

Microreactors: Enabling Resilient Energy Solutions for Critical Applications

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ABSTRACT

Microreactors are emerging as a transformative option within the Small Modular Reactor (SMR) portfolio, offering compact, transportable, and factory-fabricated solutions to deliver reliable, low-carbon energy where conventional infrastructure is impractical. Their unique attributes, such as autonomous operation, passive safety, and extended refuelling intervals, position them as a strategic enabler for resilient energy systems in remote communities, industrial sites, and specialised applications such as space missions. By replacing diesel generators and allowing companies to meet climate targets, microreactors offer a practical pathway to decarbonise niche sectors such as data centres and mining operations.

This paper examines the technical and strategic foundations of microreactor development, highlighting design features that enhance simplicity, safety and flexibility, including passive heat removal and modular deployment concepts that enable rapid installation with minimal site preparation. These characteristics support integration with microgrids, complement renewable energy sources, and provide highly reliable baseload power for critical applications. Beyond electricity generation, microreactors can enable non-electric uses contributing to sustainability objectives.

Central to this discussion is the role of the International Atomic Energy Agency (IAEA) in supporting Member States to harness microreactor technologies for their specific objectives. It highlights IAEA initiatives in technology mapping and information sharing through tools such as the Advanced Reactors Information System (ARIS) and the SMR Booklet, which consolidate global design data and deployment trends. In addition, the Agency is preparing a dedicated TECDOC on microreactor technology developments, scheduled for publication in 2026, to provide Member States with a comprehensive reference on design features, deployment models, and cross-cutting issues. These efforts aim to provide technical guidance, harmonise approaches, and facilitate knowledge exchange to accelerate safe and secure deployment. The Agency also promotes international collaboration through technical meetings, Coordinated Research Projects, and capacity-building programmes. Together, these initiatives create a foundation for informed decision-making and foster confidence in adopting microreactor technologies for specialised applications.

By integrating technical insights and collaborative frameworks, this paper demonstrates how microreactors can become a cornerstone of resilient energy strategies for specialised applications. Their successful implementation will depend on coordinated action across technology development, regulatory adaptation, and international partnerships, areas where the IAEA plays a pivotal role in shaping the future of nuclear energy.

Keywords: *Microreactors, Reactor Technology, Small Modular Reactors, Resilient Energy Systems, International Collaboration*

1 INTRODUCTION

Over the past decade, interest in Small Modular Reactors (SMRs) has grown significantly as countries seek flexible, low-carbon options to complement their energy system. Within this portfolio, microreactors are emerging as a distinct class of very small, factory-fabricated reactors designed for deployment in environments where conventional large-scale infrastructure is unavailable or impractical [1].

In addition to their compactness and modularity, microreactors offer characteristics directly aligned with the growing need for resilient and carbon-free energy systems. Their ability to operate autonomously, provide black-start capability, integrate with microgrids, and supply uninterrupted power in remote or infrastructure-constrained locations positions them as a new category of resilience-enhancing nuclear power reactors. These features complement broader SMR developments and support national strategies aimed at diversifying clean energy supply and reducing vulnerability to extreme weather events, supply chain disruptions, and fossil-fuel dependence.

Microreactors target use cases such as remote communities, mining operations, critical industrial facilities, data centres and scientific or exploration activities in harsh environments. These settings frequently rely on diesel generators or fragile supply chains for fuel delivery, leading to high costs, vulnerability to disruptions, and significant greenhouse gas emissions. By providing highly reliable, low-carbon power with limited onsite staffing and simplified logistics, microreactors can enhance energy security and resilience while enabling decarbonisation of niche but strategically important sectors.

Rather than being defined by a strict power threshold, microreactors are distinguished by their functional attributes: compact size, transportable and factory-fabricated designs, autonomous or semi-autonomous operation, and core lifetimes that range from several years to potentially the full operating life of the unit. These characteristics enable rapid installation, simplified logistics, and the ability to operate reliably in locations where traditional power reactors, including many SMRs, cannot be easily deployed. Their functional profile therefore makes microreactors an important subset of emerging advanced SMR technologies, particularly for applications requiring resilience, modularity, and minimal onsite infrastructure.

The IAEA has recognized the growing interest of Member States in microreactor technologies and is expanding its support through technology mapping, information services, and dedicated publications. Building on ongoing work for SMRs more broadly, the Agency is developing a dedicated TECDOC on microreactor technology developments to consolidate design information, deployment models, and cross-cutting technical issues.

