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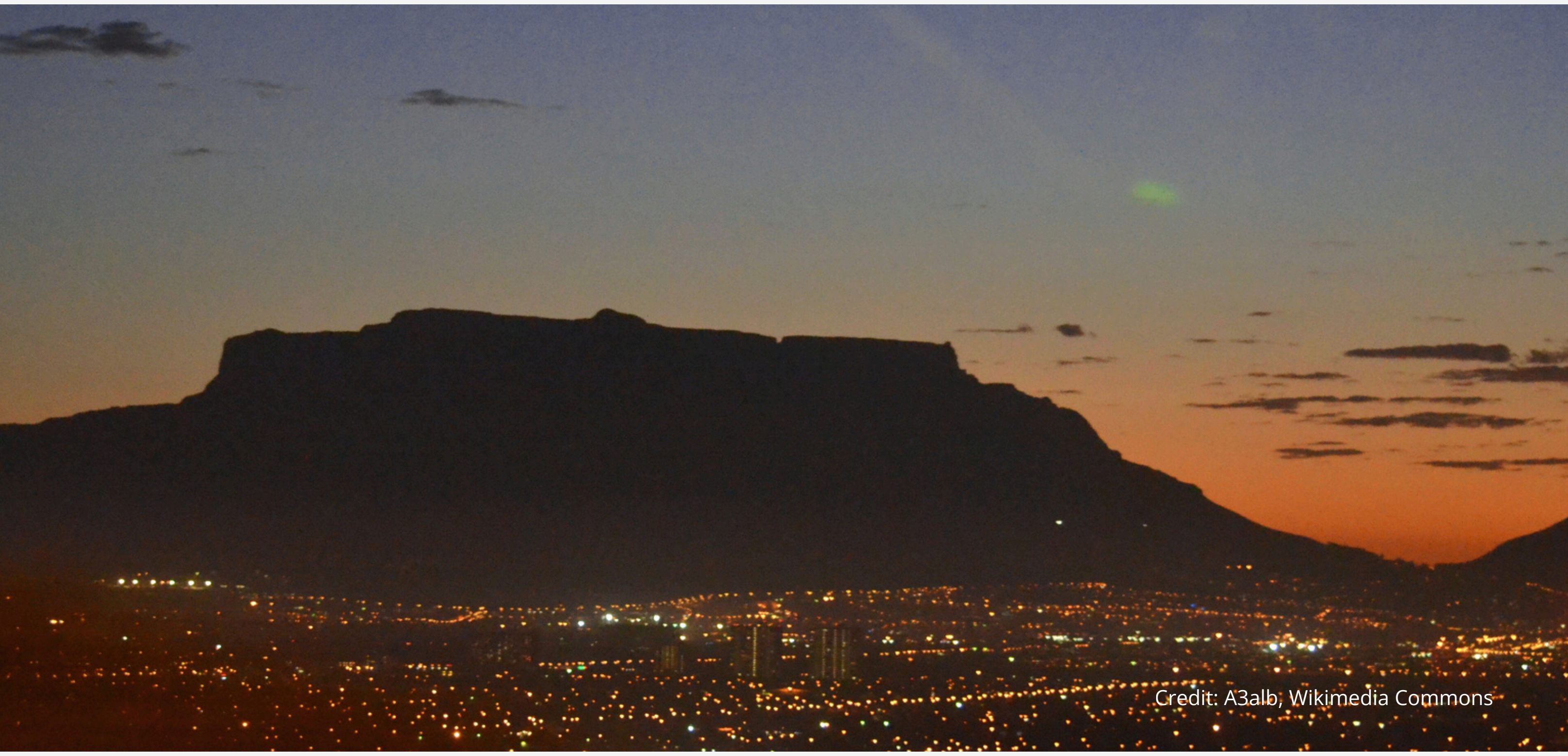

Sustainable Solutions

Small Modular Reactors: Navigating the New Nuclear Renaissance

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Introduction

Small modular reactors (SMRs) are expected to share several defining characteristics: smaller size, simpler modular construction, inherent safety, potential for factory construction, and deployment flexibility. SMRs have the potential to expand access to nuclear power for electricity generation to countries with limited resources or smaller electricity grids, and in geographically isolated locations or communities. Designed for flexibility, some SMRs will also have applications beyond electricity generation. This brief explores their core features, deployment challenges, and potential role in contributing to ending energy poverty while reducing greenhouse gas emissions.

