IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
Vol. 13, Issue 10, October 2023, ||Series -I|| PP 38-51

Emergence of Small Modular Reactors (SMRs) in the Energy Transition

Prabh Deep Singh Kang & Santosh Trimbake
College of Military Engineering (C.M.E), PUNE
Received 05 October 2023; Accepted 19 October2023

I. Introduction

1. The World Meteorological Organization's data reveals that between 1920 to 2019 50% of recorded disasters were attributable to weather, climate, and water-related hazards. Furthermore, these events were not only accountable for 45% of reported fatalities but also translated into a staggering 74% of economic losses during this period.These disasters can be attributed to climate change, primarily fuelled by the release of greenhouse gases, with carbon dioxide being a significant contributor. This release stems from the burning of fossil fuels andthe energy sector are a major contributor to these emissions. The transition to cleaner and more sustainable energy sources is essential to mitigate these environmental impacts.

2. This stark reality underscores the undeniable urgency of a transition within the energy sector. This transition serves as a vital response to the critical challenges that our world faces today. Its core objectives are clear: we must diminish our heavy reliance on fossil fuels, confront the pressing issue of climate change, and forge a path towards a sustainable future. To attain this transition, it is imperative to shift towards cleaner and more renewable energy sources, prioritize the enhancement of energy efficiency, and zealously pursue innovative technologies.The transition in energy sector is important due to following challenges posed by climate change:

a. **Intensification of Extreme Weather Events:** Climate change is inherently linked to the heightened frequency and severity of extreme weather occurrences, including hurricanes, droughts, and wildfires. These events have the potential to wreak havoc on communities, infrastructure, and agriculture.

b. **Threat of Rising Sea Levels:** Rising global temperatures lead to the melting of polar ice caps, contributing to the alarming rise in sea levels. This poses a grave risk to coastal areas, low-lying islands, and major coastal cities, rendering them susceptible to flooding and saltwater intrusion.

c. **Loss of Biodiversity:** Climate change disrupts ecosystems, leading to habitat degradation and the endangerment of species. The consequences ripple through food chains, agricultural productivity, and the overall health of the planet's ecosystems.

d. **Migration and Conflict:** Climate-induced factors like resource scarcity and population displacement can trigger migration and even conflict, which can destabilize regions and have broader security implications.

e. **Economic Turmoil:** The economic toll of climate change is substantial, encompassing damage to infrastructure, increased insurance costs, and reduced agricultural yields. These factors strain economies and governments.

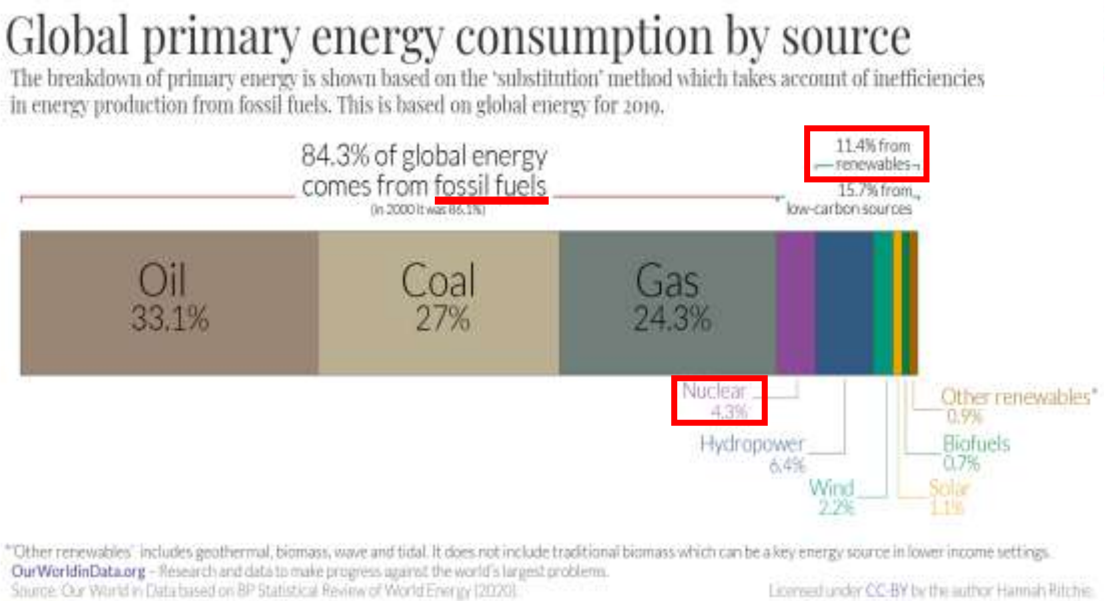
f. **Global Cooperation:** Addressing climate change is a global endeavour that necessitates international collaboration. It is crucial to reach consensus on shared goals, targets, and policies to effectively mitigate the consequences of climate change.

Energy Transition

3. Across the globe, there is a noticeable worldwide shift towards embracing renewable energy sources like wind and solar power as part of a collective endeavour to combat climate change and reduce carbon emissions. These sustainable energy options are highly esteemed for their eco-friendliness and positive environmental impact. Nevertheless, it's important to acknowledge that they present challenges due to their intermittent energy generation. To meet global climate objectives and work towards the ambitious goal of achieving net-zero emissions, it is imperative that we move away from fossil fuels and decrease carbon