This paper provides an overview of microreactor concepts and their technical features, examines deployment opportunities and challenges, and describes IAEA activities that support Member States in evaluating and potentially implementing microreactor options. The focus is on terrestrial applications for resilient energy solutions in specialised, high-value contexts, while also acknowledging the potential for space-based uses.

To understand how microreactors can meet the needs outlined above, it is essential to examine the underlying design philosophies and functional characteristics that differentiate them from other advanced reactors. The following section provides an overview of microreactor concepts, highlighting the technical features that enable their deployment.

2 MICROREACTOR CONCEPTS AND TECHNICAL FEATURES

2.1 Key Attributes of Microreactors

Microreactors can be broadly characterized by a set of functional attributes that support deployment in locations where conventional reactors or grid infrastructure are limited:

- **Compact plant footprint:** Typically, a few thousand square metres or less, allowing siting in constrained locations such as industrial sites or near-load deployment for microgrids.
- **Transportability:** Many designs fit standard transport containers, allowing shipment by road, rail, sea or, for some concepts, aircraft. This supports rapid deployment, redeployment, and logistical flexibility.
- **Extended refuelling intervals:** Operational lifetimes of 5–10 years per core, with some proposals for sealed or lifetime cores. Long core lives simplify operations and reduce dependence on frequent fuel deliveries.
- **Autonomous or semi-autonomous operation:** Advanced digital instrumentation and control systems enable reduced onsite staffing and remote monitoring, an important capability where technical personnel are scarce.
- **Passive and inherent safety:** Features such as natural circulation, passive heat removal, negative reactivity coefficients, and low stored energy inventories contribute to robust safety performance under a wide range of conditions.

These attributes differentiate microreactors from both large gigawatt-scale reactors and many current SMR designs, and they underpin their suitability for deployment in environments where infrastructure is limited, logistics are difficult, or operational conditions are challenging.

2.2 Design Features

Microreactor concepts span several reactor types, including high-temperature gas-cooled reactors (HTGRs), heat-pipe reactors, molten salt reactors (MSRs), liquid-metal-cooled fast reactors (LMFRs), and compact water-cooled reactors (WCRs).

Despite these technological differences, most designs share a set of common engineering principles aimed at simplifying construction, reducing reliance on large infrastructures, and ensuring robust safety performance.

2.2.1 Passive Heat Removal and Simplified Systems

Many microreactors prioritize passive mechanisms for heat transfer to minimize the need for active components and enhance operational reliability.

For example:

- Heat-pipe reactors use sealed heat pipes embedded in the core to transfer heat through phase change and capillary action.
- Gas-cooled and liquid-metal systems frequently rely on natural circulation during certain operating regimes.

These approaches reduce mechanical complexity, improve inherent safety margins, and support stable performance even in settings with limited supporting infrastructure.

2.2.2 Modular Construction and Plug-and-Play Deployment

Factory fabrication and modular assembly are central features of most microreactor designs. In many concepts, major subsystems, such as the reactor module, power conversion system, shielding, and auxiliary equipment, are manufactured in controlled environments and shipped as pre-assembled units.

This strategy:

- reduces onsite civil works,
- shortens installation times, and
- enables more predictable quality assurance.

Together, these advantages support rapid setup and, in some cases, relocation after mission completion.

2.2.3 *Simplified Balance of Plant*

Due to their lower thermal output and alternative cooling methods, many microreactors require minimal external infrastructure.

Examples include:

- air-cooled configurations that eliminate the need for large water supplies,
- compact power conversion options such as supercritical CO₂ cycles or Stirling engines, and
- reduced reliance on auxiliary systems typical of larger nuclear plants.

2.2.4 Robustness to External Hazards

Deployment in remote or harsh environments requires attention to seismic hazards, extreme temperatures, transport-induced stresses, and environmental degradation mechanisms such as corrosion and salt exposure during sea transport. Many concepts incorporate robust containment, below-grade siting, or protective enclosures to enhance resilience against external events.

2.3 Applications

Microreactors are being developed to address energy needs that are not well served by conventional power technologies. Their design characteristics enable deployment across a wide range of high-value use cases:

Remote and Off-Grid Communities

Many off-grid settlements in arctic, island or sparsely populated regions depend on diesel transport and storage logistics. Microreactors can provide continuous, low-carbon electricity and heat with significantly reduced fuel handling requirements and improved long-term cost stability.

Industrial and Mining Operations

Mining sites and energy-intensive industrial facilities often require stable, round-the-clock power far from large transmission networks. Microreactors can supply electricity and process heat with minimal onsite infrastructure, supporting uninterrupted operations and reduced reliance on long fossil-fuel supply chains.