Global Energy Challenges Driving SMR Interest

According to the latest data from the United Nations Development Programme (UNDP), more than one billion people were still experiencing energy poverty in 2024, despite rising levels of electricity access. Energy poverty is defined as a lack of adequate, reliable, and affordable energy for lighting, cooking, heating, and other daily activities necessary for welfare and economic development. More than half of these people live in Sub-Saharan Africa.[1]

To ensure that efforts to end energy poverty also drive economic development, the Energy for Growth Hub has proposed the adoption of a Modern Energy Minimum. Instead of the current Sustainable Development Goal 7 benchmark of 100 kWh per person per year – which provides only enough electricity to power a couple of light bulbs, charge a mobile phone, and run a small appliance – the recommended threshold is 1,000 kWh per person per year. This more ambitious target includes at least 250 kWh for household use and 750 kWh for consumption in the wider economy.[2]

At the same time, global electricity demand is projected to grow by 3.4% annually through 2026, largely driven by emerging markets. A significant share of this growth is expected to come from data centres. By 2026, their electricity use is expected to be roughly equivalent to that of Japan.[3] This growing demand underscores the urgent need to scale up reliable, low-carbon electricity sources, while also addressing persistent energy poverty around the world.

Technology Options for Reliable, Low-Carbon Energy

In a world still heavily reliant on fossil fuels, meeting growing electricity demand while reducing carbon emissions requires developing new low-carbon power sources and replacing existing fossil-fuel power plants.

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[1] Brian Min, et al., "Beyond Access: 1.18 Billion in Energy Poverty Despite Rising Electricity Access," United Nations Development Programme Futures Exchange, 12 June 2024. Available at: https://data.undp.org/blog/1-18-billion-around-the-world-in-energy-poverty.

[2] Energy for Growth Hub, The Modern Energy Minimum*. Available at: https://energyforgrowth.org/project/the-modern-energy-minimum/

[3] International Energy Agency, "Electricity 2024: Analysis and forecast to 2026", January 2024. Available at: https://www.iea.org/reports/electricity-2024

Several reliable, low-carbon energy options exist, each with different costs, scalability, dispatchability, and regional suitability, including renewables and nuclear power. The International Energy Agency 2025 report *The Path to a New Era for Nuclear Energy* identifies nuclear as a proven, mature, clean, dispatchable technology that complements variable renewables like wind and solar. Nuclear power enhances energy security and reduces emissions, forming a key component of the low-carbon transition.[4] However, unlocking its full potential requires continued innovation, investment, supportive policies, and international collaboration.

Tripling Nuclear by 2050

The goal to triple nuclear energy capacity by 2050, launched at the 2023 United Nations Climate Change Conference (COP28), has gained support from 31 countries and over 130 nuclear companies. Major financial institutions, nuclear industry, and leading energy users, including technology companies, have since endorsed this goal. This ambitious target requires increasing global nuclear energy capacity from 400 GWe to 1,200 GWe, to support energy security and net zero emissions.

According to the Organisation for Economic Co-operation and Development's (OECD) Nuclear Energy Agency, extending the operational lifespan of existing nuclear power plants (NPPs) to up to 80 years will be essential for maintaining the current 400 GWe of capacity.

In addition, already planned new builds are expected to contribute more than 300 GWe, while SMRs could add approximately 400 GWe.[5]

In practical terms, this would require constructing 10 large NPPs (each with a capacity of 1,000 MWe) every year until 2050, along with 80 SMRs of 300 MWe each per year, starting from 2035. Major technology companies are responding to their rising electricity demands by pursuing clean, dependable electricity, including through long-term agreements with existing NPPs and direct investments in SMR development and deployment.