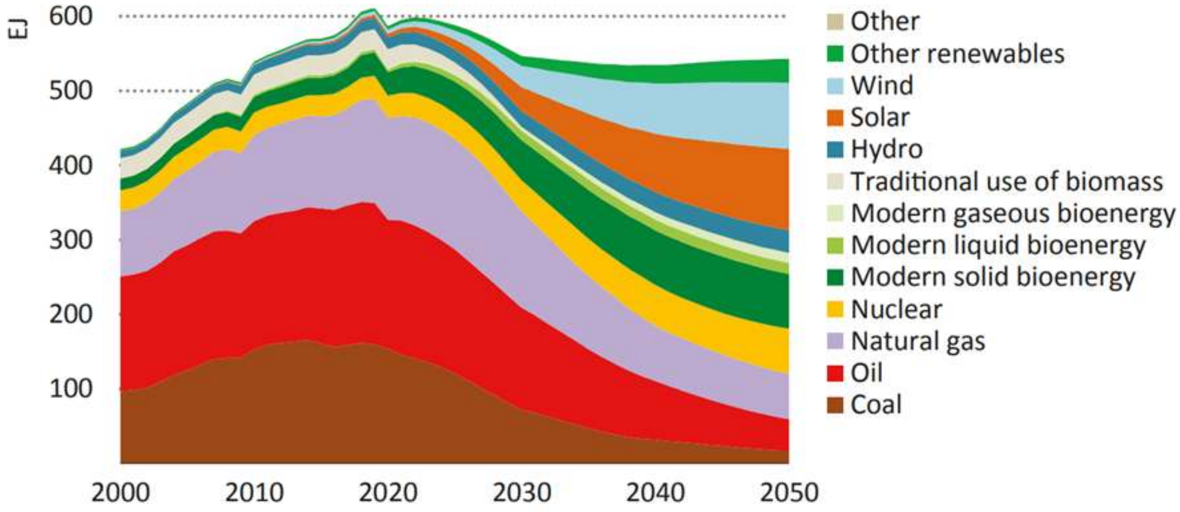
emissions from electricity production. As we make strides towards a sustainable, low-carbon energy future, nuclear energy is positioned to play a crucial role, particularly in providing a stable source of baseload power

4. The global energy consumption pattern remains heavily reliant on fossil fuels, which account for a substantial 84.3% share. This persistent dependence on fossil fuels, such as coal, oil, and natural gas, is a major concern due to its associated greenhouse gas emissions, contributing significantly to climate change. While efforts to transition towards cleaner and more sustainable energy sources have made progress, the numbers reveal the substantial challenges ahead. Renewables, including wind, solar, and hydroelectric power, represent 11.4% of global energy consumption, reflecting a growing commitment to cleaner energy solutions. However, the intermittence problem of renewables, where energy production can be inconsistent, poses a significant hurdle to their widespread adoption. To address this, there is a growing need to invest in energy storage technologies and grid improvements. Meanwhile, nuclear energy contributes 4.3%, offering a low-carbon alternative with a more consistent power output, but it also comes with its unique set of challenges, including safety and waste disposal. To combat climate change and ensure a sustainable future, further investment and policy initiatives are essential to shift the energy balance toward cleaner, more sustainable sources, address the intermittence issue of renewables, and reduce our heavy reliance on fossil fuels, potentially favoring the growth of nuclear energy as part of a diverse and low-carbon energy mix.



5. To meet the emissions reduction targets of the Paris Agreement, nuclear power is deemed essential by the IEA SDS and IPCC. However, the growth in nuclear power generation is currently insufficient due to various factors, chiefly the high costs linked to new nuclear projects, particularly in countries with limited experience in nuclear plant construction. These "first-of-a-kind" (FOAK) Generation III projects have encountered delays and cost overruns, eroding confidence, while the perception of high project risks has hindered investment, making it challenging for countries to secure funding for future nuclear endeavours.

6. Nuclear energy for electricity generation through traditional nuclear power plants (NPPs) has faced significant hurdles, mainly due to the substantial capital expenditures associated with these facilities. These costs have restricted access to nuclear energy for emerging nations. It's important to note that nuclear energy holds the potential to be both an effective solution for addressing global warming and a sustainable energy source for our growing global population. At present, nuclear energy accounts for approximately 10.5% of global electricity generation (World Nuclear Association, 2023). 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



7. A promising solution to tackle the capital cost challenges associated with conventional NPPs is the adoption of small modular reactors (SMRs). These smaller-scale reactor systems have garnered significant attention due to their benefits, including lower initial capital investment, scalability, and ease of deployment. This is particularly advantageous in regions with underdeveloped electricity grids and areas with lower electricity demand. Transitioning to SMRs offers a hopeful path to make nuclear energy more accessible and cost-effective for a broader range of applications and regions. However, it's crucial to comprehend the characteristics and potential of SMRs within this context.

Small Modular Reactors

8. 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. Small Modular Reactors (SMRs) are a type of nuclear reactor designed to be smaller in size and capacity compared to traditional, large-scale nuclear reactors. They typically have an electrical output of 300 megawatts or less, although there is no strict size limit. SMRs exhibit several key characteristics:

a. **Compact Size:** SMRs are intentionally designed to be compact, with a smaller physical footprint. This allows for factory-based manufacturing and ease of transport to the deployment site.

b. **Modularity:** SMRs are modular in design, meaning they can be built and assembled in multiple smaller modules that are later integrated to form a complete reactor. This modularity makes them more flexible in terms of deployment and scalability.

c. **Enhanced Safety Features:** Many SMR designs incorporate advanced safety features, such as passive cooling systems and improved fuel technologies, to enhance overall safety and reduce the risk of accidents.

d. **Reduced Capital Costs:** The smaller size and modular construction of SMRs can lead to reduced capital costs compared to large reactors. This can make nuclear energy more economically viable for a broader range of applications.

e. **Flexibility in Deployment:** SMRs can be deployed in a variety of settings, including remote or off-grid locations, industrial facilities, and regions with smaller electricity demands. This flexibility extends their applications beyond traditional large nuclear power plants.

