Pre-print

Small Modular Reactors: A new nuclear energy paradigm

IAEA
International Atomic Energy Agency

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FOREWORD

The International Atomic Energy Agency (IAEA) continues to monitor the efforts of Member States in the development and deployment of small modular reactors (SMRs), recognizing their potential as a viable solution to meet clean energy demand, both in expanding and embarking countries. Member State interest in SMRs, including microreactors, is increasing, and significant institutional and industrial efforts are being devoted to facilitating their development and early deployment. With this increase in global efforts and activities, the IAEA has received requests from Member States for support and general understanding of these innovative technologies, including their benefits and challenges. To provide comprehensive support to Member States and effectively coordinate internal efforts, the IAEA recently established a platform on SMRs and their applications.

To address Member States' requests, the platform has prepared this high level report on SMRs and their applications mainly addressing the needs of policymakers and relevant stakeholders. This publication is intended to provide the IAEA Secretariat's perspective on the topic, with the first three chapters explaining the IAEA Secretariat's view on SMRs, and the last chapter devoted to related IAEA projects, activities and services to Member States.

The overall objective of this report is to address the factors to be considered when deciding whether to adopt SMRs and the ways to enable their safe, secure, peaceful and sustainable deployment. The report addresses not only the reactor and applications of SMRs but also their fuel cycle, waste management, decommissioning and, more broadly, all their necessary infrastructure, including legislative, regulatory, institutional, economic competitiveness and financial aspects.

CONTENTS

1. SMALL MODULAR REACTORS AND WHAT THEY CAN OFFER — UNDERSTANDING TECHNOLOGICAL AND GLOBAL PERSPECTIVES

The interest in small modular reactors (SMRs) is increasing, and significant industrial efforts are ongoing to facilitate their development and early deployment. This chapter provides a high level understanding of SMRs, including microreactors, their main characteristics, and distinctive applications, to elucidate why they would be of interest to Member States, energy companies and other stakeholders. It is also important to understand how SMRs are bringing innovation to the global nuclear industry, enabling new opportunities and opening new markets. What is driving this innovation and how these technologies can help foster a more sustainable future will also be discussed. SMRs can play a critical role in decarbonizing the economy; it is essential to understand how and what sectors they can help decarbonize, including some hard to abate sectors, and how they can support countries in reaching net zero objectives[1]. SMRs can also support countries' energy diversity, security and grid stability. This chapter also provides an overview of countries considering SMRs in their energy mix. Different perspectives are discussed from the point of view of technology holders and embarking and expanding countries.

Chapter Highlights:

- **SMRs consist of different designs for technology lines for both electric and non-electric applications.**

- **SMRs can be game-changers with several potential benefits, including inherent safety features, and bring significant innovation to the nuclear industry, but this optimism must be weighed along with the challenges they bring.**

- **Interest in SMRs is increasing among governments and the private sector, and political support is also increasing as Member States look for all possible solutions to tackle climate change.**

Climate change presents us with a stark challenge: to reduce greenhouse gas emissions much faster than has been done so far or face the increasingly catastrophic consequences of an inexorably warming planet. The world needs to harness all low carbon sources of energy to meet the Paris Agreement goal of limiting the rise in global temperatures to well below 2°C above pre-industrial levels. Use of renewables such as wind and solar power is increasing, while nuclear power continues to make a significant contribution to energy supply, energy security and grid stability.

Of all the low-carbon energy sources, nuclear power is one of the few, if not the only one, that can generate at scale all the main energy carriers: electricity, heat and hydrogen. Advanced nuclear reactor technologies such as SMRs, including microreactors, are designed to not only produce base load and dispatchable carbon-free electricity but also to supply other clean energy products needed to decarbonize energy intensive sectors such as the transport sector, the building sector, industrial heat applications and desalination. Some SMRs are also designed to enhance flexible operations and to operate together with variable renewables and various energy storage systems.

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[1] Net zero objectives are defined in the IAEA brochure Nuclear Energy for a Net Zero World.

1.1. UNDERSTANDING SMALL MODULAR REACTORS

1.1.1. What are SMRs? Definition, categories and main characteristics

SMRs are advanced nuclear reactors with a power capacity of up to 300 MW(e), and whose components and systems can be factory-built and then transported as modules to sites for installation as demand arises. SMRs are under development for all types of reactor technologies (e.g. water cooled reactors, high temperature gas cooled reactors, liquid metal cooled and gas cooled reactors with fast neutron spectrum and molten salt reactors (MSRs)).

The global nuclear community has generally designated a power rating up to 300 MW(e) as ‘small’. Microreactors are a subcategory of SMRs with power outputs less than 10 MW(e). The maximum power levels and dimensions are limited by manufacturing and transport capability, which is a key feature of SMRs to enable serial production.

Modularization is the process by which SMRs are designed and assembled from smaller building blocks, or modules. SMR modules can be constructed in a factory and then transported to a site, making parallel construction activities possible and improving productivity. This technique aims at standardization of components to the extent practicable, factory fabrication and more simplified onsite installation of preassembled modules.

In some SMR designs, such as integral light water reactors (LWRs), a module may consist of an entire nuclear steam supply system, including all primary systems and associated instrumentation. Others may use more traditional, but integrated components designed to be easily assembled in the field, such as an instrumentation and control system module that can be tested and partially commissioned in the factory.

Factory-built modules (as opposed to stick-built construction currently used in the field) typically have been designed to be all-inclusive with regards to mechanical, electrical and instrumentation features. They can be assembled in a more controlled plant environment by fully trained labour, using the same materials, codes and standards for each subsequent module.

Modularity is predicted to reduce labour costs because the workforce does not have to be relocated each time a reactor module needs to be produced. Cost savings are also predicted to be associated with shorter project timelines linked to serial fabrication techniques and more efficient use of materials.

SMR deployment can also adopt different configurations ranging from single-unit installations or multimodule plants to mobile powersets such as floating (i.e. barge mounted) units. The degree of modularization also varies across designs.

Transportable nuclear power plants (TNPPs) are integrated land or sea based relocatable advanced reactors that can produce energy for different applications except for self-propulsion. It is assumed in this report that they will not be permitted to operate during transport. One of the approaches for TNPPs is to have a modular design with integrated reactor components that can be coupled to a power conversion system to deliver the desired energy product.

1.1.2. Why SMRs? Drivers and applications

The key driving forces of SMR development are fulfilling the need for flexible power generation for a wider range of users and applications, replacing ageing fossil-fired units, enhancing safety performance and offering better economic affordability. Small land footprint and reduced cooling water usage are added drivers.

The driving forces in the development of SMRs are their specific characteristics and diverse applications. They can be deployed incrementally to closely match increasing energy demand resulting in a moderate financial commitment for countries or regions with smaller electricity grids. SMRs offer the potential of cost reduction through modularization and factory construction.

Near-term deployable SMRs have a safety performance comparable to, or possibly better than, current evolutionary large reactor designs, thanks to inherent and passive safety features. Owing to the lower source terms and their safety features, the emergency planning zones and emergency planning distances are expected to be smaller for SMRs than for large nuclear power plants (NPPs). These goals are still to be demonstrated, and some level of (on-site and off-site) emergency planning will still be required for an SMR plant.

SMR designs and sizes provide a feasible option for partial or dedicated use in non-electrical applications close to the demand centres, such as providing heat for buildings or for industrial processes, seawater desalination and hydrogen production. Process heat supply through cogeneration results in significantly improved thermal efficiencies leading to a better return on investment. Some SMR designs may also serve niche markets to replace diesel generators in small island locations or remote regions.

1.2. BRINGING THE CHANGE

1.2.1. Driving innovation

SMRs are powering innovation across many industries and bringing new opportunities. The unique attributes of SMRs in terms of expected efficiency, flexibility and economics, as well as reduced needs for emergency planning due to inherent safety features, may position them to play a key role in the transition to clean energy. In this respect, the nuclear community is pursuing innovation in technology, market design, financing, regulation and project delivery. There are over 80 proposed designs for SMRs worldwide reflecting both the enthusiasm around their potential, and the wide spectrum of possible nuclear reactor technologies.

Although significant advancements have been made in various SMR designs in recent years, some issues still attract considerable attention from the industry and nuclear regulators. These include control room staffing, human factor engineering for multimodule SMR plants, developing new codes and standards and enhanced flexible operation. Furthermore, although SMRs may offer lower upfront capital costs per unit, their economic competitiveness is still to be proven through large deployment, which is expected to occur in the coming decades.

Other innovations concern microreactors. Their development has intensified in several countries, including Canada, the Czech Republic, Japan, the United Kingdom and the United States of America. Microreactors could provide cogeneration of heat and electricity in remote regions or small islands, where they could typically replace diesel generators.

1.2.2. Tackling climate change

Governments, industries and international organizations have important roles to play in supporting innovation and the early deployment of all clean energy technologies. According to the International Energy Agency, almost half of the emissions reductions needed to reach net zero by 2050 will have to come from technologies that have yet to be commercialized. SMRs could represent the next wave of nuclear innovation and play a critical role in reaching net zero by 2050 by enabling the decarbonization of the electricity sector as well as of other industrial sectors through the production and use of low carbon heat or hydrogen. SMRs are also suitable candidates to replace the energy supplied by fossil fuels such as coal fired power plants and diesel generation in remote communities.

Electricity represents only around 22% of final energy use, and nearly two thirds of that electricity is still generated from fossil fuels. Fossil fuels also provide the greatest share of energy for industry, transport and heating. Today, less than 1% of the heat generated in nuclear reactors worldwide is currently used for non-electric applications. However, nuclear power reactors have the potential to deliver large quantities of low carbon hydrogen or heat. SMR designs can be optimized for this purpose, with the advantage of diversifying revenue streams and improving overall plant economics.

The possibility of producing nuclear hydrogen has been explored for decades and is currently one of the options considered for the emerging green hydrogen economy. Various Member States and reactor technology holders are considering SMRs for hydrogen production. The Japan Atomic Energy Agency and Mitsubishi Heavy Industries have recently teamed up to establish a demonstration hydrogen production project at the High Temperature Engineering Test Reactor site. At the end of 2021, China's HTR-PM reactor was connected to the grid and a pilot demonstration of hydrogen generation production is expected by 2025.

1.3. GLOBAL DEVELOPMENTS

According to the IAEA's Power Reactor Information System (PRIS), as of the end of July 2022, there were 438 nuclear power reactors in operation in 32 IAEA Member States, representing 393 GW(e) total net installed capacity. A further 56 nuclear power reactors representing a total net capacity of 58 GW(e) were under various stages of construction in 17 Member States. Nuclear power provides 10% of the world's electricity and is the second largest source of low carbon electricity behind hydro, with a share of approximately 28% of the low-carbon electricity generated worldwide.

At the beginning of 2022, at least 20 Member States had active national programmes for SMR design and technology development for deployment by 2035, most of them carried out as part of international collaboration.

Currently, there are more than 80 SMR designs under development for advanced applications and different phases of deployment. The IAEA considers that SMR concepts need to address the requirements specified in the IAEA safety standards and nuclear security guidance. The market for smaller nuclear facilities has the potential to be significantly larger than for current large scale NPPs, given the potential for siting, applications beyond power and lower capital investment of SMR projects.

1.3.1. SMRs in operation or under construction

Two SMR plants were in operation in 2022. The Russian Federation's Akademik Lomonosov floating power unit (FPU) was connected to the grid in 2019 in Pevek (Russian Federation) and started commercial operation in May 2020. The FPU, with two KLT-40S reactors, has an installed capacity of 70 MW(e). The reactor power is not used for the vessel's propulsion system. Since it was transported to the site and connected to the grid, it has only been used to provide electricity and heat to local communities. The developer is also considering a modified version of the FPU for export outside the Russian Federation, based on the RITM-200N design, with an innovative refuelling approach based on the FPU replacement.

The other SMR currently in operation is the HTR-PM located in Shandong province, China. The HTR-PM is an industrial demonstration plant of a high temperature gas cooled reactor (HTGR), a two-unit design, which was connected to the grid in December 2021. It has an overall installed capacity of 210 MW(e). The objectives of this HTGR demonstration plant are to test and develop operating experience of the new and major components, such as the helium circulators and steam generators, as well as of the manufacturing and quality assurance practices for those components. The demonstration plant is expected to start commercial operation in 2022. Other domestic and international projects are also being considered based on this design, or with scaled-up versions such as a six-unit design.