However, if nuclear energy is to contribute meaningfully to climate and development goals, scaling at this pace must include the deployment of nuclear power in developing countries.

Small Modular Reactors: Enabling Clean Energy Access in the Global South

Traditional large NPPs require investment typically cited at 5 to 10 billion USD, placing them beyond the reach of most developing countries. SMRs offer a promising pathway to reliable, low-carbon nuclear power for developing countries that can alleviate energy poverty while supporting climate goals.

Owing to their compact and modular design, SMRs can be deployed in remote or infrastructure-constrained areas, enhancing energy security in regions lacking access to stable electricity.

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[4] International Energy Agency. "The Path to a New Era for Nuclear Energy." January 2025. Available at: https://www.iea.org/reports/the-path-to-a-new-era-for-nuclear-energy.

[5] OECD Nuclear Energy Agency. (2022). Meeting climate change targets: The role of nuclear energy (NEA No. 7628). OECD Publishing. Available at: https://www.oecd-nea.org/jcms/pl_69396/meeting-climate-change-targets-the-role-of-nuclear-energy?details=true

Their scalability and siting flexibility suit the needs of developing countries, though significant technical, regulatory, and financial challenges still exist. Assessing how SMRs can support a nuclear renaissance in the Global South requires an understanding of what SMRs are, the technologies under development, and how they differ from traditional NPPs.

Understanding SMRs and their Applications

SMRs are advanced nuclear reactors typically designed to generate up to 300 MWe per module, in contrast to the 1,000+ MWe outputs of large reactors. They are intended for factory fabrication and modular assembly, offering a scalable and efficient approach to nuclear power generation.

Like larger reactors, they generate heat through nuclear fission for direct use or electricity production.

Their compact size supports deployment as standalone units or in multi-module configurations, offering scalable and flexible nuclear power solutions. SMRs also promise lower initial capital costs compared to large NPPs, making them a more viable option for emerging nuclear countries.

Although their smaller output may result in higher costs per megawatt of capacity, their modular design allows for phased construction and scalable investment, which can accelerate deployment and reduce financial risk.

In addition, safety assessments could potentially qualify SMRs as lower-risk installations, requiring reduced nuclear liability insurance coverage compared to large NPPs. Construction timelines for SMRs, from groundbreaking to commercial operation, are also expected to be significantly shorter than those for large reactors.

The inaugural IAEA International Conference on Small Modular Reactors. Credit: Dean Calma/IAEA.

Some SMRs will be capable of load-following, enabling them to adjust output in response to fluctuating energy demand or variable generation of renewable energy sources. Their compatibility with smaller, decentralised grids will be particularly beneficial in countries where national grid infrastructure is limited or underdeveloped.

Beyond electricity, SMRs can support desalination, district heating, hydrogen production (essential for fertiliser production), and high-temperature heat generation for petroleum refining, steel production, or synthetic fuel. Applications for civil maritime propulsion could potentially contribute to decarbonising global shipping, which comprises 90% of global trade as of 2024.[6]

The Family of SMR Technologies: An Overview

The International Atomic Energy Agency (IAEA) publications *Small Modular Reactors: Advances in SMR Developments 2024* and its supplement *Small Modular Reactor Technology Catalogue 2024* categorise 68 SMR designs into six families of SMR technologies.[7]

About one third of SMRs under development are based on established water-cooled reactor technologies, such as pressurised water reactor (PWR), boiling water reactor (BWR), or pressurised heavy water reactor (PHWR) technology.[8] Most of these SMRs are being designed for land-based deployment, while others are intended for use in civilian maritime applications, including floating NPPs.

The remaining SMR designs are based on non-water-cooled technologies, including high-temperature gas-cooled reactor (HTGR) technology, liquid metal-cooled or gas-cooled reactors with fast neutron spectrum technologies, or molten salt reactor (MSR) technology.[9] Microreactors are a subset of SMRs, generally designed to generate up to 20 MWe.