9. **Advantages of SMRs.** Small Modular Reactors (SMRs) offer numerous advantages and benefits, making them a promising and versatile technology in the field of nuclear energy. Here's an elaboration of the key advantages and benefits of SMRs:

a. **Reduced Environmental Impact and Low Greenhouse Gas Emissions:**

i. SMRs provide a low-carbon energy source as they produce minimal greenhouse gas emissions during electricity generation. This feature is vital in the fight against climate change and the transition to a more sustainable, low-carbon energy future.

ii. By reducing reliance on fossil fuels, SMRs help decrease the release of harmful air pollutants, such as sulfur dioxide, nitrogen oxides, and particulate matter, which have detrimental effects on air quality and public health.

b. **Improved Safety Features and Passive Cooling Systems:**

i. Many SMR designs incorporate advanced safety features, including passive safety systems. These systems can shut down the reactor and remove heat without relying on active mechanical systems or external power sources, making them more robust and reliable in the event of accidents.

ii. Enhanced safety designs in SMRs aim to prevent severe accidents and limit their consequences, increasing public acceptance of nuclear power.

c. **Flexibility, Scalability, and Grid Stability:**

i. SMRs are designed with modularity in mind, allowing for more flexible deployment options. This means they can be installed in a wider range of locations and settings, including areas with limited infrastructure.

ii. SMRs can be scaled to meet varying energy demand, offering utilities the flexibility to adapt to changes in electricity consumption and to integrate renewable energy sources while maintaining grid stability through their baseload power capabilities.

d. **Potential for Repurposing Aging Fossil Fuel Plants and Rapid Deployment in Remote Areas:**

i. SMRs offer an opportunity to repurpose aging coal or natural gas power plants that are being phased out due to environmental concerns. By replacing these fossil fuel facilities with SMRs, emissions can be significantly reduced, and the existing infrastructure can be utilized efficiently.

ii. In remote or off-grid areas, SMRs can provide a rapid and reliable source of electricity. Their small size, transportability, and modularity make them suitable for powering isolated communities, industrial operations, or military bases, reducing reliance on diesel generators and enhancing energy security.

Role in Energy Transition

10. In the transition towards a sustainable and low-carbon energy future, nuclear energy, encompassing Small Modular Reactors (SMRs), plays a pivotal role due to its multifaceted contributions: -

a. **Low-Carbon Energy Source:** Nuclear energy is one of the most low-carbon energy sources available. It does not produce greenhouse gas emissions during electricity generation, making it a valuable asset in the fight against climate change. As the world strives to reduce carbon emissions, nuclear power can provide a stable, emissions-free source of energy.

b. **Baseload Power Generation:** Nuclear power plants, including SMRs, are capable of providing baseload power, which means they can operate continuously and consistently, unlike some renewable energy sources that are intermittent (e.g., solar and wind). This reliability is essential for ensuring a stable energy supply and reducing the need for fossil fuel backup.

c. **Energy Security:** Nuclear energy enhances energy security by diversifying the energy mix. It reduces dependence on fossil fuels and their associated price volatility and supply chain risks. This is particularly crucial for countries seeking to reduce their reliance on imported energy sources.

d. **Reduction of Air Pollution:** In addition to mitigating climate change, nuclear power also helps reduce air pollution. Fossil fuel combustion releases pollutants like sulfur dioxide, nitrogen oxides, and particulate matter, which have detrimental effects on air quality and human health. Nuclear energy eliminates these emissions, leading to improved air quality.

e. **Resource Efficiency:** Nuclear fuel, such as uranium, is highly energy-dense. A small amount of nuclear fuel can produce a significant amount of electricity, making it an efficient energy source. This contrasts with some renewables that require a larger physical footprint and more resources to generate the same amount of energy.

f. **SMRs and Flexibility:** SMRs offer several advantages over traditional nuclear reactors. They are designed to be smaller, more flexible, and often more cost-effective. SMRs can be deployed in various settings, including remote locations, providing power to isolated communities or off-grid industrial facilities. Their modularity allows for easier scaling, making them a more versatile option for different energy needs.

g. **Long Operational Lifespans:** Nuclear power plants, when properly maintained, can have long operational lifespans, often exceeding 40 years. This longevity ensures stable, long-term energy generation and reduces the need for frequent infrastructure replacement.

h. **Research and Development:** The development and deployment of SMRs contribute to advancements in nuclear technology. These innovations can have broader implications for the energy sector, both for civilian and military applications.

i. **Nuclear as Complement to Renewables:** Nuclear energy can complement renewable energy sources. While renewables like solar and wind are essential components of a low-carbon energy future, they can be intermittent and dependent on weather conditions. Nuclear power can provide a stable base of electricity generation while renewables are integrated to meet variable energy demand.

j. **Challenges to Address:** It's important to acknowledge and address challenges associated with nuclear energy, including concerns about safety, nuclear waste management, and proliferation risks. Proper regulation, safety measures, and responsible waste disposal strategies are essential to maximize the benefits of nuclear power while minimizing its drawbacks.

Comparison of SMRs to Large-Scale Nuclear Reactors:

11. Comparing Small Modular Reactors (SMRs) to their large-scale counterparts is an ongoing subject of discussion, influenced by various factors, such as design specifics, location considerations, regulatory frameworks, and economies of scale. SMRs provide a more flexible, modular approach to nuclear energy generation, differing from LRs in several key aspects related to execution, workforce, supply chain, design, manufacturing, investment, and on-site work. The choice between SMRs and LRs depends on specific project requirements, location considerations, regulatory factors, and evolving technological advancements. Here are some key considerations:

a. Economies of Scale: Large reactors (LRs) leverage economies of scale to achieve cost competitiveness in terms of the levelized cost of electricity (LCOE) when operating at full capacity. However, this advantage comes at the cost of requiring substantial initial capital investments and extended construction timelines, resulting in significant financing expenses.

b. Flexible Siting: SMRs offer the flexibility to be deployed in a broader range of settings, including remote areas or regions with lower electricity demands. In such cases, where large reactors may be impractical or cost-inefficient, SMRs can be a more suitable choice.

c. Execution Mode: Large reactors (LRs) typically follow a project-based mode with partial modularity, often involving custom-built components. In contrast, SMRs are executed in a product-based mode, emphasizing complete modularization and standardization.

d. Benefits of Learning Curve: LRs typically construct one unit every five to seven years. In contrast, SMRs, benefiting from modularization, have the potential to produce more units, thereby shortening construction timelines.

e. Workforce Mobilization: LRs mobilize their workforce based on the project's life cycle, resulting in high variability. On the other hand, SMRs maintain a permanent factory-based workforce, deploying skilled workers for shorter durations on-site.

f. Supply Chain Management: LRs rely on discrete, project-based supply chain management. In contrast, SMRs benefit from continuous, ongoing commercial relationships, creating an ecosystem for multiple SMR units.