Data Centres and Digital Infrastructure

The growth of data centres and AI compute facilities demands highly reliable power with strict continuity requirements. Microreactors offer a potential source of dedicated baseload supply to help operators meet availability targets and corporate decarbonisation objectives.

Disaster Response and Critical Infrastructure

Transportable microreactors could be deployed to restore power after major disruptions or to support essential services such as hospitals, communications hubs and emergency response operations when existing power systems are damaged or unavailable.

Space Missions

For lunar or planetary surface operations, as well as deep-space missions, microreactors can provide sustained power where solar generation is intermittent or insufficient. Demonstration projects such as NASA’s Kilopower programme [2] highlight the potential for compact fission systems in space applications

Non-Electric Applications

Several microreactor concepts are designed to supply heat for hydrogen production, industrial processes, desalination or combined heat-and-power applications. These non-electric outputs broaden the range of potential end-users and support energy diversification strategies.

2.4 Overview of Current Microreactor Designs

As of December 2025, more than thirty microreactor designs have been identified worldwide, reflecting a rapidly developing landscape of advanced concepts aimed at providing reliable low-carbon power in settings where larger reactors or extensive grid infrastructure are impractical. These designs vary widely in reactor type, fuel form, power output and deployment approach, illustrating the diversity of innovation across Member States.

Based on publicly available information, including vendor documentation and the IAEA SMR Catalogue [3], Table 1 summarises the range of microreactor concepts currently under development. While the designs span different levels of maturity, they collectively highlight several technological trends and common design philosophies emerging within this class of reactors.

Table 1: Overview of current microreactor designs

Design	Company	Country	Reactor Type	Power output (MWth)	Power output (MWe)
AMR	STL Nuclear (Pty) Ltd	South Africa	HTGR	10	3
AURORA	OKLO Inc.	USA	LMFR	50 -150	15 - 50
ELENA	National Research Centre “Kurchatov Institute”	Russian Federation	PWR	3.3	0.068
Energy Well™	Centrum výzkumu Řež	Czech Republic	MSR	20	8
eVinci™ Micro Reactor	Westinghouse Electric Company LLC	USA	Heat-Pipe Reactor	15	5
Holos-Quad Generators	HolosGen	USA	HTGR	22	10
Holos-Mono	HolosGen	USA	HTGR	22	10
JIMMY	JIMMY ENERGY SAS	France	HTGR	10 -20	-
MARVEL	Idaho National Laboratory	USA	LMTR	0.075 - 0.1	0.015 - 0.027
KRONOS MMR™	NANO Nuclear Energy Inc[2]	USA	HTGR	10 - 45	3.5 – 15
MoveLuX	Toshiba Corporation	Japan	Heat-Pipe Reactor	10	3 – 4
LOKI MMR™	NANO Nuclear Energy Inc24	USA	HTGR	1.5 –5	0.01 - 3
SHELF-M	NIKIET	Russian Federation	PWR	35	<10
UNITHERM	NIKIET	Russian Federation	PWR	30	6.6
XAMR	NAAREA	France	MSR	80	40
XENITH	X-energy, LLC	USA	HTGR	-	3 - 10
ODIN	NANO Nuclear Energy Inc[1]	USA	-	-	-
ZEUS	NANO Nuclear Energy	USA	Solid core	-	-

Design	Company	Country	Reactor Type	Power output (MWth)	Power output (MWe)
	Inc		battery		
Calogena	Gorgé SA	France	Pool-type	30	-
PWR-20	Last Energy Inc.	USA	PWR	80	20
MicroURANUS	MicroURANUS	Republic of Korea	LMFR	-	20 - 30
eVinci Space Microreactor	Westinghouse Electric Company LLC	USA	Heat-Pipe Reactor	-	0.1
BANR	BWXT	USA	HTGR	50	-
Kaleidos	Radiant	USA	HTGR	1.9	1
Aalo-X	Aalo Atomics	USA	LMFR	30	10
ECSPLORER	CEA and CNES	France	Heat-Pipe Reactor	-	0.01
Brazilian Microreactor	Diamante Energia, Terminus and Indústrias Nucleares do Brasil (INB)	Brazil	Heat-Pipe Reactor	-	5
R1 Microreactor	Antares	USA	Heat-Pipe Reactor	-	0.1 – 1
Rolls Royce Space AMR	Rolls Royce SMR	United Kingdom	HTGR	75	25
GA-EMS' NTP	General Atomics	USA	HTGR	-	-
NuGen Engine™	NuGen	USA	HTGR	4 - 6	2 - 3
U-Battery	Urenco	United Kingdom	HTGR	10	4
Kilopower	Los Alamos National Laboratory	USA	Heat-Pipe Reactor	-	0.1

2.4.1 Technology Families

Current microreactor concepts can be grouped into several major technology families, reflecting diverse approaches to achieving compactness, simplified operation, and extended core lifetimes. Table 2 summarises the principal categories and representative designs.