The Central Argentina de Elementos Modulares (CAREM) reactor is a prototype small, integral, pressurized LWR currently in an advanced stage of construction in Argentina, near Buenos Aires. It will have a capacity of 27 MW(e). A future larger version that will be rated at between 150 and 300 MW(e) is planned. All the primary coolant system components have been incorporated inside the reactor vessel (i.e. integral to the reactor vessel). According to the developer, the project's target date for commissioning and first fuel loading is the second half of 2023. The regulator has established a staged licensing approach suitable for this prototype to demonstrate specific safety milestones before proceeding to the next phase of project work.

Another SMR under construction is China's ACP100, or Linglong One, in Changjiang. The ACP100 is a multipurpose 125 MW(e) pressurized water reactor (PWR) whose construction started in July 2021.

1.3.2. Rationales of countries interested in SMRs

SMRs have the potential to expand the peaceful application of nuclear power by meeting the energy needs of those market segments that the large NPPs cannot serve. The economy of scale is a key advantage in the operation of large reactors, but their capital costs are very high. SMRs lose the benefit of economy of scale due to the lower electrical output per reactor; however, for nth-of-a-kind (NOAK) plants, SMRs could compensate with lower capital cost and lower capital risk due to smaller and standardized components, mass-produced components and systems, and shorter construction time. Further modules could be added as needed. Regarding the challenge of entering the market, the levelized cost of electricity (LCOE) for SMRs will decrease in the case of large scale serial production, so a large initial order may be useful for launching the programme.

As examples of potential markets for SMRs, one can cite archipelago countries in Southeast Asia with isolated population areas and limited grids that may need distributed generation. In North America, SMRs are options for replacing ageing coal power plants as well as independent power supply applications to support mining and remote communities.

1.3.3. Countries advancing SMRs

The following tables list Member States already operating nuclear power and developing near-term SMR projects (Table 1.1), and Member States without nuclear power that have expressed an interest in SMRs (Table 1.2). The types of SMRs listed in the table comprise PWRs, boiling water reactors (BWRs), HTGRs, gas cooled modular fast reactors (GMFRs), other types of fast reactor and MSRs.

Table 1.1: Examples of Design and Status of SMRs for Near-Term Deployment

Design	Output MW(e)	Type	Designers	Country	Status
			WATER COOLED SMALL MODULAR REACTORS		
CAREM	30	PWR	CNEA	Argentina	**Under construction**
ACP100	125	PWR	CNNC	China	**Under construction**
NUWARD	2 × 170	PWR	EDF, CEA, TA, Naval Group	France	Conceptual design
SMART	107	PWR	KAERI and K.A.CARE	Republic of Korea	Standard design approval received
KLT-40S	2 × 35	PWR in floating NPP	JSC Afrikantov OKBM	Russian Federation	**In operation**
RITM-200N	2 × 53	PWR	JSC Afrikantov OKBM	Russian Federation	Detail design
UK SMR	443[a]	PWR	Rolls-Royce and Partners	United Kingdom	Conceptual design
NuScale	6 × 77	PWR	NuScale Power Inc.	United States of America	Received US NRC certification
BWRX-300	270–290	BWR	GE-Hitachi Nuclear Energy and Hitachi GE Nuclear Energy	United States of America and Japan, Canada	Pre-licensing
			HIGH TEMPERATURE GAS COOLED SMALL MODULAR REACTORS		
HTR-PM	210	HTGR	INET, Tsinghua University	China	**In operation**
GTHTR300	100–300	HTGR	JAEA	Japan	Pre-licensing
Xe-100	82.5	HTGR	X-Energy LLC	United States of America	Basic design
			FAST NEUTRON SPECTRUM SMALL MODULAR REACTORS		
EM^2	265	GMFR	General Atomics	United States of America	Conceptual design
			MOLTEN SALT SMALL MODULAR REACTORS		
Integral MSR	195	MSR	Terrestrial Energy Inc.	Canada	Conceptual design
KP-FHR	140	Pebble bed salt cooled Reactor	KAIROS Power, LLC.	United States of America	Conceptual design
			MICROREACTORS		
U-Battery	4	HTGR	Urenco	United Kingdom	Conceptual design
MMR	5–10	HTGR	Ultra Safe Nuclear Corporation	United States of America, Canada	Conceptual design
Aurora	1.5	FR	OKLO, Inc.	United States of America	Conceptual design

Note: CNEA — National Atomic Energy Commission (of Argentina); CNNC — China National Nuclear Corporation; EDF — Électricité de France; CEA — French Alternative Energies and Atomic Energy Commission; KAERI — Korea Atomic Energy Research Institute; K.A.CARE — King Abdullah City for Atomic and Renewable Energy, Saudi Arabia.

[a] Power rating above 300 MW but considered an SMR by the UK government.

Table 1.2: Examples of Member States without Nuclear Power interested or participating in SMRs development at various stages (list non-exhaustive)

No.	Member States without nuclear power	Rationales of interest and/or key projects developed by national organizations or private companies
1	Australia	Australian Nuclear Science and Technology recently joined the Generation IV International Forum for a very high temperature reactor study; national collaboration is ongoing to commission expert monitoring on the commercialization of new nuclear reactor designs, including SMRs, that may offer economic value for nuclear power generation.
2	Denmark	Developing at least two designs of molten salt reactor-type of SMR. A memorandum of understanding (MOU) was set to collaborate with South Korean regulators to identify and meet requirements for

No.	Member States without nuclear power	Rationales of interest and/or key projects developed by national organizations or private companies
		the construction and export of the Danish company's floating NPPs with MSRs.
3	Estonia	Conducting a feasibility study on the suitability of SMRs for ensuring the country's electricity supply and meeting climate goals beyond 2030. The study suggests that there is market demand and vast potential for SMRs.
4	Ghana	Given the size of electricity grid, Ghana Atomic Energy Commissions has used the IAEA's reactor technology assessment method for SMR studies for the country.
5	Indonesia	Embarking country with a national nuclear lab performing basic R&D on HTGRs, and the regulatory body studying regulatory framework for HTGR-type SMR design under development.
6	Israel	Given the country's specific geological hazard and population density, Israel plans to deploy an SMR by the 2030s. The government has conducted years of site studies and selected Shivta Rogem as the only site feasible for NPP construction.
7	Italy	National energy laboratories and leading universities active on supporting international SMR technology development, particularly thermohydraulic testing.
8	Jordan	Given that any site will have with limited access to cooling water, the country is actively preparing to deploy SMRs by the early 2030s by assessing the need for infrastructure and reactor technology.
9	Kenya	Given the size of its electricity grid, the Kenya Nuclear Energy Board has participated in IAEA activities on SMRs. The country's nuclear engineers have used the reactor technology assessment method to explore the options for an SMR.
10	Latvia	Latvia has joined the Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology (FIRST) program, established by the United States of America. The program is designed to strengthen strategic links, support the development of clean energy and promote technical cooperation with partner countries to ensure the safe and responsible use of nuclear infrastructure.
11	Morocco	The national utility s developing technological-economic top-tier requirements for SMRs. The country performed reactor technology assessments that focused on SMR options.
12	Philippines	Since 2014, the Ministry of Energy has expressed a strong interest in developing an NPP with an SMR option. In January 2022, the country has conducted a feasibility study on SMRs.
13	Poland	Poland has been the most active embarking country in Europe, with a strong interest in both SMRs (PWRs and HTGRs) and large commercial LWRs. Under the letter of intent between ENEA and Last Energy, the two companies will initially cooperate on the development, construction and further deployment of SMRs.
14	Saudi Arabia	An embarking country with a strong interest in sharing intellectual property on SMRs for production of electricity and non-electrical applications, in cooperation with the Republic of Korea.
15	Singapore	A country identifying SMRs as a possible future option, through the IAEA TC national project.
16	Tunisia	Given the country's small electricity grid, SMRs are a possible future option when nuclear is adopted. STEG, the national utility, has come up with a top-tier utility requirement for SMRs.
17	Uganda	An embarking country with an interest in SMRs, Uganda is focusing on preparing its national infrastructure for a nuclear power programme.

2. SUCCESS — WHAT WILL IT LOOK LIKE?

This chapter describes the ‘enabling environment’ that needs to be in place for the successful deployment of SMRs and the delivery of benefits described in Chapter 1. There are some core elements needed to enable the deployment of SMRs that mirror those already established for larger installations. These include proven reactor technologies and nuclear fuels that are demonstrably safe, secure and economically competitive. Specific features unique to SMRs, most notably their modular construction and ability to transport these modules to sites, will need to be addressed. Innovative fuels and waste streams must also be considered.

In an enabling environment, the regulatory framework will clearly define the general rules, technical requirements, means, roles and responsibilities required for successful deployment of SMRs. This will note the possibility for design, construction, operation and decommissioning to be performed by different organizations in different countries, which may require coordination of more than one country’s regulatory environment. The regulatory framework will also take account of any unique features or infrastructure that may be required for the transport and management of spent fuel and radioactive waste, some of which will be unfamiliar compared with spent fuel and waste managed routinely today. The regulatory framework will ensure that SMRs can be regulated in a manner that is appropriate for and proportionate to the risks.

Proponents of any reactor new build, including SMRs, will consider whether the enabling environment supports the business case. This will include a description of how everything is brought together in the value proposition or business case prepared by the technology developer and the technology recipient. The business case will inform decisions about whether to develop SMR projects.

The business case will compare SMRs with alternative low-carbon technologies and will assess if there is a net benefit to moving ahead taking into account all the goals described above. Securing an enabling environment will ensure that SMRs can be confidently introduced into the energy mix with public acceptance.

Chapter Highlights:

- **Proven SMR technology is crucial but is not enough on its own.**
- **Interested parties (including investors) will not have confidence in SMRs unless:**
    - **SMRs are able to operate in a demonstrably safe, secure and safeguarded way throughout their lifetime and can ultimately be decommissioned and released from regulatory control;**
    - **There are clear economic and environmental benefits to the Member States and companies operating such reactors: i.e. there is a clear value proposition.**
- **An enabling environment involves global harmonization and standardization.**

2.1. POLICY, LEGISLATION AND REGULATION

2.1.1. Policy

Countries that intend to deploy nuclear power projects will need stable and well-accepted energy policies that recognize nuclear energy's contribution to energy security and sustainable development objectives. The policies can be explicit on the type of nuclear technology.

Electricity regulations and, more generally, those for the energy market that recognize the contribution of dispatchable low-carbon sources can also favour the deployment of nuclear energy. Specific market mechanisms guaranteeing revenues for investors may also be needed to attract investment in capital-intensive nuclear projects.

Policies supporting nuclear power projects will need to ensure that provisions exist for an appropriate legal and regulatory framework, clear allocation of responsibilities and adequate human and financial resources. The clear allocation of responsibilities is especially important when multiple parties must work together to ensure successful deployment (e.g. different parties responsible for design, supply, operation and decommissioning of installations), which may be the case in some countries deploying SMRs.

2.1.2. Development and maintenance of adequate legal frameworks

For countries engaged in any activity involving the use of nuclear energy and ionizing radiation it is important to develop and maintain an adequate national legal framework for the safe, secure and peaceful use of SMRs. The starting point for all countries seeking to deploy SMRs is adherence to and implementation of all the applicable international legal instruments in the fields of nuclear safety and security, safeguards and civil liability for nuclear damage.

In implementing international obligations at the national level, many countries follow a comprehensive approach, addressing all aspects of nuclear law, from safety and security to safeguards and nuclear liability, in a single piece of legislation. Aligned with general policy objectives and adapted to the nature and extent of the facilities and activities to be regulated, such legislation establishes the general framework, leaving more technical requirements to regulations. To establish the needed regulatory framework, the legislation prescribes the regulatory body with the legal authority, independence, competence and resources necessary to fulfil its statutory obligation for the regulatory control of facilities and activities. In doing so, the legislation also provides for clear delineation of regulatory functions among different authorities and bodies.

For TNPPs, the legal and regulatory framework for safe and secure international transport may need to be revised.

2.1.3. Regulatory framework

The regulatory body established by legislation requires a regulatory approach, taking into account the State's legal and industrial practices and the guidance provided in the IAEA safety standards and nuclear security guidance. The regulatory approach and stringency of control applied to SMRs need to be commensurate with the risk (likelihood and consequence) associated with a loss of control (i.e. a graded approach). The regulatory body requires a licensing process and compliance programme that cover the full life of the installation from siting and design to operations and decommissioning.

International cooperation between SMR technology vendors and Member State regulators, including the regulators of the countries wishing to deploy SMRs, and the evolution of the international legal framework, safety standards and security guidance may result in further harmonization of requirements among Member States, which may in turn facilitate the deployment of SMRs globally.