g. Civil Design: LRs often require site-specific design adjustments due to geological and environmental factors. In contrast, SMRs are standardized, featuring seismic isolation, making them suitable for multiple locations.

h. Manufacturing: LRs involve partly modularized, on-site construction, while SMRs are fully modularized, with over 90% of components prefabricated in a controlled factory environment.

i. Investment: LRs demand substantial national infrastructure investments with extended gestation periods (5 to 10 years) before revenue generation begins. In contrast, SMRs require relatively smaller investments per reactor, enabling quicker revenue generation (around 5 years or less) with potential further reductions through learning and factory standardization.

j. In-situ Work Component: LRs often have significant site-specific work components, making them location-dependent. SMRs, due to quality control in a factory setting and standardized on-site assembly, offer a relatively lower in-situ work component.

k. Operational Costs: The smaller size and enhanced safety features of SMRs can contribute to reduced operating and maintenance costs throughout the reactor's lifespan, potentially enhancing their cost-effectiveness

12. **SMR Designs and Technologies:** Several SMR designs and technologies are being developed worldwide, each with its unique characteristics. Some notable examples include:

a. **Pressurized Water Reactors (PWRs):** These are scaled-down versions of traditional PWRs, utilizing pressurized water as both coolant and moderator. PWR SMRs are known for their safety features and relatively straightforward design.

b. **Boiling Water Reactors (BWRs):** BWR SMRs use boiling water to directly produce steam for electricity generation. They are compact and can be designed for various power outputs.

c. **Molten Salt Reactors (MSRs):** MSRs use a liquid fuel composed of molten salts, offering advantages in terms of safety and fuel utilization. They have the potential to be used for both electricity generation and high-temperature process heat applications.

d. **High-Temperature Gas-Cooled Reactors (HTGRs):** HTGR SMRs utilize helium as a coolant and are designed to operate at high temperatures. They are well-suited for applications like hydrogen production and district heating.

Current Status of SMRs

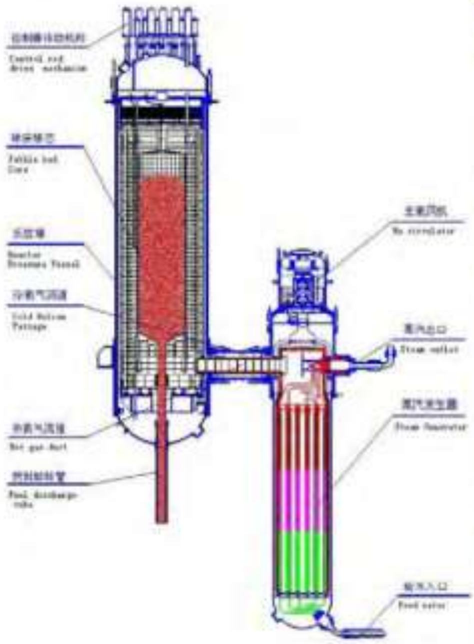
13. The development and deployment of Small Modular Reactors (SMRs) have made significant progress in recent years, contributing to the diversification of the global energy landscape. An overview of the current state of SMRs globally is at Annex I, few operational & key SMRsin advanced stages of development are covered below:

Operational SMRs Worldwide

a. **Russia:** Russia's floating nuclear power plant, the Akademik Lomonosov, became operational in 2019. It is equipped with two KLT-40C pressurized water reactors and is designed to provide electricity and heat to remote areas. The KLT-40C pressurized water reactor is a compact and modular nuclear reactor designed by Russia primarily for use in icebreakers and remote areas, where a reliable power source is essential. With a power output of approximately 35 to 40 megawatts thermal, it has been deployed in Russian icebreakers. Its safety features, such as control rods and emergency shutdown systems, make it a dependable choice for critical applications. The modular design of the KLT-40C facilitates easy transportation and installation, and it has generated interest for potential export to regions in need of small modular nuclear power plants to meet their energy needs.

MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	JSC "Afrikantov OKBM", Rosatom, Russian Federation
Reactor type	PWR
Coolant/moderator	Light water / light water
Thermal/electrical capacity, MW(t)/MW(e)	150 / 35
Primary circulation	Forced circulation
NSSS Operating Pressure (primary/secondary), MPa	12.7
Core Inlet/Outlet Coolant Temperature (°C)	280 / 316
Fuel type/assembly array	UO_2 pellet in silumin matrix
Number of fuel assemblies in the core	121
Fuel enrichment (%)	18.6
Core Discharge Burnup (GWd/ton)	45.4
Refuelling Cycle (months)	30-36
Reactivity control mechanism	Control rod driving mechanism
Approach to safety systems	Active (partially passive)
Design life (years)	40
Plant footprint (m^2)	4320 (Floating NPP)
RPV height/diameter (m)	4.8 / 2.0
RPV weight (metric ton)	N/A
Seismic Design (SSE)	9 point on the MSK scale
Distinguishing features	Floating power unit for cogeneration of heat and electricity; no onsite refuelling; spent fuel take back
Design status	Connected to the grid in Pevek in December 2019. Entered full commercial operation in May 2020.

