantially to decarbonization of energy sector. Therefore, it is important to enhance efforts towards exploiting the full potential of nuclear energy. At the same time, the highest standards in safety and security already reached by the nuclear industry need to be maintained and continuously strengthened. There is a need to have research and innovation in the current nuclear fleet to extend the life of NPPs, reduce construction time and costs of nuclear power installations, develop new financial mechanisms that favour investments in advanced nuclear technologies including SMRs, adapt nuclear technologies for integration with other low-carbon technologies and diversify the use of nuclear energy in non-electrical applications such as co-generation, hydrogen production and general industrial applications.

SMRs can play an important role in mitigation efforts and strengthening the nuclear industry. They can accelerate energy transition by facilitating greater penetration of nuclear energy as they possess attributes such as low inventory of nuclear material per reactor, speedy fabrication through standardization, fast realization using modularization techniques, feasibility of deployment at difficult sites and phased capital expenditure by adding successive batches of SMR modules. As many SMR designs are under various stages of research, development and licensing in different countries, global regulatory harmonization, developing manufacturing ecosystem and bringing in public as well as private capital would be the key for growth of SMR industry.

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