Table 2: Overview of microreactor technology families and representative concepts

Technology Family	Representative Designs	Key Characteristics
Heat-pipe reactors	eVinci™, MoveLuX, ECSPLORER, Brazilian heat-pipe microreactor, R1 (Antares), Kilopower, eVinci Space Microreactor	Use sealed heat pipes for passive heat transport; very low part-count; inherent safety; air-cooled operation; suitable for transportable and space applications.
HTGR	AMR, Holos-Quad, Holos-Mono, JIMMY, KRONOS MMR™, LOKI MMR™, BANR, Kaleidos, XENITH, NuGen Engine™, U-Battery, Rolls Royce Space AMR, GA-EMS' NTP	TRISO-based fuels; high outlet temperatures; applications in electricity, industrial heat, and hybrid systems; modular plant layouts; strong inherent safety characteristics.
MSRs	Energy Well™, XAMR	Molten-salt fuel or coolant; high thermal efficiency; simplified power conversion; requires further materials and chemistry qualification.
LMFRs / LMTR	AURORA (Oklo), MicroURANUS, Aalo-X, MARVEL (LMTR)	Use sodium or other liquid metals; compact cores; long refuelling intervals; suited for industrial or remote applications, can be in the fast spectrum (LMFR) or in the thermal (LMTR).

Compact WCRs	ELENA, SHELF-M, UNITHERM, PWR-20, Calogena (pool-type)	Based on established PWR technologies; familiarity may ease licensing; relatively mature engineering basis.
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2.4.2 Power Ranges and Functional Boundaries

The thermal power of microreactor concepts ranges from tens of kilowatts (as in MARVEL and certain space-oriented systems) to approximately 150 MWth at the upper boundary between microreactors and very small SMRs. Most concepts fall between 0.1 MWth and 50 MWth, consistent with the functional attributes discussed earlier and with current IAEA usage of the term “microreactor”.

2.4.3 Geographic Distribution

Microreactor development is concentrated primarily in technologically advanced Member States, with activity observed in North America, Europe, and parts of Asia. Figure 1 illustrates the geographic distribution of identified designs. While no embarking country is currently pursuing indigenous microreactor development, interest in potential future deployment continues to grow, particularly for specialised applications and remote regions.