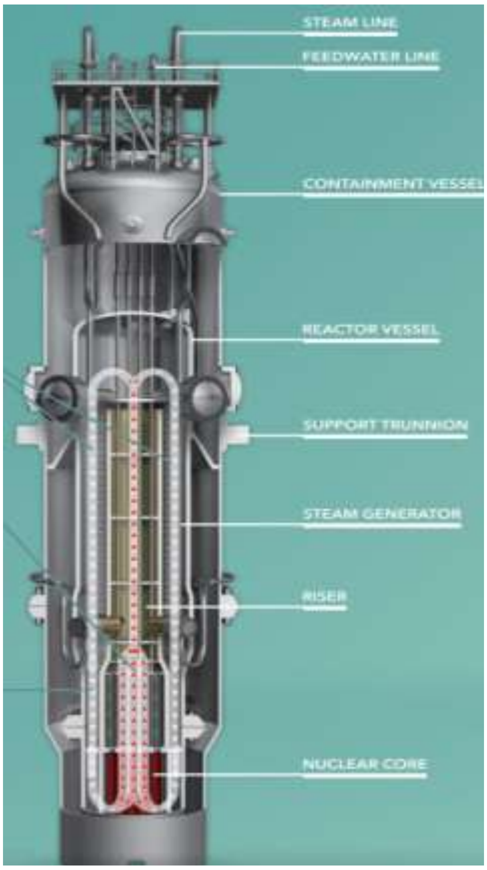
b. **China:**China has been actively involved in the development of Small Modular Reactors (SMRs), with notable projects such as the HTR-10, a high-temperature gas-cooled reactor primarily used for research purposes. Furthermore, China has been constructing its first grid-connected SMR, known as the ACP100. The HTR-10, a prototype high-temperature gas-cooled, pebble-bed reactor, is situated at Tsinghua University in China. Its construction dates back to 1995, and it reached its first criticality in December 2000. This reactor is composed of an impressive 27,000 fuel elements and utilizes low enriched uranium with a design mean burn up of 80,000 MWd/t. The reactor core boasts a diameter of 1.8 meters, an average height of 1.97 meters, and occupies a volume of 5.0 cubic meters. It is enveloped by graphite reflectors and employs spherical fuel elements with ceramic-coated fuel particles. Notably, the outlet temperature of this reactor falls within the range of 700 to 750 degrees Celsius (1,300–1,375 degrees Fahrenheit).



MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	INET, Tsinghua University, People's Republic of China
Reactor type	Modular pebble bed high temperature gas-cooled reactor
Coolant/moderator	Helium/graphite
Thermal/electrical capacity, MW(t)/MW(e)	2x250 / 210
Primary circulation	Forced circulation
NSSS Operating Pressure (primary/secondary), MPa	7 / 13.25
Core Inlet/Outlet Coolant Temperature (°C)	250 / 750
Fuel type/assembly array	Spherical elements with coated particle fuel
Number of fuel assemblies in the core	420 000 (in each reactor module)
Fuel enrichment (%)	8.5
Core Discharge Burnup (GWd/ton)	90
Refuelling Cycle (months)	On-line refuelling
Reactivity control mechanism	Control rod insertion
Approach to safety systems	Combined active and passive
Design life (years)	40
Plant footprint (m^2)	--
RPV height/diameter (m)	25 / 5.7 (inner)
RPV weight (metric ton)	800
Seismic Design (SSE)	0.2g
Fuel cycle requirements / Approach	LEU, open cycle, spent fuel intermediate storage at the plant
Distinguishing features	Inherent safety, no need for offsite emergency measures

SMRs Under Construction and in Advanced Stages of Development

c. **NuScale Power (United States):**NuScale is one of the leading companies in the development of SMRs. Their 12-module NuScale Power Module design has received approval from the U.S. Nuclear Regulatory Commission (NRC), and the first commercial project is planned for construction at the Idaho National Laboratory.



MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	NuScale Power, LLC, United States of America
Reactor type	Integral PWR
Coolant/moderator	Light water / Light water
Thermal/electrical capacity, MW(t)/MW(e)	200 / 60 (gross)
Primary circulation	Natural circulation
NSSS Operating Pressure (primary/secondary), MPa	13.8 / 4.3
Core Inlet/Outlet Coolant Temperature (°C)	265 / 321
Fuel type/assembly array	UO_2 pellet / 17x17 square
Number of fuel assemblies in the core	37
Fuel enrichment (%)	< 4.95
Core Discharge Burnup (GWd/ton)	> 30
Refuelling Cycle (months)	24
Reactivity control mechanism	Control rod drive, boron
Approach to safety systems	Passive
Design life (years)	60
Plant footprint (m^2)	140 000
RPV height/diameter (m)	17.7 / 2.7
Seismic Design (SSE)	0.5g horizontal and 0.4g vertical peak ground accelerations
Fuel cycle requirements / Approach	Three stage in-out refuelling scheme
Distinguishing features	Unlimited coping time for core cooling without AC or DC power, water addition, or operator action
Design status	Under regulatory review

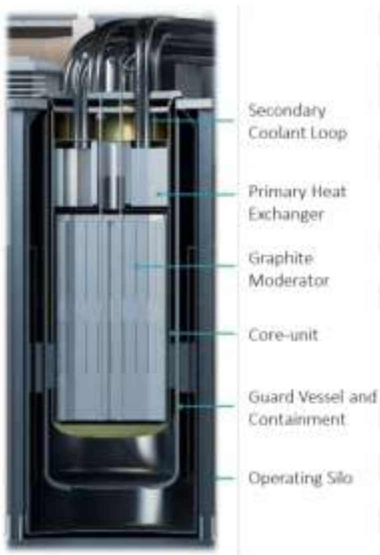
d. **Rolls-Royce (United Kingdom):** Rolls-Royce is developing the UK SMR, a pressurized water reactor with a capacity of 440 MW. The UK SMR has been developed to deliver a market driven, affordable, low carbon, energy generation capability. The developed design is based on optimised and enhanced use of proven technologies that presents a class leading safety outlook and attractive market offering with minimum regulatory risk. A three loop, close-coupled, Pressurised Water Reactor (PWR) provides a power output of 443 MW(e) from 1276 MW(t) using industry standard UO2 fuel. Coolant is circulated via three centrifugal Reactor Coolant Pumps (RCPs) to three corresponding vertical U-tube Steam Generators (SGs). The design includes multiple active and passive safety systems, each with substantial internal redundancy. Rapid, certain and repeatable build is enhanced through site layout optimisation and maximising modular build, standardisation and commoditisation. The UK SMR is primarily intended to supply baseload electricity for both coast and inland siting. The design can be configured to support other heat-requiring or cogeneration applications, as well as provide a primary, carbon free, power source for the production of e-fuels.

MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	Rolls-Royce and Partners, United Kingdom
Reactor type	3-loop PWR
Coolant/moderator	Light-water / Light-water
Thermal/electrical capacity, MW(t)/MW(e)	1276 / 443
Primary circulation	Forced (3 pumps)
Operating Pressure (primary/secondary), MPa	15.5 / 7.6
Core Inlet/Outlet Coolant Temperature (°C)	296 / 327
Fuel type/assembly array	UO_2 / 17x17 Square
Number of fuel assemblies in the core	121
Fuel enrichment (%)	4.95 (max)
Core Discharge Burnup (GWd/ton)	55 – 60
Refuelling Cycle (months)	18 – 24
Reactivity control mechanism	Rods and Gd_2O_3 solid burnable absorber
Approach to safety systems	Active and passive
Design life (years)	60
Plant footprint (m²)	10 000
Site footprint (m²)	40 000
RPV height/diameter (m)	11.3 / 4.5
RPV weight (metric tonnes)	220
Seismic Design (DBE)	> 0.3g
Fuel cycle requirements / Approach	Open cycle; Spent fuel transferred to a pool for storage prior to transfer to long term dry cask storage.
Distinguishing features	Modular approach facilitating rapid and cost-effective build.
Design status	Conceptual design

e. **X-energy (**United **States):** X-energy is developing the Xe-100, a high-temperature gas-cooled pebble bed reactor. Their design has received U.S. Department of Energy (DOE) funding for its continued development.

MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	X Energy, LLC, United States of America
Reactor type	Modular HTGR
Coolant/moderator	Helium/graphite
Thermal/electrical capacity, MW(t)/MW(e)	200 / 82.5
Primary circulation	Forced helium circulation
NSSS Operating Pressure (primary/secondary), MPa	6.0 / 16.5
Core Inlet/Outlet Coolant Temperature (°C)	260 / 750
Fuel type/assembly array	UCO TRISO/pebbles
Number of fuel assemblies in the core	220 000 pebbles per reactor
Fuel enrichment (%)	15.5
Core Discharge Burnup (GWd/ton)	165
Refuelling Cycle (months)	Online fuel loading
Reactivity control mechanism	Thermal feedback & control rods
Approach to safety systems	Passive
Design life (years)	60
Plant footprint (m^2)	340m x 385m (4 reactor modules with 4 turbines)
RPV height/diameter (m)	16.4 / 4.88
RPV weight (metric ton)	274
Seismic Design (SSE)	0.5g
Fuel cycle requirements / Approach	Uranium once through (initially)
Distinguishing features	Online refuelling, core cannot melt and fuel damage minimized by design, independent radionuclide barriers, potential for advanced fuel cycles

f. **Terrestrial Energy (Canada):** Terrestrial Energy is working on the Integral Molten Salt Reactor (IMSR), a molten salt-cooled and fueled design. They are in advanced stages of development and have been working closely with regulatory authorities.



MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	Terrestrial Energy Inc., Canada
Reactor type	Molten salt reactor
Coolant/moderator	Fluoride fuel salt/graphite
Thermal/electrical capacity, MW(t)/MW(e)	440 / 195
Primary circulation	Forced circulation
Operating Pressure (primary/secondary), MPa	< 0.4 (hydrostatic)
Core Inlet/Outlet Coolant Temperature (°C)	620 / 700
Fuel type/assembly array	Molten salt fuel
Fuel enrichment (%)	<5%, low enriched uranium
Fuel cycle (months)	84; before core-unit replacement
Main reactivity control mechanism	Short term: negative temperature coefficient Long term: online liquid fuel additions
Approach to safety systems	Passive
Design life (years)	56
Plant footprint (m^2)	45 000
RPV height/diameter (m)	10.0 / 3.7
RPV Weight (metric ton)	154 000
Seismic design (SSE)	0.3g
Distinguishing features	Core-unit is replaced completely as a single unit every seven years
Design status	Conceptual design complete – basic engineering in progress

Future Outlook of SMRs in the Energy Sector

14. The future outlook for Small Modular Reactors (SMRs) in the energy sector appears promising:

a. **Market Growth:** The SMR market is expected to grow significantly in the coming decades. Various countries and organizations are investing in research, development, and deployment. This growth is driven by the need for low-carbon, reliable energy sources that can complement intermittent renewables and support energy access in remote areas.

b. **Diverse Applications:** SMRs offer diverse applications beyond electricity generation, such as providing high-temperature heat for industrial processes, desalination, and hydrogen production. Their modularity and flexibility make them suitable for a wide range of energy needs.

c. **Global Expansion:** The potential for international deployment of SMRs is substantial. Countries with a strong interest in nuclear energy are actively considering SMRs for their energy portfolios, and the export potential of SMR technology is significant.

15. **Key Challenges in the Development and Deployment of SMRs:**Despite their potential, SMRs face challenges and opportunities in their continued development and deployment

a. **Regulatory Hurdles:** Adapting regulatory frameworks to accommodate SMRs efficiently is a significant challenge. Streamlining the licensing process and ensuring safety and security standards are met are essential.

b. **Public Perception:** Overcoming public concerns about nuclear energy, safety, and waste management is crucial. Effective communication and education are necessary to build public acceptance.

c. **Financing and Investment:** Securing funding for SMR projects and attracting private sector investment can be challenging. Governments and industry stakeholders need to collaborate to address financial barriers.

d. **Supply Chain Development:** Developing a specialized supply chain for SMR components is an opportunity for economic growth. Strengthening the supply chain can reduce costs and improve project efficiency.

e. **Global Collaboration:** Collaborating on international standards, sharing best practices, and harmonizing regulatory processes can enhance the global deployment of SMRs.

f. **Waste Management:** Dealing with nuclear waste from SMRs is an ongoing challenge. Developing safe and sustainable solutions for long-term waste management is critical.