2.2. SAFETY, SECURITY AND SAFEGUARDS

The demonstration that SMR designs meet the goals of safe, secure and peaceful operation are key for the success of SMR technologies. Safety, security and safeguards (3S) considerations focus on different aspects of reactor design and operation but have multiple interfaces. Recognizing these interfaces and prioritizing synergies will enhance the deployment of SMRs. Currently there is limited experience and a lack of comprehensive guidance on integrated approaches to 3S for new reactors. These issues are being amplified in light of specific challenges to 3S raised by innovative technologies and solutions in SMRs.

Safety demonstrations for SMRs address the specific challenges associated with the innovative technologies used in their design. These challenges include a lack of comprehensive knowledge about specific phenomena, limited operational experience and limitations in the application of traditional approaches to design safety and safety assessment. Therefore, safety related decisions might need to be implemented in the context of large uncertainties.

Regardless of the SMR design a graded approach is needed to develop justified and optimized arrangements for preparedness and response for a nuclear or radiological emergency.

Security arrangements also encounter specific challenges in terms of the transportability of SMRs, designs using remote operation concepts without a human presence and deployment of SMRs close to urban areas. These novelties in SMR design require unique solutions in terms of security.

Safeguards implementation processes are also expected to face certain challenges related to the innovative solutions in SMR designs. Existing safeguards approaches may not be suitable to fully address challenges such as transportability, accessibility of remote locations, new fuel concepts, longer refuelling periods and higher enrichment levels associated with SMRs.

2.3. SAFE AND SECURE MANAGEMENT OF SPENT FUEL, RADIOACTIVE WASTE AND DECOMMISSIONING

Just as the design and operation of SMRs can be built based on knowledge gained from current power reactors, that experience can also provide initial guidance on assessing and planning for spent fuel management, waste management and decommissioning of SMRs. For SMRs to be sustainable, it is necessary to plan for the safe and secure management of spent fuel, waste and decommissioning before deployment. Planning early for spent fuel management, waste management and decommissioning will ensure that the right infrastructure is in place to minimize the cost and complexity of clean-up, gain the confidence of interested parties and avoid unwanted liabilities and legacies for future generations.

Regardless of the specific SMR design considered, all the responsibilities related to spent fuel management, waste management and decommissioning remain in place. These areas will be assessed before the design is finalized and the SMR is deployed. The concept of SMRs, particularly the transportable nature of modules and reactors, introduces some additional factors to consider. For example, from a security perspective, the potential for remote deployment and/or transportable designs underscores the importance of early decisions on nuclear fuel arrangements, with resulting implications for design basis threat, the frequency of refuelling and associated spent fuel transport security concerns.

It is essential that responsibilities (including financial responsibilities) are clearly assigned for planning and implementing safe decommissioning and safely and securely managing spent fuel and waste produced during operation and decommissioning.

The wide range of SMR concepts and designs indicates the potential for diverse forms of spent fuel and radioactive waste. Water cooled SMRs can benefit from operational experiences and lessons learned from existing reactors. While there is less information and experience today about the management of spent fuel and radioactive waste from more innovative designs, developers and regulators are addressing the issue early on.

There is potential for a wide geographical spread of SMRs, sometimes in remote locations, potentially increasing the need for on-site storage of radioactive waste and spent fuel, which will require careful consideration to avoid implications for the maintenance of 3S over the long term.

Another challenge relates to the possible co-location of several SMRs on the same site, or near an industrial site to which SMRs provide electricity or heat. This might bring additional complexity to the decommissioning process, due to interfaces with other SMRs on the site that are still in operation or even under construction, and with the industrial facility. These interfaces should be accounted for in any safety considerations.

The best time to address these challenges is at the design stage, which offers the greatest potential for minimizing waste and maximizing recycling and reuse opportunities, which could form part of the safety case and licensing process.

2.4. PREPARING FOR THE RESPONSE TO EMERGENCIES

The concept of defence in depth, as already in use for ‘large’ NPPs, fully applies to SMRs. Regardless the degree to which layers (1st to 4th) of the defence in depth SMRs are strengthened by safety improvements, effective emergency arrangements for taking protective actions off the site should still be in place (5th and final layer). In addition, requirements from the IAEA safety standards in the area of emergency preparedness and response (EPR) fully apply to SMRs. Therefore, in preparing arrangements to respond to an emergency associated with any SMR, relevant requirements from IAEA safety standards in the area of EPR need to be applied. The on-site and off-site emergency arrangements for all SMRs should be commensurate with the hazards associated with these reactors and with the potential consequences of an emergency should one occur.

2.5. RELIABLE TECHNOLOGY

2.5.1. Front end and nuclear fuel technologies for SMRs

There are different types of nuclear fuels being developed for the various SMR designs. Each type of fuel is currently at different levels of development, from proof of performance, proof of principle or proof of concept. To be deployed, SMRs will need to have proven fuel designs (i.e. tested and licensed) and a reliable supply chain for that fuel.

2.5.2. Reactor design

SMR designs will need to have been proven, through the construction and operation of prototypes and first-of-a-kind reactors. The feedback experience from the construction and operation of these SMRs will help consolidate and optimize their design for safe and cost-effective operation.

2.5.3. TNPPs and safe transport of modules and waste

Using factory manufacturing techniques would result in SMR modules, and in some cases the reactor vessels loaded with fuel, being transported to their operating sites for installation and operation. The reverse would happen during the decommissioning phase. Those SMR modules containing radioactive material would be regarded as nuclear cargo and therefore subject to regulatory requirements extant at the time of transport.

It is important that the design of a TNPP and its fuel consider the safety and security aspects of transport. These reactors can be relocated from one site to another or back to a manufacturing site. Therefore, the impact of each life cycle stage of a TNPP (design, sitting, commission, operation and decommissioning) on its safe transport needs to be evaluated. After a period of operation at one site, the effects of degradation and ageing could impact safe transport and should be assessed in order to comply with safety justification throughout the operation and verify transportability after operation. This poses a challenge from a transport safety perspective to be considered in the design of a TNPP for the 'shipment after operation' life cycle stage. Further if the conveyance (rail, vehicle, ship, vessel) is used as a platform or site for a TNPP, the design safety of that conveyance also needs to be assessed. With respect to transport security a number of factors should be considered, including whether the TNPP is transported with fuel or fuelled later, the quantity and type of fuel and its associated material attractiveness and the transport security requirements for fresh and spent fuel.

2.5.4. Industrial supply chain

Robust supply chains, capable of delivering high quality nuclear grade equipment and systems, are needed in vendor countries but also locally (i.e. where SMRs are built and operated) to provide engineering, operation and maintenance (O&M) and fuel services in the long run. A stable and sustained demand for systems, components and engineering services is also required to keep the industry thriving, ensure a return on investments and retain experience and skilled teams.

2.6. PEOPLE AND RESOURCES

For the successful deployment of SMRs, stakeholders need to be suitably informed, knowledgeable and involved in decisions related to their deployment (e.g. national regulatory bodies need to have sufficient capacity to review, inspect and oversee the deployment and use of SMRs). In addition, stakeholders will need to have appropriate leadership, management systems and an understanding of safety and security culture.

There is a specific need to build up human resource capacity to manufacture components, build SMR modules and operate these new reactors, and for the broader human resource development that is part of the infrastructure of any nuclear power programme. Several years are needed to prepare and train a workforce for construction and operation, even in the case of SMRs, which have a potential for shorter construction time than large reactors. There will be some specifics for operation. For example, some multimodule SMRs are envisioned to be operated with a single control room and some are also intended for non-standard applications such as operation in remote regions, coupling with chemical plants and other industries and hydrogen production. Specific competencies and skills to manage and address the needs of different industries, including the related interfaces, have to be considered and planned for well ahead of the related deployments.

New manufacturing techniques might call for skills and expertise not yet widely available. Whereas the human capacity is available in the R&D field, it might prove more difficult to attract those skills in the industry without a clear prospect for deployment. There is a need to identify the new skills required by the industry to manufacture SMRs as this could benefit the whole industry.

Embarking countries, whose first nuclear installation will be an SMR, need to properly assess the scope and size of the national human infrastructure that needs to be created and developed to support the new nuclear programme. The correct estimation of the investment on human resource development will be a critical input for informed decision making, both at the national and project developer levels.

As with any new technology, there are challenges with the available competent resources. The lack of available competency in SMR technologies in regulatory bodies may be a challenge, as will be the insufficient workforce in the startup companies that develop new designs. Countries with a clear SMR strategy have understood that having adequate human resources in regulatory bodies is critical.

2.7. SOUND BUSINESS CASE

Both the vendor and the end-user will need a sound business case before SMR technology is scaled up as a source of electricity, heat and ancillary services in evolving power grids and energy markets. For the vendor or project developer, the business case will demonstrate that the SMRs are ready to be launched and that SMRs fulfil the needs of the end-user. For the end-user, the business case will consider the extent to which all elements of the enabling environment are in place and whether the benefits of SMRs justify the work required to establish the enabling environment and secure successful deployment of SMRs in the prevailing circumstances.

For a project developer, demonstrating the business case usually starts with market research and an analysis of the competitive landscape. Then, based on this assessment, a value proposition is developed to meet the needs and expectations of the targeted customer segments. Finally, the SMR business model is built, often around two pillars, the cost structure on the one hand and the revenue streams on the other hand. The next few paragraphs provide insights into the steps required to demonstrate the SMR business case.

2.7.1. Market research and analysis of the competitive landscape

SMR potential end-users need to be identified, secured and segmented (i.e. classified into customer segments having similar requirements, needs and expectations). SMRs can potentially target multiple consumer segments, depending on the technology and the location, such as the following:

- Electricity
- Combined heat and power
- Low-grade heat for district heating and desalination
- Off-grid applications

The size of each market segment should be evaluated. Analysts should also seek to determine who is present (competitive landscape) and what is missing in a particular market — what needs exist that are not being adequately met.

2.7.2. Value proposition

The SMR value proposition and strategic positioning versus other nuclear or non-nuclear alternatives are developed building on the market and competitors' research.

A value proposition describes how the targeted customer groups' unique needs and expectations are met. For SMRs, the value proposition can be built around their ability to operate as a low carbon and dispatchable technology complementing variable renewables, power storage systems and other energy system components. With their modular architecture and versatility, producing both electricity and process heat, SMRs can also bring flexibility to power grids as they evolve towards a larger, more complex and more integrated system, with strong couplings across the broad energy sector.

2.7.3. Business model

The business model defines the SMR value proposition, how it is created, and how it is communicated to the targeted customer segment. It describes the approach to cost reduction and control and revenue diversification and generation. For SMR developers, capital expenditure amortization assumptions are an additional parameter for their business model.

The cost structure breaks down the expenditures incurred to generate electricity, heat and services to the power system (i.e. capital costs, O&M, fuel cycle costs). As for capital costs, usually the most significant driver of LCOE in nuclear projects, SMRs could benefit from the efficiencies associated with the repeated manufacture of a standard design and from carrying out much of the inspection, testing and interaction with the regulator at the factory. The costs of O&M are very much related to labour intensity in the nuclear industry, depending on the degree of automatization and the regulatory requirements. Finally, the expected SMR fuel costs will be on the same order of magnitude as for large, GW-scale reactors, except, perhaps, for designs relying on enriched fuel — the so-called high assay — which are not currently readily available in the market.

In addition to the cost structure, the business model of a project is based on revenues, which must be secured, diversified and sustained over time to ensure profitability and competitiveness with other technologies. By selling a combination of electricity, heat and flexibility, SMRs can achieve this diversification and send positive signals to investors, who are usually risk-averse when considering nuclear projects. SMR projects could also benefit from revenue guarantee mechanisms — well-designed power purchase agreements — allowing project developers to pay back the invested capital and generate acceptable returns to their investors.

3. WHAT'S NEXT FOR SMRs?

The eventual market size for SMRs could be hundreds of modules and have the potential to involve a broader set of industries, contributing to an increased national infrastructure and economic prosperity. Technology developers have made significant progress in developing SMR designs but deployment is still very limited, as highlighted in Figs 3.1 and 3.2 below. This chapter focuses on how we get from where we are today to an enabling environment for the safe, secure and successful introduction of SMRs globally. It will cover the work to be done by governments to establish the appropriate policies, programmes and legal and regulatory frameworks that would govern the full life cycle of nuclear power programmes based on SMRs; the work to be done by technology developers and technology recipients to ensure the value proposition exists; the work to be done by operators and regulators to ensure adequate capability and capacity; and the work to be done by all to build public confidence.