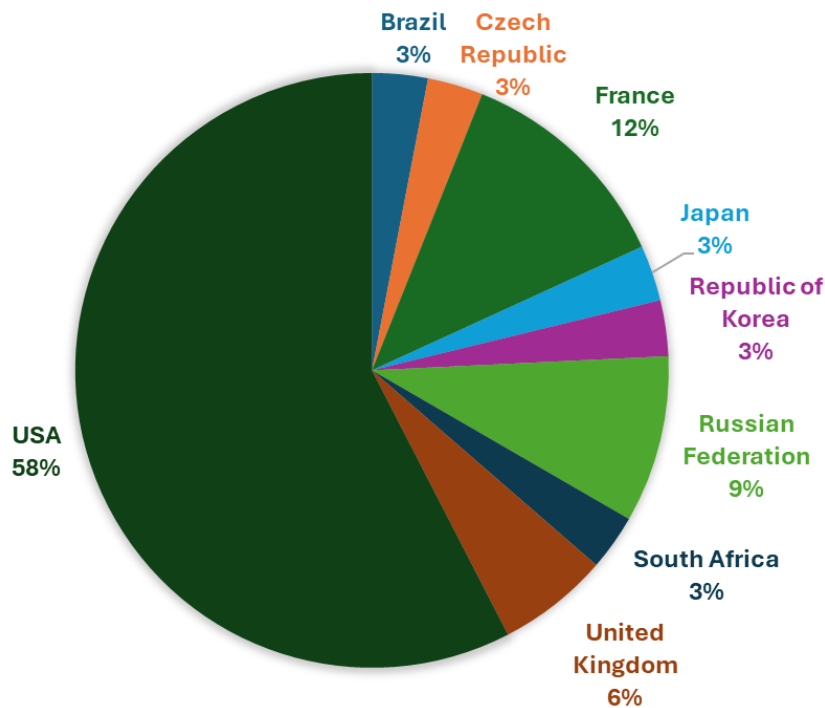


Figure 1: Geographic distribution of microreactors worldwide

2.4.4 Overall Observations

The diversity of concepts shows that microreactors are not defined by a single design philosophy but rather by their functional attributes: compactness, transportability, autonomous operation, passive safety features, and long core lifetimes. These characteristics underpin their potential to provide highly reliable, low-carbon power for niche, high-value applications where alternatives are limited. The technology landscape is progressing steadily but will require continued demonstration, regulatory innovation, and international collaboration to achieve commercial deployment.

3 DEPLOYMENT OPPORTUNITIES AND CHALLENGES

3.1 Deployment Models

Microreactor deployment models reflect the diversity of potential applications and operational contexts:

- *Stationary Modular Installations*

In this configuration, microreactors are installed at a fixed site, such as a remote community, research campus, industrial facility or dedicated test location, and operate for their full design life. At end-of-life, the core or entire module may be returned to a central facility for defueling and decommissioning, as proposed for systems such as eVinci.

- *Transportable Units*

Some concepts emphasise mobility, with reactors designed to be transported between sites during or after operation. Factory-fuelled modules could be deployed to support temporary missions, exploration projects or disaster response, then returned or relocated when the mission is completed.

- *Microgrid Integration*

Whether stationary or mobile, many microreactors are intended to operate as part of microgrids, supporting local energy autonomy, black-start capability, and seamless interaction with variable renewable energy or storage systems.

These deployment approaches reduce the need for extensive civil works or transmission infrastructure and can shorten project schedules while enabling flexible matching of supply to local demand.

3.2 Technical and Infrastructure Challenges

Despite their potential, several technical and infrastructural challenges must be addressed for microreactor deployment:

- **Technology Readiness:** While some concepts have undergone experimental testing or detailed design studies, many remain at intermediate Technology Readiness Levels (TRLs), often between 3 and 6 [4]. Demonstrated systems include NASA's KRUSTY experiment [2] and the MARVEL test reactor [5], while designs such as eVinci™ and PWR-20 have engaged in pre-application regulatory interactions.
- **Fuel Cycle and Supply Chain:** Several concepts rely on advanced fuel forms and high-assay low-enriched uranium (HALEU). Global HALEU availability remains limited, and significant investment is required to expand enrichment, deconversion and fabrication capacities. These constraints represent a key bottleneck for scaling multiple designs in parallel.
- **Transport and Siting considerations:** Factory-fuelled modules raise specific licensing and safety questions related to transport containers, route selection, physical protection, and emergency preparedness. Siting microreactors close to end-users may also require updated regulatory guidance on emergency planning zones, environmental assessments and interactions with existing infrastructure.

- **Digital Systems and Cybersecurity:** The extensive use of digital instrumentation, automation and remote monitoring improves operational efficiency but introduces cybersecurity considerations. Ensuring the integrity of control systems and safeguards-related data is essential for safe and secure operation.
- **Waste Management:** Novel fuel designs and sealed-core configurations may require new approaches to spent fuel management, including take-back agreements, centralised handling, transport logistics and safeguards. These considerations will shape future deployment models and supporting infrastructure.

Addressing these challenges will require coordinated efforts by designers, regulators, operators and international organizations to develop appropriate technical solutions and regulatory frameworks [6].

4 IAEA ACTIVITIES SUPPORTING MICROREACTOR DEVELOPMENT

4.1 Technology Mapping and Information Sharing

The IAEA supports Member States by providing impartial, up-to-date information on advanced reactor technologies, including microreactors. Two key tools are presented on the following sections.

4.1.1 Advanced Reactors Information System (ARIS)

ARIS is an online database containing technical and deployment information on a wide range of advanced reactor concepts, including SMRs and microreactors. It allows users to search and compare designs based on reactor type, power level, coolant, deployment status and other parameters.

4.1.2 SMR catalogue [3]

The SMR Catalogue 2024 is a technical supplement to ARIS and provides detailed, parameter-based design descriptions submitted in standardized templates. It includes structured information on reactor physics parameters, cooling systems, engineered safety systems, fuel characteristics, plant layout, development milestones, and technology readiness indicators. It is updated periodically (multiple editions in 2024–2025) to reflect new vendor submissions and corrections. The Catalogue is intended as a technical reference to support design comparison, technology assessment, and informed decision-making by Member States.