16. **International Organizations and Initiatives Promoting SMR Development:**International cooperation and harmonization are critical for advancing SMR technology on a global scale. Collaborative efforts help overcome technical, regulatory, and financial challenges, while international organizations and initiatives provide the necessary framework and support for the development and deployment of SMRs as a sustainable and low-carbon energy solution.Several international organizations and initiatives playing a significant role in promoting the development and deployment of SMRs are:

a. **International Atomic Energy Agency (IAEA):** The IAEA is a key organization responsible for promoting the peaceful use of nuclear energy and ensuring nuclear safety and security. It provides guidance and support for member states in SMR development and safety standards.

b. **NICE Future (Nuclear Innovation: Clean Energy Future):** NICE Future is an initiative led by Canada, Japan, and the United States, with participation from several other countries. It focuses on advancing nuclear energy innovation, including SMRs, to address climate change and energy security.

c. **Multinational Design Evaluation Program (MDEP):** MDEP is an international initiative that aims to enhance collaboration in nuclear regulatory matters. It fosters harmonization in safety standards and reviews for SMRs and other advanced reactor designs.

d. **Generation IV International Forum (GIF):** GIF is an international organization focused on the research and development of advanced nuclear energy systems, including Generation IV reactors. While not exclusive to SMRs, GIF's efforts encompass innovative nuclear technologies that can be applied to SMR development.

e. **International Framework for Nuclear Energy Cooperation (IFNEC):** IFNEC is a global partnership aimed at facilitating international cooperation on the development and deployment of nuclear energy. It covers various aspects of nuclear energy, including SMRs.

f. **Global Nexus Initiative:** The Global Nexus Initiative is a platform for governments, industry, and civil society to explore the role of nuclear energy, including SMRs, in achieving energy, water, and food security while addressing climate change.

Status of SMRs in Various Countries

17. SMRs have gained attention and are being explored in various countries and regions for their potential to address energy and environmental challenges. Some regional perspectives on the role of SMRs:

a. **United States:** The U.S. has seen significant interest in SMRs, with companies like NuScale Power and Bill Gates' TerraPower leading the way. NuScale received NRC approval for its SMR design, and the first commercial SMR plant is planned for construction in Idaho. These initiatives aim to provide carbon-free electricity and bolster the resilience of the power grid. Challenges include regulatory hurdles, financial support, and public acceptance.

b. **Canada:** Canada is actively exploring SMRs to address the energy needs of remote communities and industries in northern regions. The Canadian Nuclear Laboratories (CNL) and private companies are conducting research and development. SMRs have the potential to replace aging diesel generators, significantly reducing greenhouse gas emissions and operating costs.

c. **Russia:** Russia has been operating the Akademik Lomonosov, a floating nuclear power plant with two SMRs, since 2019. These SMRs provide electricity and heat to remote areas in the Arctic. Russia has also been working on land-based SMR projects, with a focus on export potential.

d. **United Kingdom:** The UK government is actively supporting the development of SMRs to meet its clean energy goals. Rolls-Royce is leading an effort to build SMRs in the UK, with plans to have them operational by the early 2030s. The UK SMR design aims to provide a secure and low-carbon energy source.

e. **China:** China is a significant player in SMR development. The country has an operational high-temperature gas-cooled reactor (HTR-10) and is constructing its first commercial SMR, the ACP100. The Chinese government's support for SMR research aligns with its efforts to reduce carbon emissions and expand access to electricity.

f. **South Africa:** South Africa is exploring SMRs as part of its energy diversification strategy. SMRs are being considered for applications such as desalination, process heat, and grid stability. They can help address electricity shortages and reduce the country's reliance on coal.

18. **The Indian Perspective on SMRs and Their Potential:** Challenges in India include regulatory frameworks that need to adapt to SMR technology, financial support, public acceptance, and addressing nuclear liability and safety concerns. Indian authorities, research organizations, and industry stakeholders are actively exploring the potential of SMRs in the country. In conclusion, SMRs are being actively explored in various countries and regions, each with unique energy and environmental challenges. The modular, flexible, and low-carbon nature of SMRs positions them as a promising solution for clean energy generation and industrial applications. However, challenges related to regulation, financing, and public perception must be overcome to unlock their full potential.

a. **Energy Access:** SMRs can provide electricity to remote and off-grid areas in India, where millions still lack access to reliable power. Their modular design and scalability make them suitable for small-scale and distributed power generation.

b. **Carbon Emissions Reduction:** India is committed to reducing its carbon emissions and increasing the share of renewables in its energy mix. SMRs, with their low-carbon emissions, can complement intermittent renewable sources, ensuring a stable power supply while reducing greenhouse gas emissions.

c. **Industrial Applications:** SMRs can supply high-temperature process heat for various industrial applications, including manufacturing and desalination. This can boost industrial productivity and reduce emissions associated with conventional fossil fuel processes.

d. **Grid Stability:** As India's energy demands grow, maintaining grid stability becomes increasingly critical. SMRs can provide baseload power, helping stabilize the grid and reducing the reliance on fossil fuels for peaking power.

e. **Nuclear Energy Expansion:** India has a well-established nuclear power program. SMRs can complement large-scale reactors and provide flexibility in meeting varying energy demand, especially in regions with limited grid access.

Conclusion

19. Inconclusion, SMRs are poised to play a pivotal role in the global energy transition. Their unique advantages, combined with ongoing technological advancements and policy support, make them a compelling solution for a sustainable energy future. As nations grapple with the challenge of reducing emissions, securing a reliable energy supply, and transitioning to cleaner sources, SMRs represent a promising pathway forward. To realize their full potential, collaboration between governments, industry stakeholders, and the scientific community will be critical in surmounting the challenges and harnessing the advantages that SMRs bring to the forefront of the energy revolution.

20. In summary, Small Modular Reactors (SMRs) represent a promising technological advancement in the quest to transition away from carbon-based energy sources and mitigate the adverse impacts of climate change. This comprehensive review underscores the significant progress achieved in SMR technology and its potential to revolutionize the energy sector, notwithstanding the various challenges it faces.

21. Nuclear energy, which has served as a reliable base-load power source for decades, is evolving with the advent of SMRs. These innovative reactors not only offer enhanced flexibility in power generation but also extend their applicability to polygeneration, making them versatile and adaptable to shifting energy demands. Crucially, SMRs have integrated advanced safety features to reduce the risk of catastrophic incidents, drawing valuable lessons from past nuclear accidents.