Fuel Types and Fuel Cycles in SMRs

Most large nuclear reactors use uranium fuel enriched to 3–5% in the isotope U-235, known as low-enriched uranium (LEU). A small number also use mixed-oxide (MOX) fuel, made from uranium and reprocessed plutonium. SMRs follow similar fuel approaches but also explore novel fuel types, including uranium, plutonium or thorium in metallic, oxide, nitride, or molten salt form.

[6] Spencer Feingold and Andrea Willige, "These are the world's most vital waterways for global trade", World Economic Forum, 15 February 2024. Available at: https://www.weforum.org/stories/2024/02/worlds-busiest-ocean-shipping-routes-trade/.

[7] IAEA, "Small Modular Reactors: Advances in SMR Developments 2024", 2024. Available at: https://doi.org/10.61092/iaea.3o4h-svum; IAEA, "Small Modular Reactor Technology Catalogue 2024, IAEA, Vienna, https://aris.iaea.org/publications/SMR_catalogue_2024.pdf.

[8] See International Atomic Energy Agency (IAEA), "Water cooled reactors". Available at: https://www.iaea.org/topics/water-cooled-reactors.

[9] Fast neutron spectrum technology refers to a type of nuclear reactor, known as a fast neutron reactor, that uses fast neutrons (energies above 1 MeV) to sustain the nuclear fission reaction, unlike the commercial nuclear reactors in operation today that rely on slower neutrons. See IAEA, "Fast Reactors", available at: https://www.iaea.org/topics/fast-reactors. See also IAEA, "What are Molten Salt Reactors?", IAEA, 11 March 2025. Available at: https://www.iaea.org/newscenter/news/what-are-molten-salt-reactors.

Uranium ore in barrels. Credit: Dean Calma/IAEA.

Some SMRs are being designed to use so-called high-assay low-enriched uranium (HALEU), enriched to between 5% and 20% U-235. While still categorically LEU, HALEU's higher enrichment supports longer fuel cycles and compact reactor cores, enabling more efficient fuel utilisation – more energy from the same amount of fuel – and reducing the frequency of refuelling. These features can have a direct positive economic impact on SMR deployment, particularly in remote or high-cost logistics environments.

However, there currently is limited supply capacity and steps are being taken to diversify supply chains and ensure sustainable capacity.

Fuel cycle lengths for SMRs range from 12 to 24 months in many designs – similar to current large reactors – while some SMRs are being designed for cycles of two to 10 years or even up to 30 years.

Some designs feature sealed reactor modules that are assembled and fuelled at the factory, then transported to the site for operation. For such designs, the entire module is replaced at the end of the fuel cycle, avoiding the need for on-site refuelling. In contrast, large PWRs and BWRs require shutdowns for refuelling, while PHWRs can be refuelled continuously during operation.

Pathways to Deployment

There are a range of technical, regulatory, infrastructure, and financial challenges that must be addressed over the next 10 to 15 years by developers, prospective end users, and the international community if SMRs are to help realise a new nuclear renaissance. The last 60 years of nuclear power deployment have provided a foundation of resources and experience that can be adapted to support SMR deployment.