The chapter will also cover the key national drivers and the relevant nuclear infrastructure needed to deploy SMRs, including their fuel cycles. The chapter highlights SMR capabilities beyond electricity, such as industrial heat, and potable water, in line with the United Nations Sustainable Development Goals.

Chapter Highlights:

An enabling environment would include:

- **A global nuclear market that is ready and able to support the full deployment of these advanced technologies, from the technology supplier countrie's ability to supply these reactors, to the embarking and expanding recipient countries' having the necessary infrastructure to own and operate these reactors;**

- **Leadership by national governments in the development of suitable legal frameworks, policies and capabilities;**

- **Implementation of lessons learned in harmonization when developing new regulations for advanced technologies;**

- **Enhanced collaboration among governments, international organizations, regulators and industry to streamline international licensing, regulatory frameworks, codes and standards, and utility requirements;**

- **Creation of a sustainable advanced nuclear fuel pipeline to support broad deployment of SMRs;**

- **Ensuring that the needed human resources and competencies are available for deployment of SMRs.**

Fig. 3.1: Summary of SMR designs and technologies across the world's regions

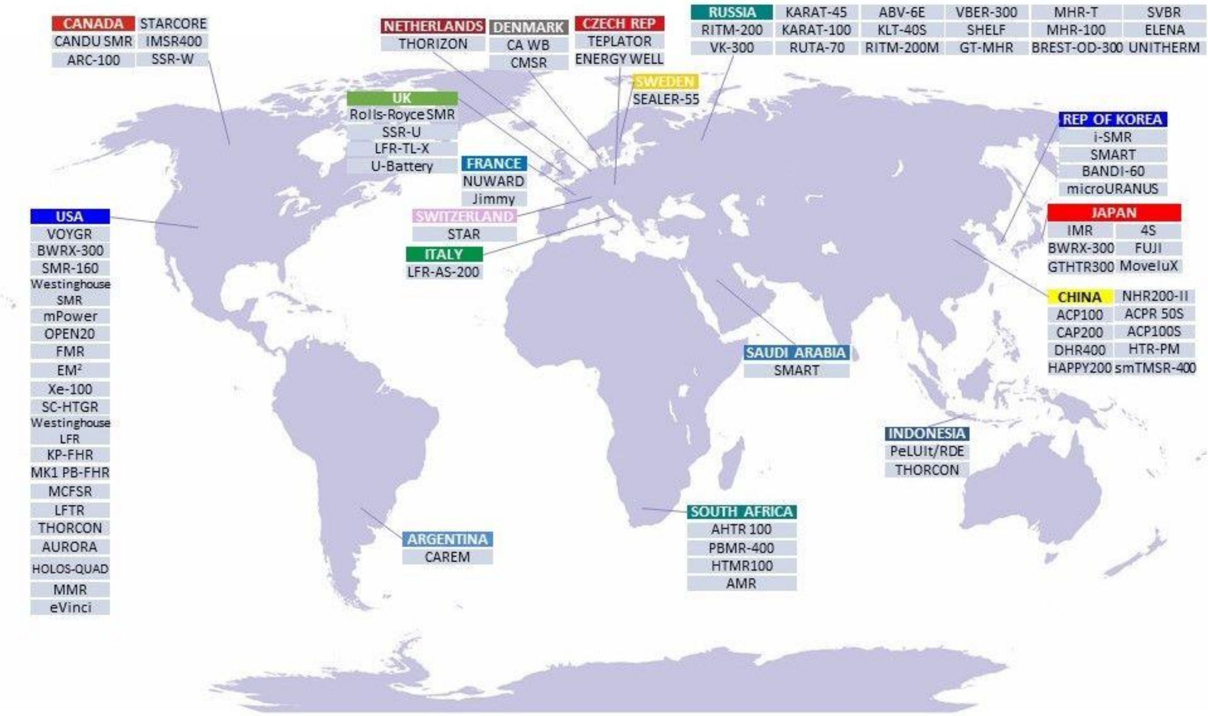
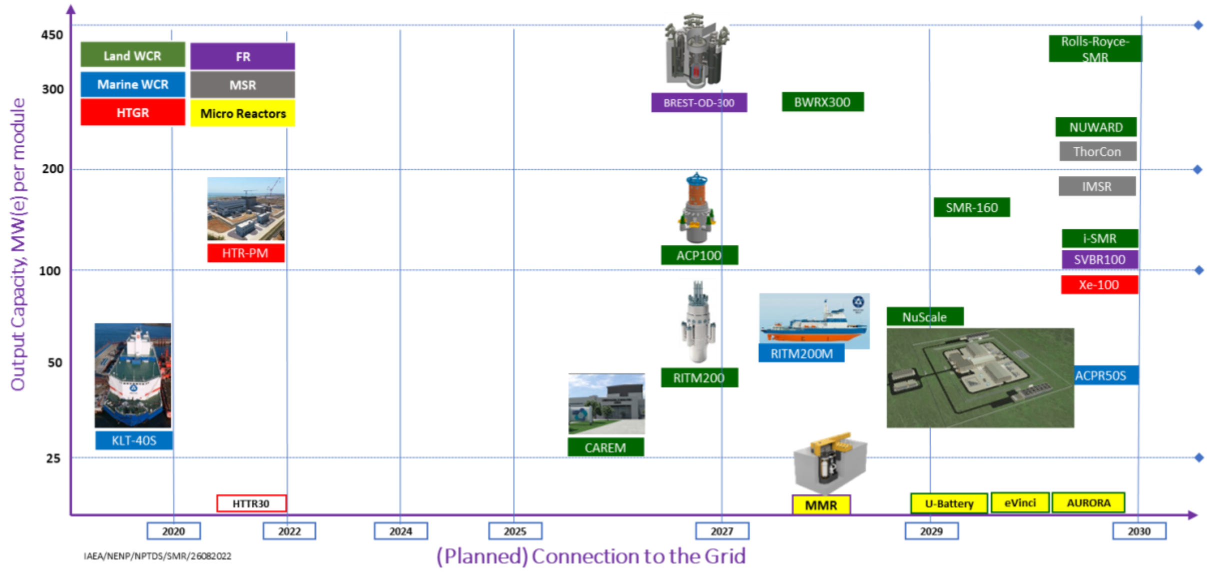


Fig. 3.2: SMR deployment timeline by design — through 2030



3.1. WHAT IS NEEDED TO SUSTAIN AN ENABLING ENVIRONMENT THROUGH 2050

The nuclear industry continues to move forward in developing advanced reactor technologies to support climate change mitigation and security of energy supply. However, to meet these objectives the transition to low carbon energy systems requires a substantial effort by various stakeholders — research and development, innovation, diffusion of know-how, effective commercialization, accelerated deployment — and the availability of funding and financing to support this effort. Establishing and maintaining an enabling environment for SMRs requires well-designed policies and strategies, which are crucial to triggering ongoing efforts over time and transforming today's energy systems.

3.1.1. Energy policy

An effective energy policy framework provides incentives for developing and rolling out low carbon energy technologies. A key element of such a framework is a widely accepted, technology neutral 'clean energy standard' inclusive of all low emitting sources that generate electricity heat ammonia or hydrogen. An effective and independent nuclear regulatory framework that is stable and predictable is also crucial for delivering SMRs in a safe, timely and cost-effective manner.

3.1.2. Access to capital

Scaling up clean energy generation can be achieved only if public, private and alternative funding sources are available, including through development finance institutions. The ecosystem should be able to provide access to a variety of financing services — from 'seed' capital for innovation and spin-off companies to funding for demonstration and commercialization to financing for growth and deployment acceleration.

3.1.3. Industrial involvement

SMR designs have entered a phase in which there is a need to consider how to make their projects and operations work with the necessary suppliers beyond the original technology developer and vendor organizations. Such considerations will include the different types of suppliers of products and services on many different levels ranging from gravel delivery to reactor vessels and their respective safety analyses. Consequently, assuring the quality, safety, economy and scheduling of SMRs will necessitate proactive supply chain planning and management.

As with large power reactors, SMRs of today will have heavy components with long lead times and safety related components with rigorous requirements. These may lead to industrial bottlenecks. At the same time, new approaches to using more of the components used in other safety critical industries are emerging, and such components — often referred to as commercial or industrial grade as they are not based on nuclear quality assurance codes — are being approved more widely to be used in nuclear power plant safety systems. Together with potentially less active SMR safety systems and components, these approaches have the potential to open the global industrial supplier base to SMR projects and make nuclear power projects more interesting to global manufacturers.

Another developing area is advanced manufacturing. While there are demonstration projects with operating NPPs, SMRs are expected to be one large application area (e.g., for 3D printed parts). Advanced manufacturing is expected to introduce several efficiencies and commercial advantages while focusing on nuclear safety, quality, and reliability.

Global industrial suppliers are already envisaging adapting the manufacture of their products to different legislation, regulations and standards on different continents, and SMR vendors are no exception. Harmonization efforts such as the IAEA's Nuclear Harmonization and Standardization Initiative (NHSI), described further in Chapter 4, are also envisaged to improve the enabling environment for SMRs. In addition, it should be possible to continue operation during supply related disturbances, such as those encountered in times of pandemic and conflict;

securing global and local supply capability is an important area of risk management. Equally, one should not forget services like inspections and capability testing, although recently remote and hybrid inspections and auditing have gained acceptability in some instances, for practical reasons.

3.1.4. Educational and R&D infrastructure

High-quality education systems (in both vendor and end-user countries) stimulate innovation and knowledge spillover and supply the necessary human resources and skills to R&D organizations, manufacturing industries, engineering service providers and utilities.

3.2. OTHER AREAS OF INFRASTRUCTURE REQUIRED TO CREATE AN ENABLING ENVIRONMENT

3.2.1. Addressing the challenges for technology developer countries and embarking and expanding countries to ensure market readiness

The value proposition for technology developer countries and technology recipient countries is to have available a slate of proven and operating reactors (reference plant concept) to achieve NOAK plants that can be built on time and on budget and are safe. Most of the near term SMR designs are derived from current LWRs operating worldwide. These SMRs benefit from many decades of operational and regulatory experience. However, the other advanced SMR designs require further development in advanced fuels, different coolants and other advanced passive safety systems. The drivers for these advanced designs were laid out and discussed in Chapter 1. The compelling features or differentiators these technologies offer to countries and what embarking and expanding recipient countries seek may not come to fruition if the market is not ready and prepared with the relevant infrastructure in place.

The IAEA has concluded that the necessary infrastructure for SMRs is largely similar to that of large NPPs. However, there are certain aspects of infrastructure that could be enhanced, shortened, made more proportionate or need fewer resources for development. The IAEA has launched a new SMR initiative to develop a publication to examine and identify infrastructure areas that could be enhanced to bridge the current gaps to enable the potential accelerated deployment of SMR technologies s.

Among the 50 technology recipient countries that have expressed interest in introducing nuclear power, about half are in the pre-decision phase or just after and are engaged in energy planning activities. The other half are pursuing the introduction of nuclear power. Based on the current national plans of the 23 mentioned, approximately a dozen newcomer countries are expected to introduce nuclear power by 2035, allowing further work to support market readiness. These countries need to be knowledgeable customers to decide whether to embark on or expand their nuclear power programmes based on SMRs or other advanced reactor types. These Member States continue to utilize and follow the IAEA Milestones in the Development of a National Infrastructure for Nuclear Power, or what is commonly referred to as the ‘Milestones approach’ in developing their nuclear programmes. Embarking countries such as Estonia, Ghana, Jordan, Kenya, Poland, Saudi Arabia and Sudan and expanding countries such as South Africa have expressed interest in the potential use of SMRs. Many of these countries recognize the potential benefits for their national goals and objectives of acquiring SMR technologies.

3.2.2. Applicability and adequacy of the international legal framework

Depending on the specific characteristics and potential future deployment scenarios of SMRs, contracting parties may need to consider the applicability and adequacy of the existing relevant international legal instruments in the fields of nuclear safety, nuclear security and civil liability, as well as compatibility with relevant instruments in other fields such as law of the sea and maritime law. From the point of view of safeguards obligations, there is nothing distinctive about the characteristics of the design or operation of an SMR that would differentiate it from the design or operation of a large nuclear facility. It is, however, important to highlight that should the facility be constructed in a nuclear weapon State party to the Nuclear Non-Proliferation Treaty and exported to a non-nuclear-weapon State, specific arrangements between the supplier State, the technology recipient State and the IAEA may have to be made for the technology recipient State to meet its safeguards obligations.