22. Economic analyses indicate that SMRs exhibit strong economic viability, driven by factors such as learning, co-siting, and efficient construction scheduling. These factors translate into cost savings, bolstering the economic feasibility of SMR deployment. Furthermore, environmental assessments suggest that SMRs hold substantial potential to contribute to decarbonization efforts, aligning with the objectives of other renewable energy technologies.

23. However, it is imperative to acknowledge that SMRs confront significant socio-political challenges. These encompass concerns related to public acceptance, nuclear proliferation, political influences, institutional inertia, and more. To assess the readiness of nations or specific regions to adopt SMRs, precise measurements and sophisticated integration of various criteria are essential. These aspects demand meticulous consideration in the decision-making process.

24. In this context, it is crucial to recognize that while SMRs offer significant technological advantages and environmental benefits, the absence of a robust regulatory framework and international cooperation remains a significant gap. Addressing these regulatory and political challenges is pivotal to fully realizing the potential of SMRs as a sustainable and decarbonized energy solution.

REFERENCES

[1]. Nuclear Power and Secure Energy Transitions - From Today's Challenges to Tomorrow's Clean Energy Systems, International Energy Agency (IEA), 2022.
[2]. Climate Change and Nuclear Power 2022 - Securing Clean Energy for Climate Resilience, International Atomic Energy Agency (IAEA), 2022.
[3]. Net-zero by 2050 - A Roadmap for the Global Energy Sector, International Energy Agency (IEA), 2021.
[4]. World Energy Outlook 2022, International Energy Agency (IEA), 2022.
[5]. A Report on the role of Small Modular Reactors in the Energy Transition, The National Institution for Transforming India (NITI Aayog), The Department of Atomic Energy (DAE).
[6]. Advances in Small Modular Reactor Technology Developments A Supplement to: IAEA Advanced Reactors Information System (ARIS) 2020 Edition. International Atomic Energy Agency (IAEA).
[7]. IAEA (2020), Advances in Small Modular Reactor Technology Developments, A supplement to: IAEA Advances Reactors Information System (ARIS), 2020 Edition, IAEA, Vienna.https://aris.iaea.org/Publications/SMR_Book_2020.pdf
[8]. IAEA (2019), Interim Report on Multi-unit/Multi-module Aspects Specific to SMRs, IAEA,Vienna. ww.iaea.org/sites/default/files/19/12/smr_rf_dsa_interim_report.pdf.
[9]. IAEA (2018), Advances in Small Modular Reactor Technology Developments, A supplement to: IAEA Advances Reactors Information System (ARIS), 2018 Edition, IAEA, Vienna, https://aris.iaea.org/Publications/SMR-Book_2018.pdf.,
[10]. Small Modular Reactor Deployment and Obstacles to Be OvercomeEnergies 2023-04-15 | Journal article, Elaheh Shobeiri; Filippo Genco; Daniel Hoornweg; Akira Tokuhiro.
[11]. Small Modular Reactors: Challenges and Opportunities, Nuclear Technology Development and Economics 2021, OECD, NEA

Annex I

Table 1: Representative sample of SMR designs under development globally

Design	Net output per module (MWe)	Number of modules (if applicable)	Type	Designer	Country	Status
Single unit LWR-SMRs						
CAREM	30	1	PWR	CNEA	Argentina	Under construction
SMART	100	1	PWR	KAERI	Korea	Certified design
ACP100	125	1	PWR	CNNC	China	Construction began in 2019
SMR-160	160	1	PWR	Holtec International	United States	Conceptual design
BWRX-300	300	1	BWR	GE Hitachi	United States-Japan	First topical reports submitted to the US NRC and to the CNSC as part of the licensing process
CANDU SMR	300	1	PHWR	SNC-Lavalin	Canada	Conceptual design
UK SMR	450	1	PWR	Rolls Royce	United Kingdom	Conceptual design
Multi-module LWR-SMRs						
NuScale	50	12	PWR	NuScale Power	United States	Certified design. US NRC design approval received in August 2020
RITM-200	50	2	PWR	OKBM Afrikantov	Russia	Land-based nuclear power plant – conceptual design
Nuward	170	2 to 4	PWR	CEA/EDF/Naval Group/ TechnicAtome	France	Conceptual design
Mobile SMRs						
ACPR50S	60	1	Floating PWR	CGN	China	Under construction
KLT-40S	35	2	Floating PWR	OKBM Afrikantov	Russia	Commercial operation
Gen IV SMRs						
Xe-100	80	1 to 4	HTGR	X-energy LLC	United States	Conceptual design
ARC-100	100	1	LMFR	Advanced Reactor Concepts LLC	Canada	Conceptual design
KP-FHR	140	1	MSR	Kairos Power	United States	Pre-conceptual design
IMSR	190	1	MSR	Terrestrial Energy	Canada	Basic design
HTR-PM	210	2	HTGR	China Huaneng/CNEC/ Tsinghua University	China	Under construction
EM2	265	1	GMFR	General Atomics	United States	Conceptual design
Stable Salt Reactor	300	1	MSR	Moltex Energy	United Kingdom	Pre-conceptual design
Natrium	345	1	SFR	Terrapower/GE Hitachi	United States	Conceptual design
Westing-house Lead Fast Reactor	450	1	LMFR	Westinghouse	United States	Conceptual design
MMRs						
eVinci	0.2-5	1	Heat pipe reactor	Westinghouse	United States	Basic design
Aurora	2	1	LMFR	Oklo	United States	Licence application submitted to the US NRC
U-Battery	4	1	HTGR	Urenco and partners	United Kingdom	Basic design
MMR	5-10	1	HTGR	USNC	United States	Basic design

Source: NEA, IAEA (2020).

Note: BWR = boiling water reactor; CEA = Alternative Energies and Atomic Energy Commission; CGN = China General Nuclear; CNEA = Comisión Nacional de Energía Atómica; CNEC = China Nuclear Engineering Corporation; CNNC = China National Nuclear Corporation; KAERI = Korea Atomic Energy Research Institute; PWR = pressurised water reactor. If not specified, all of the reactors are land-based. RITM-200 units have already been constructed for "Arktika", "Sibir" and "Ural", all of which are nuclear-powered icebreakers.