Fuel Type	Composition	Typical Enrichment	Used In	Key Features	SMR Relevance
Natural Uranium	Uranium oxide	~0.7% U-235 (as found in nature)	Pressurised Heavy Water Reactors (PHWRs)	Well-established infrastructure for PHWRs	None
LEU (Low Enriched Uranium)	Uranium oxide	3–5% U-235	Large Light Water Reactors (LWRs), some SMR designs	Widely used, well-established infrastructure for LWRs	Fuel for several water-cooled SMR designs
HALEU (High Assay LEU)	Uranium metal or oxide, nitride, carbide, fluoride, and/or chloride	5–20% U-235	Advanced (non-water-cooled) SMR designs, microreactor designs	Supports compact cores, longer fuel cycles, higher efficiency	Key to long fuel cycle duration SMR designs; supply chain is currently limited
MOX (Mixed Oxide Fuel)	Plutonium + uranium oxide (PuO_2/UO_2)	5–10% PuO_2 in LWRs, 15–30% PuO_2 in fast breeder reactors, with 60-70% fissile plutonium (Pu-239 and Pu-241), natural/depleted uranium	Some large LWRs and fast breeder reactors	Enables plutonium recycling; non-proliferation considerations	Possible for some SMR fast reactor designs
Thorium-based fuels	Thorium + uranium or plutonium oxides	Not directly fissile	Experimental reactors	Thorium (Th-232) is converted to U-233 which can fission; good long-term potential and waste characteristics	Considered for some molten salt reactor (MSR) and high temperature gas cooled reactor (HTGR) designs
Metallic fuels	Uranium, U-Zr alloy, plutonium, Pu-U alloy, Pu-Zr alloy	HEU in fast breeder reactors, LEU or HALEU in advanced SMR designs	Fast reactors, some advanced SMR designs	High thermal conductivity, compact core design	Proposed for several fast-neutron spectrum SMR designs
Molten salt fuels	Uranium or thorium dissolved in salt	LEU or HALEU	MSRs (under development)	Liquid fuel form; allows online refuelling and fission product removal	Core element of molten salt SMR designs
Nitride fuels	Uranium or plutonium nitrides	LEU or HALEU, 15-30% plutonium with 60-70% fissile plutonium (Pu-239 + Pu-241)	Fast reactors (experimental)	High density and thermal conductivity	Considered for advanced fast-neutron spectrum SMRs

Table 1: Nuclear fuel types

Nuclear security equipment demonstration at the IAEA. Credit: Anass Tarhi/IAEA.

The unique characteristics of SMRs, as outlined throughout this brief, also lend themselves to innovative deployment models that could help overcome some of the financial barriers that have historically constrained nuclear energy.

The IAEA Milestones Approach

The IAEA Milestones Approach is a framework for managing the development of national infrastructure for a new nuclear power programme. It covers 19 areas of infrastructure development, including safety, security, and non-proliferation, and divides progress into three phases. For each area, it outlines activities to be completed in each phase and defines a milestone marking the end of that phase. Originally developed for large NPPs, the Milestones Approach remains applicable to SMR deployment, though some adaptation may be required for SMR-specific considerations. The IAEA also supports countries in developing or strengthening nuclear infrastructure through capacity building, advisory services, and review missions. This support is primarily delivered through the IAEA Technical Cooperation Programme.

Ensuring Safety, Security and Safeguards for SMR Deployment

SMRs are designed with enhanced safety features, including passive safety systems and lower power outputs. Safety is enhanced through simplified reactor designs, passive cooling mechanisms, and in some cases, underground siting for added protection. While the IAEA's safety standards were originally developed for large, land-based NPPs, the Agency is actively adapting them to address the unique characteristics of SMRs. This includes developing a comprehensive, technology-neutral framework, applicable across diverse SMR designs without compromising safety.

All NPPs, including SMRs, require robust security measures that protect against theft of nuclear material and sabotage. This includes events that could lead to a significant radioactive release, unauthorised access to nuclear material or to the facility and site, as well as cyberattacks. The geographic dispersion of SMR units, their smaller footprint, and novel deployment concepts, such as in populated areas or in seagoing civilian vessels, introduce new security challenges.

At the same time, certain SMR design features may reduce vulnerability to insider threats. These include sealed reactor units, reduced on-site staffing, and remote monitoring or operation, which can limit access to sensitive systems and materials. Underground siting, where used, may also improve security by making unauthorised access or external attacks more difficult.

While existing guidance, such as the IAEA Nuclear Security Series, remains broadly applicable, additional guidance may be needed for these new deployment concepts. International cooperation will be essential as States share information and lessons learned during SMR deployment.

All non-nuclear-weapon States under the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) must conclude comprehensive safeguards agreements with the IAEA. These agreements commit States not to use nuclear technology for weapons development and to provide the IAEA with access to locations and information for verification of all of the State's nuclear material and facilities. These activities enable the IAEA to provide credible assurance to the international community that States abide by their non-proliferation commitments.