3.2.3. Enhancing government and international support and collaboration

Governments will need to continue to set up the appropriate policies, programmes and legislative and regulatory frameworks to govern the full life cycle of nuclear power programmes based on SMRs. Table 3.1 provides a non-exhaustive list of national initiatives. There is a need also to support embarking countries through bilateral and international engagement and collaboration. These efforts are vital to transferring knowledge and expertise from countries that already have nuclear institutions, industry and capacity building capabilities to countries embarking on a nuclear power programme for the first time. International collaboration, like the IAEA Nuclear Harmonization and Standardization Initiative (see Chapter 4), is also essential to developing a harmonized approach to legal frameworks, licensing regimes, utility requirements and codes and standards.

Table 3.1: Support for global SMRs engagement/collaboration (non-exhaustive)

No.	Member States with Nuclear Power	Rationales of Interest and/or Key Projects
1	Argentina	Technology developer of CAREM; regulatory body active on SMR licensing; CAREM in final stage of construction for operation in 2023.
2	Brazil	A practical arrangement was signed between the IAEA and the ABDAN in 2021 on cooperation in the area of nuclear power technology and applications, including SMRs.
3	Bulgaria	In 2021, KNPP-NB signed an MOU with NuScale Power Inc. (USA) to discuss possible deployment of an SMR at the Kozloduy site.
4	Canada	Implementing Canada's Roadmap for SMR; regulatory body active on reviewing SMR designs; utilities, including OPG and Bruce Power, are collaborating on SMRs for near-term deployment. OPG has selected a site for construction.
5	Czech Republic	Conducting technology developments for two SMR designs and technologies, including a microreactor.
6	China	Technology developer of several SMR designs; regulatory body active on SMR licensing.
7	Finland	VTT active on the R&D for SMRs, the country has also a focus on nuclear district heating using SMRs.
8	France	Technology development for NUWARD; regulatory body active on SMR licensing.
9	India	Technology developer of several SMRs; regulatory body active on SMR licensing.

No.	Member States with Nuclear Power	Rationales of Interest and/or Key Projects
10	Iran, Islamic Republic of	Expanding country interested in SMR deployment, in current cooperation with both China and the Russian Federation.
11	Japan	Developing design and technology of BWR-type and HTGR-type SMRs; operating a high temperature test reactor at the Japan Atomic Energy Agency.
12	Korea, Republic of	National laboratory and national universities active in supporting international SMR technology development.
13	Pakistan	Expanding country interested in SMRs, experienced in constructing the operating medium sized reactors; interested in indigenization and development of supply chain of SMRs, in cooperation with China.
14	Romania	Nuclearelectrica and NuScale Power Inc. (USA) plan to construct an SMR plant in Romania by 2028. The announcement came during a meeting between US Special Presidential Envoy for Climate and Romanian President on the sidelines of the COP26 climate conference in Glasgow.
15	Russian Federation	Technology developer of several SMRs, including the operating floating NPP Akademik Lomonosov; regulatory body active in SMR licensing; planning to start construction of RITM-200N in 2024 in the Yakutia region for target operation in 2028.
16	South Africa	Regulatory body active in the IAEA's SMR Regulators' Forum; the country is experienced with HTGR.
17	Sweden	Vattenfall is conducting a pilot study on the feasibility of deployment of at least two units of SMR at the site of the Ringhals NPP.
18	Ukraine	Member of TWGs of SMR and HTGR, the country has an MOU with SMR technology developers for potential deployment of SMRs.
19	United Kingdom	Technology developer; regulatory body active in SMRs and advanced modular reactors.
20	United States of America	Technology developer of several SMRs, including microreactors; regulatory body active in SMR; NuScale Inc. received design approval in 2020; the NuScale Power Module in Idaho Falls, Idaho, is planned to begin generating power in 2029.

Note: CAREM — Central Argentina de Elementos Modulares; ABDAN — Brazilian Association for the Development of Nuclear Activities; KNPP-NB — Kozloduy nuclear power plant–new build; VTT — Technical Research Centre of Finland.

3.2.4. Realizing harmonization and standardization

With respect to the compatibility of security, safety and licensing requirements from country to country to facilitate the deployment of SMRs globally, many of the components of the regulatory framework of any jurisdiction (in terms of both requirements and processes) are determined by the legal framework of the country. In the field of safeguards, the enactment of laws and regulations is essential to control and oversee the use of nuclear material and nuclear related activities in the State, consistent with the State's obligations under its safeguards agreements and additional protocol thereto (if applicable). Provisions in the national implementing legislation should address all safeguards obligations of the State, while regulations provide more detailed requirements for licensees concerning safeguards implementation.

Significant international effort has been devoted in the last few years by stakeholders, including regulators, to striving for and achieving harmonization of design and safety requirements to enable designers to license standardized designs in different jurisdictions without design modifications. There appears to still be a long way to go to achieve that goal. Notwithstanding, the IAEA has undertaken a major review of the Safety Standards to evaluate their applicability to non-water-cooled reactors and SMRs that provides a mapping of potential issues in the application of the safety standards to these technologies. Based on the review results, the IAEA has developed a programme of work to progressively revise the Safety Standards and develop other publications as necessary to ensure these technologies are accounted for in the IAEA safety framework.

Approaches to harmonization have proven to be challenging for many reasons. As an intermediate step, further work on processes to promote collaboration among regulators in different jurisdictions is needed. This collaboration may include facilitating joint reviews or recognition of safety assessments while applying due diligence to discharge each regulator's obligations. It is expected that the success of these processes will reduce regulatory duplication and hence regulatory burden to designers and vendors.

Collaboration will be essential as deployment of factory fueled and hot commissioned SMRs may necessitate the parallel application of licensing requirements and processes of both the regulatory body in a vendor country and that in a recipient country for the same SMR (e.g. design, manufacturing, construction, (parts of) commissioning). The regulatory approach and licensing process in each recipient country need to be considered. Additionally, further challenges arise if such SMRs are built before the licensee in a recipient country has been identified.

Licensing is a sovereign activity of each recipient country fulfilled through its own regulatory body. Changes in the licensing process may be needed in many jurisdictions and necessitate collaboration between countries and their regulatory bodies.

3.2.5. Safety, security and safeguards (3S)

A thorough understanding of potential interfaces, conflicts and synergies among safety, security and safeguards is an essential prerequisite for the sustainable deployment of SMRs. Proper consideration of their interfaces will allow setting up the relevant measures (e.g. design solutions, organizational matters, regulatory framework) to effectively integrate these three disciplines for SMRs and avoid or minimize potential negative interactions. With many SMRs at the early design stage, there is a unique time window to develop and effectively utilize an integrated approach to 3S.

Safe design and operations

In general, the current approaches that are being used for safety demonstration apply to SMRs. However, for many types of innovative SMRs, there are uncertainties related to the limited knowledge of physical phenomena, lack of comprehensive experimental and operational data, and challenges in addressing those uncertainties. Benchmarks and efforts to harmonize safety assessment approaches are needed that are specially tailored to the treatment of innovative features used in SMRs. International organizations such as the IAEA facilitate this process by providing fora and relevant platforms for the harmonization of approaches.

SMR designs provide new design concepts, and there is a need for a better level of consensus on design safety approaches. Current safety standards do not cover all aspects of SMR design safety (particularly for non-water-cooled SMRs). Clearly, this requires intensification of international co-operation in this area. The IAEA will need to play an essential role in facilitating the process.

There are limited expertise and capabilities in the various areas related to nuclear safety (e.g. design safety, safety assessment, operations). Therefore, successful development and deployment of SMRs will require capability and capacity building in these areas. Given the dynamic developments in the field, it is important to ensure that the capacity building activities are implemented in a timely manner and are tailored to the needs of various stakeholders (e.g. regulators, designers, operators).

Existing operational safety approaches do not always cover all the activities currently being proposed for SMR operations. This refers to various areas of novelty, such as remote re-fuelling concepts, transporting the fuelled reactor to the site, shifting significant portions of the commissioning activities to the factory, increases in autonomous operations concepts (e.g. remote surveillance, interventions, testing), and long operating cycles. The potential impact of the above mentioned specifics on operational safety requires further guidance and standards.

IAEA Safety Standards are a key international reference for the design and operational safety of SMRs. A review of the applicability of IAEA Safety Standards revealed areas that require further guidance in the context of SMRs. These efforts create an important basis for the IAEA to support Member States with independent peer reviews aligned with the IAEA Safety Standards for SMR design safety (e.g. Technical Safety Review Service Guidelines).

The majority of SMR designs are currently at the early design stage (i.e. conceptual design) in which the optimization of design and operations is one of the key aspects to success. Optimization of design and operational safety is challenging and requires consideration of numerous inputs. An integrated decision making process is an important prerequisite which will allow for various factors and considerations (e.g. deterministic considerations, use of risk information, human and organizational aspects, results of R&D activities) to be taken into account while implementing decisions related to design and operational safety.

Security by design

SMRs as well as other nuclear facilities are expected to face increasing challenges in meeting evolving security requirements caused by emerging technological trends and threats. Enhancement of security arrangements after the SMR design is finalized can lead to operational cost overruns. Therefore, incorporating security in the design stage will provide robust, cost effective and optimized physical protection systems.

‘Security by design’ is a concept in which security plays an integral role throughout the design process. It is a risk-informed approach that requires multidisciplinary teamwork and a clear security strategy. For SMRs, the relevant regulatory framework needs to be in place to allow for consideration of security throughout the design process, with specific emphasis on unique SMR aspects.

For instance, security by design should consider new potential risks posed by the transportability aspects of SMRs, remote operation without a human presence, and other factors that would need to be addressed as part of the design basis threat.

A completed gap analysis, initiated in 2018 along with early Member State engagement, suggests that existing IAEA guidance, together with the planned publication Security for Novel and Advanced Reactors, may be sufficient for SMRs.

However, due to the dynamic nature of the international nuclear security landscape — based on technological trends, other emerging world developments and national- and site-based threat assessments — today's security measures may not be sufficient to meet tomorrow's security threats.

While nuclear security is a sovereign responsibility, the IAEA will continue to develop expert technical guidance, recommendations, and — upon request — provide assistance to Member States, including in the area of SMRs.

Safeguards by design

IAEA safeguards are a set of technical measures that allow the IAEA to independently verify a State's legal commitment to use nuclear material and technology exclusively for peaceful purposes. The safeguards framework will also need to be applied for SMRs and will need to cope with specific challenges connected with innovative solutions utilized in SMRs.

For purposes of both effectiveness and efficiency of safeguards implementation for SMRs States are encouraged to take safeguards requirements into consideration as early as possible in the design process (for vendor States), and project development (for customer States). This concept is known as safeguards by design (SBD) and currently, there is no formal international standard on how to implement it during the conceptual or design stage. However, the IAEA has developed guidance for States on SBD that would need to be thoroughly applied to SMRs.

The implementation of SBD for SMRs is tightly connected with the challenges brought by each specific SMR design. Thus, the designers would need take into consideration various aspects, such as transportability, remote locations, new fuel concepts, long refuelling periods and high fuel enrichment levels. Ensuring the applicability of safeguards to SMRs is an important prerequisite for their successful deployment. To not do so, particularly where innovative designs are involved, is to risk expensive retrofits, project delays and additional operational burden due to late and/or inefficient incorporation of safeguards needs.

Successful implementation of SBD will require the active engagement of various stakeholders (e.g. State or regional authorities, regulators, operators, suppliers, IAEA) throughout the design stage and entire life cycle of SMRs. In this context, it is important to ensure that the designers and the IAEA are in contact starting from the early stages of the design. This will allow all stakeholders to benefit in terms of effectiveness and efficiency of safeguards implementation, including reducing the burden for operators.

3.2.6. Actions to support a competitive business case

As explained in Chapter 2, the development of a competitive business case for SMRs, including microreactor deployment, relies on thorough market research and analysis of the competitive landscape, on the development of the value proposition and on the associated business case.

To be competitive against large nuclear reactor designs that benefit from the economy of scale, SMRs need to compensate by faster construction due to their modular design and factory fabrication, by achieving operations economy through innovative concepts such as improving efficiency through technology, innovative schemes for enabling human and system interfaces, a high level of automation, and through the potential for cogeneration. Thus, the specific cost structure of SMR projects needs to be fully analysed and understood. The cost structure of SMRs will depend on the type of technology employed and how they will be operated. For example, the near-term integral PWR-type, pressurized SMRs with reduced number of systems and components will support reduced plant staffing. The most significant element of O&M cost in SMRs is the direct and indirect cost of personnel; hence vendors and regulators are also evaluating control room staffing requirements for single and multimodule SMR facilities. High availability is also achieved by minimizing outage time — simplifying refuelling and extending operating cycles by reducing refuelling frequency.