4.1.3 SMR Booklet – Advances in SMR Technology Developments 2024 [7]

The SMR booklet is a non-serial publication produced for the 2024 IAEA International Conference on Small Modular Reactors and Their Applications. It provides a high-level, narrative overview of global SMR and microreactor developments.

Key features include:

- Descriptive summaries of development trends, market interest, new end-users, and role of SMRs in industrial decarbonisation.
- Contextual analysis of SMR deployment worldwide.
- Selected design snapshots based on the latest “active” entries in ARIS.
- A focus on communicating the broader role of SMRs in energy systems, rather than detailed technical specifications.

To complement these resources, the IAEA is preparing a dedicated TECDOC on microreactor technology developments, planned for publication in 2026. The TECDOC will synthesize information on microreactor design characteristics, enabling technologies, deployment models, technology readiness, and cross-cutting issues such as fuel cycle considerations, safeguards, and digitalization. This publication aims to serve as a comprehensive reference for Member States considering microreactor options.

4.2 International Collaboration and Capacity Building

Beyond information tools and publications, the IAEA advances international collaboration and strengthens capacity building through several additional mechanisms, as outlined in the sections below.

4.2.1 Technical Meetings and Workshops

The IAEA convenes technical meetings and workshops that bring together experts from industry, research institutions, regulatory bodies and prospective end-users to exchange knowledge on microreactor designs, deployment pathways and cross-cutting technical issues. For example, a consultancy meeting held in June 2025 supported the development of the planned TECDOC on microreactor technology developments, while a Technical Meeting on Advances in Design Development for Microreactors and their Applications was organized in May 2026, broadening participation to additional stakeholders. These events facilitate discussion of emerging design trends, enabling technologies and lessons learned, while promoting a shared understanding among Member States of the opportunities and challenges associated with microreactor deployment.

4.2.2 Coordinated Research Projects (CRPs)

CRPs provide a structured framework for collaborative research among institutions from different Member States on topics relevant to advanced reactors. Ongoing CRPs address areas such as fuel performance modelling, hybrid energy systems, digitalisation and advanced simulation, all of which are applicable to microreactors. While these programmes are not microreactor-specific, many of the research outputs, such as improved modelling tools, materials data, or integration strategies, support enabling technologies that microreactor developers may adopt. Participation in CRPs strengthens scientific cooperation and helps Member States build capacity for assessing innovative reactor systems.

4.2.3 Capacity-Building Programmes

The IAEA supports Member States through training activities, guidance materials and workshops aimed at developing the skills needed to evaluate and potentially implement advanced reactor technologies. This includes support in technology assessment methodologies, economic evaluation, infrastructure considerations and integration of advanced reactors into national energy strategies. In 2026, for example, an Interregional Training Course on Advances in Microreactor Designs and Applications is planned to provide participants with practical insights into design considerations, system integration and emerging applications. These activities help Member States strengthen institutional capacity and prepare for informed decision-making on advanced nuclear energy options.

5 CONCLUSION

Microreactors are emerging as a versatile option within the broader SMR landscape, with design features that enable deployment in locations where conventional reactors or extensive grid infrastructure are not feasible. Their compact size, transportability, long core lifetimes and passive safety characteristics position them as a practical solution for delivering reliable, low-carbon energy to specialised applications ranging from industrial sites to off-grid communities and critical facilities.

At the same time, further progress is needed to advance microreactor concepts toward commercial deployment. Key challenges include increasing technology readiness, expanding fuel cycle capabilities, addressing transport and siting considerations, enhancing digital resilience and defining suitable waste management pathways. Continued work in these areas will be essential to ensure that microreactors can operate safely and effectively across different national contexts.

The IAEA plays an important role in supporting this development through technology mapping, information services, coordinated research and capacity-building initiatives. By providing harmonised data through ARIS and the SMR Catalogue, preparing technical guidance such as the forthcoming TECDOC on microreactor technologies, and facilitating international dialogue, the Agency helps Member States assess the potential of microreactors within their energy strategies.

Looking ahead, microreactors have the potential to complement large nuclear power plants and other SMRs by providing an additional pathway for clean, dependable energy supply. As interest grows in decentralised, climate-resilient energy solutions, microreactors may become an important component of future low-carbon energy systems. Their successful implementation will depend on sustained technological progress, adaptive regulatory approaches and continued international cooperation, areas in which ongoing IAEA activities can contribute substantially.

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