SMRs will compete with large nuclear plants in terms of electricity generation, if these are a viable option, but mostly with alternative technologies such as renewables (wind or solar), or with fossil plants equipped with carbon capture and storage (CCS). Straightforward comparison on the basis of LCOE should be avoided as this does not account for the real system costs of the technologies, for example, the costs of generation backup or energy storage for non-dispatchable technologies like wind or solar. Full system cost analysis is therefore preferred to inform policy makers. A competitive wholesale power market with low barriers to entry and a 'level playing field' for all low-carbon technologies is a vital enabler of the transition to net zero. Other enabling factors include well-designed power grid access policies — favourable to nuclear, hydro and variable renewables — and 'smart' price setting rules (and revenue securing mechanisms), allowing project developers to offset generation costs and guarantee acceptable returns to their investors.

For non-electric products, the competitive landscape varies depending on the product. For low-carbon heat supply, SMRs will compete against fossil fuel or biomass with CCS. For the production of low-carbon hydrogen, SMRs will compete against fossil fuel with CCS (blue hydrogen) or against renewables (green hydrogen). In both cases, the cost of the transport infrastructure (heat pipelines or hydrogen pipelines) will need to be assessed depending on the distance between the source and the end user.

The full value proposition and the business case for an SMR project will depend on identifying the costs and revenue streams, considering the market characteristics, the financial instruments and the market mechanisms available to the project developer. Recognition of the production of electricity, heat or hydrogen by an SMR as a clean, sustainable activity (taxonomy) — through labelling of the products, can significantly impact the value of the project.

3.2.7. Supporting an advanced nuclear fuel pipeline

The successful deployment of all types of SMR fuel requires the maturity of fuel production technologies, from the R&D stage to the industrialization stage. The types of fuel needed for the various SMR designs are at different stages of development.

The majority of the SMR reactor concepts (some water cooled SMRs like marine based, gas cooled SMRs; some liquid metal cooled fast neutron SMRs with U-Zr alloy; some MSR SMRs and all modular microreactors) require high assay low enriched uranium (HALEU) fuels, enriched between 5 and 19.75 percent in ^{235}U, to enable smaller designs, longer operating cycles and increased efficiencies. Yet, there is only one facility in the world, located in the Russian Federation, that can manufacture HALEU at commercial scale. The lack of a widely deployed commercial HALEU supply chain is one of the major impediments to the deployment of a number of SMR designs. The most urgent task for the next ten years is the creation of such a supply chain. That task includes upgrading the current nuclear fuel cycle infrastructure to meet all the necessary requirements, in particular the development of enrichment, re-conversion and fuel fabrication facilities. The certification of a transportation package able to contain enriched uranium hexafluoride up to 19.75 wt% ^{235}U is currently expected early in 2023 and will help enable the large scale deployment of SMRs with HALEU fuel.

Notwithstanding the critical need for HALEU fuel, the successful deployment of all types of SMR fuel requires the maturity of fuel production technologies, from the R&D stage to the industrialization stage.

For water cooled SMRs with conventional UO_2 fuel, fuel designs with minor modifications (under similar design and operating envelopes with conventional LWR fuels) are considered to benefit from existing licensing tests and fuel supply chains, and to reduce the development risks of water cooled SMRs. Use of evolutionary accident tolerant fuel (ATF, after 2030) and use of HALEU (with the challenges for supply chain of HALEU) is foreseen. Future R&D should therefore include simulation tools and database development to cover ATF and HALEU.

For HTGR-type SMRs that are designed to use HALEU and additive manufacturing (3D printing) of the fuel matrix, future challenges include the supply chain of HALEU, developing methods for 3D printing of fuel kernels and qualification of fuel designs. The technological challenge is scaling the fuel fabrication up to commercial scale. For MSR SMRs, fuel and fuel cycle infrastructures should first be developed from the stage of proof of concept to the stage of demonstration, and then to the industrial stage, after addressing many current engineering challenges (for fuel production and recycling facilities, new materials development due to corrosive environment the database with salts properties creation, technical specifications (e.g. impurities) developments, various fuel cycle scenarios, etc.).

3.2.8. Spent fuel, waste and decommissioning of SMRs

The back end implications are very dependent on the characteristics of the nuclear fuel (e.g. enrichment, different matrices) and its irradiation history (e.g. burnup). For those nuclear fuels foreseen to be deployed in the next decade, like HALEU and HTGR fuels, the short term challenges will relate to higher enrichments and higher burnups as well as to new matrices.

These parameters impact the different stages of spent fuel management, requiring or accommodating higher thermal outputs, higher criticality risks and different radionuclide inventories. To meet safety requirements to move forward in the implementation of subsequent spent fuel management steps, spent fuel storage periods might be increased and new container designs and licences will be required. Recycling options for spent fuel reprocessing capacities are currently limited. Industrial processes will require adaptation to address HALEU spent fuel recycling; developing and demonstrating new industrial processes for new spent fuels recycling will be challenging.

Waste management and long term disposal implications for current NPP designs are well defined. This is not necessarily the case for some emerging technologies. Some of the most innovative SMR technologies will generate completely new waste streams that the nuclear industry has very limited experience with, underpinning the need to assess any unforeseen technological, environmental or financial implications.

For water cooled SMRs, current back end infrastructures and storage systems could be used with some modifications. HALEU spent fuel will have higher burnups and enrichments, challenging storage and transportation systems. Therefore, current recycling processes will need to be adapted to different radionuclide compositions and higher enrichments as well as to industrially reprocessed uranium oxide fuel. For HTGR-type SMRs, the properties of tristructural isotropic fuel (TRISO) allow the use of established industrial technologies for storage and management of spent fuels. For liquid metal cooled fast neutron SMRs, there is limited experience in managing spent fuels. The reference scenario for a large deployment of fast reactors is the multi-recycling of valuable materials that needs a scaling up of recycling to an industrial level. For MSR SMRs, fuel recycling will depend on the successful separation of fission products from the molten salt mixture, overcoming chemical and engineering issues. In addition, the management of spent salts needs to be considered.

Identifying different waste streams from any potential design and processing each stream, including adapting or developing a new decommissioning infrastructure for final disposition need to be considered in the early design stage. To minimize the potential impacts of SMRs, all of these factors should be considered with a view to minimizing the end-of-life risks and burdens on future generations.

3.2.9. Aligning human resource development for SMRs

Human resource needs will depend on the scope of the nuclear power programme for the SMR or microreactor designs. Building up national capabilities will require the appropriate mix of education, training and practical experience. Preparing a workforce for operation is one of the most demanding issues in terms of resources and time, even in the case of SMRs, which have a potential for shorter construction time (3–4 years). Depending on the designs, this preparation will require specific training as defined by the regulatory requirements of each country. This includes job specific training based on the systematic approach to training (SAT), simulator training, on-the-job training and regulatory certification for key safety related positions.

Embarking countries will need to plan and consider these factors. The IAEA's Nuclear Power Human Resources (NPHR) tool was developed for embarking countries to evaluate workforce planning for their nuclear power programmes. The tool is intended to take a comprehensive view to reflect all aspects of the nuclear power workforce, including the influence on that workforce by a country's educational system and other industries and events and decisions within the overall nuclear power programme. Of particular interest for new programmes are the workforce issues during the initiation of a new nuclear power programme, including plant startup. The model is helpful for examining the decision space facing programme planners by providing a long range, holistic perspective of the nuclear power programme. The NPHR model provides a starting point for developers to construct a model reflecting their programme and its unique decision points. There will be specific areas that will be challenging for the technology recipient country that is developing a nuclear power programme based on SMRs. An example of a challenge will be building competency in the regulatory body for SMRs. Some technology developer countries with a clear SMR strategy understand that human resources are critical for the regulatory framework. The IAEA also provides guidance as to the resources required for infrastructure development related to nuclear power programmes.

Technology developer countries' SMR designs will have features for non-standard applications such as remote regions, emergency situations, integrated energy systems, coupling with chemical plants and other industries, and hydrogen production. Both developer and recipient countries will need specific competencies and skills to manage and address the needs of different industries and related interfaces, as well as to manage the associated risks. In countries' human resources plan for programme deployment, these non-standard applications should be included.

3.2.10. Preparing for the response to emergencies

A hazard assessment should be performed at the preparedness stage to identify events and the associated areas in which emergency response actions might be warranted, and actions that might be effective in mitigating the consequences from such events. The conduct of a hazard assessment needs to be based on a large spectrum of emergency scenarios — including design and beyond design basis accidents; beyond design extension condition accidents; events of very low probability, including those triggered by a nuclear security event or combined with a conventional emergency; events affecting more than one SMR module at a given site or involving an SMR collocated with an existing 'large' NPP. In SMRs that are coupled with industrial facilities, including hydrogen plants, risk should be assessed considering the nearby industrial facility. The results from the threat assessment performed for nuclear security purposes should also inform the hazard assessment, particularly as SMRs will likely rely on digital instrumentation and control and/or remote operation so that information security will be of particular importance. Based on the outputs from a hazard assessment, a protection strategy should be developed, justified and optimized to enable effective protection of affected populations during an emergency response. Justification aims to show that the protection strategy and associated protective actions do more good than harm, taking into account various factors. Optimization aims to demonstrate that the best protection can be achieved under the prevailing emergency conditions, although it may not result in the lowest levels of radiation exposure for part of the public. Based on the protection strategy, a concept of operations should be developed, including allocation of emergency response roles and responsibilities.

The development of on-site and off-site emergency response plans should elaborate on specific arrangements through which the protection strategy is implemented in practice and should address aspects such as infrastructure, human resources, organization, processes, and tools. These two types of plans aim to document the operational arrangements to be in place to achieve an effective EPR framework on the site and off the site, given that their integration and coordination is essential. As part of this effort, training programmes should be established and delivered to certify emergency workers' knowledge and skills. Furthermore, on-site and off-site response capabilities should be tested regularly through drills and exercises. A quality management programme should be established to ensure that arrangements function and are readily available when needed, and to collect and address feedback from various activities. Lessons learned from these activities should be documented and serve as the basis for the maintenance and continuous improvement of the emergency response framework and capabilities, including training programmes.

3.2.11. Furthering public confidence and support

Some stakeholders, such as scientists, policy makers, and the public, recognize nuclear as a critical part of decarbonized energy systems to combat climate change. It is essential that the nuclear community continue to invest resources in stakeholder communication and cooperation to build trust in nuclear energy. Building trust is critical for broad nuclear deployment, including new designs such as SMRs. Trust is dependent on confidence in the national regulators, but also on the effectiveness of the global nuclear safety and security regime. Public acceptance of nuclear power is one of the issues under the Milestones approach. Public acceptance and public participation in the decision making process are also embedded in several United Nations Economic Commission for Europe conventions such as the Espoo and Arhus conventions.

SMR features that could facilitate public acceptance of a nuclear programme include: enhanced safety features, reduced emergency planning zone and cooling water requirements, integration with other clean energy sources such as renewables, the ability to address the energy needs of remote communities, their suitability for replacing aging fossil fuel plants, and to produce other clean energy products such as hydrogen or process heat.

3.3. SMRs — APPLICATION BEYOND POWER GENERATION

Currently, most of the carbon dioxide emissions are produced from sectors other than power generation such as heat, transportation and various industrial activities. Therefore, to effectively achieve the decarbonization goals set by the Paris Agreement, it is vital to decarbonize these sectors.

Nuclear reactors, and SMRs with the capability to co-produce heat and electricity with zero carbon emissions, are uniquely suited to satisfy at least part of this demand. The use of nuclear heat directly is not new; large conventional reactors have been utilized for decades for uses such as district heat, desalination and other industrial uses. This represents a total of about 750 years of reactor experience from about 70 nuclear power plants in several countries.

An expansion of the use of those existing applications to future SMRs and the development of new non-power applications will provide additional benefits, taking advantage of some of the intrinsic features of SMRs that make them uniquely attractive for non-power uses. These features include smaller sizes, which better match the size of the heat needs for most types of non-electric applications, and higher temperatures for some advanced SMR designs, which would allow a whole set of industrial uses as described in Chapter 1.

Several applications of SMRs outside of the power sectors are currently envisioned, including the production of hydrogen, clean and potable water, supply of heat for district heating, and supply of heat at different temperatures for numerous industrial applications, from low-temperature processes for paper manufacturing and urea synthesis, to high-temperature processes in refineries and steel making. However, achieving a significant level of deployment of non-electric applications of SMRs also comes with challenges. These include identifying the optimal technologies for coupling with nuclear (from a technical as well as an economic viewpoint), overcoming the remaining technology gaps for each of the most promising technologies, demonstrating the coupling of non-electric applications and SMRs, successfully deploying the first industrial prototypes of the coupled systems, developing the business cases and commercial deployment of facilities in concert with expected demand growth and developing all the safety, regulatory and licensing issues of the coupled systems.

Successful deployment of SMRs will require a concerted effort by multiple stakeholders, from technology developers to policy makers, from end users to regulatory authorities, as well as international collaboration to effectively share the experiences and lessons learned.

4. IAEA AGENCY-WIDE SUPPORT AND SERVICES

The IAEA offers a broad range of programmatic support to its Member States related to the deployment and development of sustainable nuclear energy programmes. The support the IAEA provides related to SMRs, at the request from its Member States, can be categorized as follows: key programmes; technical cooperation; legislative assistance; review missions and advisory services; education, training and toolkits; and capacity building.

The support activities highlighted in this section, organized according to the categories identified above, were identified by the IAEA as being either immediately implementable for ongoing SMR programs or ready to be implemented with SMR projects within the next 3–4 years. This time frame was identified to better highlight and facilitate programs that focus on the near-term deployment of SMRs. As the global SMR industry develops and matures, the IAEA will be able to offer a wider range of services to its Member States and other stakeholders. The list below is non-exclusive and other programmes of support not listed here may be applicable to assist Member States upon request.

4.1. KEY PROGRAMMES SUPPORTING SMR DEVELOPMENT AND DEPLOYMENT

Reflecting the growing importance of SMRs and microreactor deployments in the near term, several key programs have been identified that are currently pursuing work in this area:

4.1.1. The IAEA Platform on SMRs and their Applications (SMR Platform)

The IAEA Platform on Small Modular Reactors (SMRs) and their Applications (SMR Platform) coordinates the IAEA's activities in this field and provides a 'one-stop shop' for Member States and other stakeholders. The SMR Platform offers expertise from the entire IAEA, encompassing all aspects relevant to the development, early deployment and oversight of SMRs and their applications.

Member States can request assistance on general issues related to SMRs and their applications through official channels, addressing their request to the Chair of the Steering Committee of the Platform, IAEA Deputy Director General and Head of the Department of Nuclear Energy. Once received, the request will be channeled to the appropriate personnel within the IAEA. The SMR Platform enables the IAEA to handle Member States' requests in an effective and efficient manner, providing comprehensive support. More information about the SMR Platform as well as relevant agency outputs (e.g. publications, databases, IT tools, events, news) can be found on the portal for the SMR Platform at https://smr.iaea.org.

4.1.2. The Nuclear Harmonization and Standardization Initiative (NHSI)

The Nuclear Harmonization and Standardization Initiative (NHSI) launched by the IAEA aims at promoting the effective global deployment of safe and secure advanced nuclear reactors, through a dual track approach that consists of: (1) developing common industrial approaches by technology holders and users' requirements and criteria by operators, consistent with fair global competition, intellectual property rights protection and not hampering innovation and continuous improvement, and (2) developing harmonized regulatory approaches between national regulatory bodies, including a common set of internationally recognized requirements, while maintaining national responsibilities for safety and security.

4.1.3. Technology Roadmap for Small Modular Reactor Deployment

The IAEA's Technology Roadmap for Small Modular Reactor Deployment provides Member States with a set of generic roadmaps that can be used as a reference in the deployment of SMRs. The roadmaps place emphasis on the activities of owners/operating organizations, who drive the demand and requirements for reactor designs; designers, who develop the technologies; and regulators, who establish and maintain the regulatory requirements that owners/operating organizations are obliged to meet. This IAEA Nuclear Energy Series publication presents two sample roadmaps for Member States to follow and to reference. The first roadmap's primary target audience is for owners, licensees, buyers or utilities that acquire SMR technology. The roadmap is consistent with the well-known IAEA's milestone approach for nuclear infrastructure development because some embarking countries are considering SMRs as their near-term viable option owing to their grid capacity and limited investment capital. The second roadmap is geared towards SMR technology developers, designers or vendors. It reflects common project activities for vendors to develop an SMR product from concept to licensing to deployment.

4.1.4. Coordinated research activities

The IAEA supports research under its programmes, subprogrammes and projects that are listed in its approved programme and budget. These coordinated research activities are normally implemented through coordinated research projects (CRPs), which bring together research institutes in both developing and developed Member States to collaborate on research topics of common interest. Research, technical and doctoral contracts and research agreements are awarded to institutes in Member States for their completion of research work under these CRPs.

Each established CRP consists of a network of 10 to 15 research institutes that work in coordination for three to five years to acquire and disseminate new knowledge. The IAEA may also respond to proposals from institutes for participation in the research activities under individual research contracts not related to a CRP. CRP results are available, free of charge, to scientists, engineers and other users from all Member States. More information on ongoing CRPs can be found at www.iaea.org./projects/coordinated-research-projects.

Another IAEA mechanism to support R&D activities is the Collaborating Centre found at https://www.iaea.org/about/partnerships/collaborating-centres.

There are several concluded, ongoing and planned CRPs and Collaborating Centres related to SMRs and their applications. Their description can be found at https://smr.iaea.org.

The IAEA also facilitates an international collaboration framework for the development and application of open-source multi-physics simulation tools to support research, education and training for the analysis of advanced nuclear power reactors through the Open-source Nuclear Codes for Reactor Analysis (ONCORE) initiative. ONCORE promotes collaboration and sharing of resources, materials and tools for research and education. ONCORE members actively contribute to the development of new software, receive community support for the use of available software and participate in the organization of training events and outreach activities. ONCORE also disseminates the high temperature reactor code package for high temperature reactor safety performance analyses that was developed and released by the Jülich

Research Centre to the IAEA so that Member States can use this computer code to perform safety analyses of HTGRs.

4.1.5. International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) is a membership-based project that supports its members in their long term planning and collaboration on innovations in reactors, fuel cycles and institutional approaches that promote the sustainable development of nuclear energy. INPRO performs analysis and assessment of the sustainability of reactor designs and fuel cycles. Specific to SMRs, INPRO engages in the following activities:

- The collaborative project "Sustainable deployment scenarios for small modular reactors" using toolkits in Analysis Support for Enhanced Nuclear Energy Sustainability (ASENES) — ASENES SMR;
- Nuclear Energy System Assessments (NESAs) for SMRs, examining specific planned SMRs and their fuel cycles.

Member States can access and find INPRO activities on its collaboration platform at www.iaea.org/resources/databases/inpro-collaboration-platform.

4.1.6. The Peaceful Uses Initiative (PUI)

Launched in 2010, funds from the Peaceful Uses Initiative (PUI) have become instrumental in mobilizing extrabudgetary contributions that supplement the Technical Cooperation Fund to support technical cooperation projects and other unfunded projects of the IAEA in the areas of the peaceful application of nuclear technology. The PUI has also allowed the IAEA to be more flexible and quicker in responding to shifting priorities of Member States, such as funding some of the new projects that have recently been launched supporting the near-term deployment of SMRs, in particular for interested newcomer countries. Member States that are considering a contribution through the PUI are encouraged to closely consult with the Secretariat prior to making an official pledge.

4.2. TECHNICAL COOPERATION PROGRAMME

The technical cooperation programme is the IAEA's primary mechanism for transferring nuclear technology knowledge to Member States, helping them to address key development priorities. The programme also helps Member States to identify and meet future energy needs and assists in improving radiation safety and nuclear security worldwide, including through the provision of legislative assistance.

The interregional project INT2023, Supporting Member States' Capacity Building on Small Modular Reactors and Microreactors and their Technology and Applications — A Contribution of Nuclear Power to the Mitigation of Climate Change, was launched in January 2022. The project's objective is to raise awareness and improve knowledge, capacity building and safety review capability in developing countries of all the fundamental aspects of SMRs, micro reactors and their electric and non-electric applications. Interregional projects deliver support across national and regional boundaries and address the needs of several Member States in different regions. They are categorized as transregional, global, capacity building or as joint activities with an international entity.

4.3. LEGISLATIVE ASSISTANCE PROGRAMME

Comprehensive and coherent national legislation is essential to ensure the safe, secure and peaceful use of all nuclear technologies. The IAEA offers legislative assistance to its Member States in developing such legislation.

The programme covers all branches of nuclear law: nuclear safety, nuclear security, safeguards and non-proliferation, and liability for nuclear damage. It seeks to create awareness among Member States of the international instruments in the nuclear field and assists them in complying with their international obligations and commitments, as well as with the drafting of corresponding national nuclear legislation. Legislative assistance is available upon request to all Member States in the form of regional and national workshops, awareness missions, bilateral legislative assistance and scientific visits and fellowships, regardless of the extent of their nuclear activities. The programme is of particular benefit to those States that are in the process of establishing new national nuclear legislation, updating existing legislation or otherwise consolidating their national nuclear legal framework.

4.4. REVIEW MISSIONS AND ADVISORY SERVICES

The IAEA offers its Member States a wide array of review services, in which an IAEA-led team of experts compares actual practices with IAEA standards. The full range of services provided by the IAEA can be seen on the IAEA website https://www.iaea.org/services/review-missions. Below is a non-exclusive list of the services and missions that may be immediately applicable for Member States interested in deploying SMRs or microreactors in the near term.

4.4.1. Integrated Nuclear Infrastructure Review (INIR) missions

An Integrated Nuclear Infrastructure Review (INIR) mission enables a Member State to have in-depth discussions with international experts about experiences and best practices in nuclear power development. A comprehensive assessment of all facets of a Member State’s nuclear programme is performed. Recommendations and suggestions are provided to the Member State to support the development of a national action plan to address the gaps identified during the review assessment. The INIR is a valuable tool to ensure that the infrastructure required for the safe, secure and sustainable use of nuclear power is developed and implemented responsibly and in an orderly manner. The IAEA is updating the Milestone approach document to begin to address SMRs. The Milestones approach document underpins the focus of the assessment areas for an INIR mission. As a result, as SMRs are deployed, the Milestones approach document will reflect such deployment updates and their impact on specific infrastructure issues. The IAEA will adapt the INIR for SMRs to address these changes.

4.4.2 Reactor technology assessments of advanced nuclear power reactors for near-term deployment

A major challenge in this undertaking, especially for newcomer Member States regarding nuclear power, is the process associated with reactor technology assessment for near-term deployment. This assessment considers the whole process of selection of the most suitable reactor technology to meet the objectives of the Member State’s nuclear power programme.

Documenting and defending the basis for this reactor technology assessment requires the application of best practices and deep reactor technology knowledge.

4.4.3 Technical Working Group on Small Modular Reactors (TWG-SMR)

The Technical Working Group on Small Modular Reactors (TWG-SMR) focuses on the technology development, design, deployment and economics of SMRs that can be used for the production of electricity and/or industrial process heat in both expanding and embarking countries. The technical working group provides advice, recommendations and programmatic guidance for the IAEA's activities on SMRs, specifically in the following areas:

- Research, technology development and innovation;
- Development of generic technical requirements for user countries;
- Technology assessment approaches for advanced SMR designs;
- Reliability, safeguards ability and construction ability;
- Codes and design standardization of structures, systems and components;
- Industrialization of SMRs, covering design, engineering, manufacturing and supply chain;
- Site characterization;
- Economic competitiveness, financial considerations, market needs and cost analysis;
- Capacity building for embarking and expanding nuclear countries;
- International cooperation.

One of the primary functions of the TWG-SMR is to provide advice and guidance, and to marshal support in interested Member States for implementation of the relevant IAEA's programmatic activities on The technical working group will also provide guidance on developing roadmaps to assess the technology readiness level of SMR designs for deployment in Member States.

4.4.4 Small Modular Reactor (SMR) Regulators' Forum

The establishment of regulatory controls for this relatively new type of reactor requires focused and consistent attention. The SMR Regulators' Forum, created in March 2015, enables discussions among Member States and other stakeholders to share their regulatory knowledge and experience of SMRs.

The forum enhances nuclear safety by identifying and resolving common safety issues that may challenge regulatory reviews associated with SMRs and by facilitating robust and thorough regulatory decisions.

The forum's work results in outputs such as:

- Position statements on regulatory issues;
- Suggestions for revisions to (or new) IAEA documents;
- Information to help regulators enhance regulatory frameworks;
- Reports on regulatory challenges with discussion on paths forward;
- Suggestions for changes to international codes and standards.

4.4.5 Technical Safety Review Service

The Technical Safety Review Service is a peer review service offered by the IAEA to review the safety of the design and safety assessment at different stages (e.g. conceptual design, generic reactor design or detailed plant specific design). This service includes organizing educational workshops on SMR safety assessments.

4.4.6 The Site and External Event Design Service

The Site and External Event Design service is a bundle of technical safety reviews aimed at the assessment of nuclear installation safety in relation to external natural and human induced hazards in all stages of project development: from siting to design to safety assessment and operation. This service includes organizing educational workshops on SMR siting, design and safety assessments in relation to external events.

4.5. EDUCATION, TRAINING AND TOOLKITS

The IAEA offers a wide spectrum of education and training activities. These include face-to-face training courses and workshops, as well as online learning, fellowship programmes and schools on various nuclear related topics. Additional learning tools and initiatives may become available in the near future and will be highlighted on the SMR Platform website at https://smr.iaea.org.

4.5.1. Advanced Reactors Information System (ARIS) and its biennial supplementary booklet Advances in Small Modular Reactor Technology Developments

ARIS is the IAEA's comprehensive and up-to-date database on advanced nuclear reactor designs with detailed information on advanced nuclear power plant designs of major line categories, including SMRs, as well as their important development trends. The IAEA has also published a biennial booklet, Advances in Small Modular Reactor Technology Developments, a non-serial publication supplementary to ARIS, since 2011. The 2022 edition has been just released.

4.5.2. Supporting nuclear cogeneration, including hydrogen production, desalination and industrial applications of nuclear heat

The IAEA continues to organize meetings to facilitate the exchange of information and to collect state of the art and best practices in the area of nuclear cogeneration, including hydrogen production, desalination and industrial applications of nuclear heat. The IAEA offers publications in the areas of nuclear cogeneration and non-electric applications of nuclear energy, including with SMRs.

4.5.3. Competency framework for new nuclear power programmes

The competency framework is a database for assisting Member States in planning the activities required throughout all phases of introducing a new nuclear power programme and developing the competencies and capabilities needed to implement these activities. The framework builds on the Milestones approach and other supporting documents by identifying key activities to be implemented in each phase, the responsible organization and the competencies required for their implementation. As a result, as SMRs are deployed, the Milestones approach document will reflect such deployment updates and their impact on specific infrastructure issues. The IAEA will adapt the framework for SMRs to address these changes.

4.5.4. The Nuclear Supply Chain Toolkit

An effective and efficient nuclear supply chain is crucial to the safety and reliability of NPP operations. Operating organizations for SMRs will need to procure efficiently and at high quality from suppliers that comply with well-established requirements and have their own pool of suppliers and subcontractors for subassemblies, parts and services. In 2020, the IAEA launched the Nuclear Supply Chain Toolkit in the CONNECT platform to provide examples, case studies and good practices to assist both nuclear newcomer and operating Member States in the use of sound quality and management principles. This toolkit is updated regularly with the addition of new relevant content.

4.5.5. PC-based nuclear power reactors for education and training

The IAEA established education & training (E&T) courses based on active learning (learning by doing) with nuclear reactor simulation computer programmes (basic principle simulators) and other toolkits to assist Member States in educating and training their nuclear professionals on the physics and technology of nuclear power reactor designs. The basic E&T simulators operate on personal computers and are provided for a broad audience of technical and non-technical personnel as an introductory educational and training set of tools. Their configuration is suited to classrooms and self-learning as a complement to textbooks and manuals. They provide subsystem training and overall plant training (startup, shutdown, malfunctions). The IAEA's collection of simulators includes that for (1) part tasks (e.g. microphysics), (2) PWRs, (3) BWRs, (4) PHWRs (Pressurized Heavy Water-cooled Reactors), (5) integral PWR-type SMRs and (6) innovative reactors that cover SFRs (Sodium-cooled Fast Reactors) and HTGRs. The beta version of the HTGR simulator from China's Institute of Nuclear and New Energy Technology (INET), Tsinghua University, is undergoing testing.

4.5.6. Technological-economic assessment tools for non-electric applications of nuclear power

The IAEA provides a number of tools for the technological-economic assessment of non-electric applications of nuclear energy that include SMR considerations. The tools offered are: nuclear hydrogen production (HEEP, HydCalc), desalinated water produced with nuclear energy (DEEP), water management in nuclear plants (WAMP), the thermodynamic analysis of nuclear plants (DE-TOP) and the framework for the modelling of energy systems (FRAMES).

4.5.7. Educational workshops on SMR regulation

Based upon Member State requests and regional efforts, these regulatory workshops present the latest in SMR regulation challenges, based mainly on the outputs of the SMR Regulators' Forum.

4.6. CAPACITY BUILDING

The IAEA offers a wide spectrum of training courses and capacity building programmes. They cover such diverse areas as economic appraisal and energy planning, nuclear safety and security, radiation protection, human resource management, sustainable energy development, safeguards by design, emergency preparedness and response, and technical cooperation.

4.6.1. Supporting the implementation of safeguards by design (SBD)

SBD is an approach whereby early consideration of international safeguards is included in the design process of a nuclear facility, allowing informed design choices that are the optimum confluence of economic, operational, safety and security factors, in addition to international safeguards. The series of publications on this topic reflects the application of SBD to all aspects of the nuclear fuel cycle, from initial planning and design through construction, operation, spent fuel management and decommissioning. To support States in implementing SBD, the IAEA has published a series of guidance documents, found at www.iaea.org/topics/assistance-for-states/safeguards-by-design-guidance, that encompasses all aspects of the nuclear fuel cycle.

4.6.2. Supporting decision makers regarding investments in SMRs

The IAEA provides services specifically geared toward assisting public sector and private sector key decision makers regarding investments in nuclear projects, including SMRs. These services rely on the use of tools, frameworks, publications, review services, and capacity building workshops covering the following topics:

- Scenario development, supply and demand, and options analyses for assessing the contribution of SMRs to the transition towards net zero energy systems, using technology neutral approaches and energy planning and modelling tools;
- Economic appraisal (plant and system costs, financing approaches) and macroeconomic impact assessment (including impacts of nuclear investments on economic growth and job creation);
- Strategic environmental assessment;
- Analysis of the potential role of SMRs in addressing the combined climate, land, energy and water (CLEW) challenges

4.6.3. Supporting SMR project developers working towards demonstrating the business case for SMRs

The IAEA can support SMR project developers in analysing and demonstrating the business case for an SMR project, investigating available options for securing funding and financing, as well as gaining public support for the project. The IAEA can offer specific economic and financial analysis support to help proponents of SMR projects develop sound management of the following:

- Approaches to project planning cost forecasting and analysis;

- Business model development/reviews/assessments;
- Guidance on approaches to securing revenue through power purchase agreements and other mechanisms;
- Project structuring and funding and financing issues.

4.6.4. Regulatory Cooperation Forum (RCF)

The RCF is a member-driven forum of nuclear safety regulators. The forum promotes the sharing of regulatory knowledge and experience through international cooperation with the goal of achieving a high level of nuclear safety that is consistent with the IAEA safety standards. The RCF comprises countries with advanced nuclear power programmes and countries that are planning to expand or introduce the use of nuclear power. The RCF is open to all IAEA Member States. Senior regulatory body representatives take part in forum meetings, which also include representatives from the IAEA, the European Commission and the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development.

4.6.5. Planning for workforce staffing for SMR projects

Embarking and expanding Member States need to properly assess the scope and size of the human resource development effort and investment entailed by an SMR nuclear project. Understanding which operating organization needs to be in place, the necessary staffing levels and associated competencies, will be critical to making an informed decision, in particular when the SMR will be the first nuclear installation in the country. The IAEA is developing a TECDOC publication to support Member States in understanding the different size and type of operating organizations that need to be established for different SMR technologies.

4.6.6. E-learning modules for new nuclear power programs

The IAEA interactive e-learning modules cover various aspects of developing a safe, secure and sustainable nuclear power programme. The modules explain the Milestones approach document, which provides a comprehensive phased method covering nuclear infrastructure issues to assist countries considering, planning or expanding their nuclear power programmes in understanding the commitments and obligations associated with nuclear power. As a result, as SMRs are deployed, the Milestones approach document will reflect such deployment updates and their impact on specific infrastructure issues. The IAEA will adapt the e-learning modules for SMRs to address these changes.

4.6.7. Nuclear Infrastructure Bibliography (NIB)

The Nuclear Infrastructure Bibliography (NIB) facilitates the identification of and access to the main IAEA reference publications related to the 19 issues outlined in the Milestones approach document and underlining areas not sufficiently covered by existing IAEA guidance materials and publications. The NIB is intended for use by technology recipient Member States that are developing or expanding their nuclear power infrastructure. As a result, as SMRs are deployed, the Milestones approach document will reflect such deployment updates and their impact on specific infrastructure issues. The IAEA will adapt the NIB for SMRs to address these changes.

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[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Technology Roadmap for Small Modular Reactor Deployment, IAEA Nuclear Energy Series No. NR-T-1.18, IAEA, Vienna (2021).

ABBREVIATIONS

3S	safety, security, and safeguards
ABDAN	Brazilian Association for the Development of Nuclear Activities
ANSTO	Australian Nuclear Science and Technology
ARIS	Advanced Reactors Information System
ASENES	Analysis Support for Enhanced Nuclear Energy Sustainability
ATF	Accident Tolerant Fuel
BWR	boiling water reactor
CAREM	Central Argentina de Elementos Modulares
CC	Collaborating Centre
CEA	French Alternative Energies and Atomic Energy Commission
CF	Competency Framework
CHP	Combined Heat and Power
CNNC	China National Nuclear Corporation
CNEA	National Atomic Energy Commission (of Argentina)
CRP	coordinated research project
CSS	carbon capture and storage
DFI	Development Finance Institutions
E&T	Education and Training
EC	European Commission
EDF	Électricité de France
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
EPR	Emergency Preparedness and Response
FIRST	Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology
FPU	floating power unit
FR	Fast Reactor
FZJ	Forschungszentrum Jülich (Jülich Research Centre)
GIF	Generation IV International Forum
GMFR	Gas-cooled Modular Fast Reactor
HALEU	high assay low enriched uranium
HTGR	high temperature gas cooled reactor
HTTR	High Temperature Test Reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
INET	Institute of Nuclear and New Energy Technology
INIR	Integrated Nuclear Infrastructure Review
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
JAEA	Japan Atomic Energy Agency
JSC Afrikantov OKBM	Joint Stock Company Afrikantov OKB Mechanical Engineering
K.A.CARE	King Abdullah City for Atomic and Renewable Energy, Saudi Arabia
KAERI	Korea Atomic Energy Research Institute
KNPP-NB	Kozloduy Nuclear Power Plant — New Build
LCOE	Levelized Cost of Electricity
LWR	light water reactor
MOU	Memorandum of Understanding

MR	micro reactor
MSR	molten salt reactor
NEA	Nuclear Energy Agency
NESA	Nuclear Energy System Sustainability Assessments
NHSI	Nuclear Harmonization and Standardization Initiative
NIB	Nuclear Infrastructure Bibliography
NOAK	Nth of a kind
NPHR	Nuclear Power Human Resources
NPP	nuclear power plant
NPT	Nuclear Non-proliferation Treaty
NSSS	Nuclear Steam Supply System
O&M	Operations and Maintenance
OECD	Organisation for Economic Co-operation and Development
ONCORE	Open-source Nuclear Codes for Reactor Analysis
OPG	Ontario Power Generation
PPA	Power Purchase Agreement
PRIS	Power Reactor Information System
PUI	Peaceful Uses Initiative
PWR	pressurized water reactor
R&D	research and development
RCF	Regulatory Cooperation Forum
RTA	Reactor Technology Assessment
SAT	Systematic Approach to Training
SBD	safeguards by design
SEED	Site and External Event Design
SMR	small modular reactor
STEG	Tunisian Electricity and Gas Company
TNPP	transportable nuclear power plant
TRISO	Tri-structural Isotropic particle fuel
TSR	Technical Review Service
TWG	technical working group
VHTR	Very High Temperature Reactor
VTT	Technical Research Centre of Finland