The IAEA is working with Member States and SMR designers on a voluntary basis to assess how existing safeguards measures apply to SMRs and identify any adjustments needed to maintain safeguards effectiveness and efficiency.

A key strategy for supporting SMR deployment is the integration of safety, security, and safeguards aspects directly into the reactor design through so-called "3S-by-design" approaches. This approach embeds these elements throughout the reactor lifecycle – from planning and construction to operation, waste management, and decommissioning – ensuring safety, security, and safeguards activities are complementary and mutually reinforcing.

IAEA Nuclear Safeguard Inspectors at the Mochovce Nuclear Power Plant in Slovakia. Credit: Dean Calma / IAEA.

Addressing these aspects early, 3S-by-design can help avoid costly retrofits, minimise deployment delays, and tailor designs to national conditions. This approach is voluntary and imposes no additional obligations on the State concerned, legal or otherwise. It does, however, offer economic and operational benefits to designers, end users and regulators, and can reduce the regulatory burden on both the IAEA and national authorities.

Harmonising National Regulatory Requirements

Accelerated harmonisation of the licensing process is essential for the successful deployment of SMRs globally. Harmonisation would enable standardised designs to be accepted across countries, contributing to mitigating the delays and high costs associated with first-of-a-kind deployments in individual jurisdictions.

Serial production – repeatable manufacturing of multiple standardised units – which is critical to reducing costs, improving efficiency, and achieving commercial scalability, depends on such standardisation. However, differing regulatory approaches across nations could pose barriers to achieving this.

Several initiatives are aimed at addressing this challenge. The European Parliament is encouraging greater international cooperation among nuclear safety regulators, joint SMR design reviews, and the formation of harmonised regulatory approaches.

Similarly, the IAEA is advancing its Nuclear Harmonisation and Standardisation Initiative (NHSI), which aims to align global regulatory and industrial approaches for SMR design and deployment. The NHSI seeks to create frameworks that promote consistent safety standards, reduce duplication, and enable faster, safer, and

IAEA Director General Rafael M. Grossi at the opening of the Nuclear Harmonization Standardization Initiative (NHSI) 3rd Plenary meeting held at the Agency headquarters. Credit: Dean Calma/IAEA.

more efficient deployment of SMRs, supporting a global strategy for sustainable energy solutions.

Building Inclusive Partnerships

The World Bank's recent decision to lift its long-standing ban on funding nuclear energy projects marks a momentous shift and represents a critical first step toward removing the financial barriers that have long hindered developing countries from pursuing nuclear power. This shift is underpinned by a partnership with the IAEA, through which the Agency will provide the World Bank with the knowledge and expertise needed to responsibly support countries in their pursuit of reliable, low-carbon energy solutions.

Crucially, this decision also signals to other multilateral banks and private investors that nuclear power is a viable option for advancing sustainable development and energy security.

At national and regional levels, nuclear power projects will benefit from inclusive partnerships that bring together governments, industry, the private sector, local communities, civil society, development partners, and relevant international and regional organisations. Early engagement of these stakeholders will help ensure that projects reflect local needs, build trust, and contribute to broader economic and development goals. In particular, active dialogue with local communities and civil society is critical to fostering transparency, addressing concerns, and securing the public confidence that underpins the long-term sustainability of nuclear power initiatives.

The Demand-Driven Future of SMRs: Private Sector Momentum

Recent investments in nuclear technologies by major technology firms signal growing private-sector interest in SMRs as a clean energy solution. This influx of private capital highlights the potential of SMRs to attract non-traditional investors, complementing conventional models, such as government or utility-led funding.

Unlike traditional large nuclear power projects, SMR demand is increasingly shaped by specific industry needs. Sectors such as digital infrastructure, manufacturing, and other energy-intensive industries are seeking reliable, low-carbon power solutions tailored to their operations. The involvement of technology companies underscores both the financial viability of SMRs and their ability to decarbonise energy systems while meeting sector-specific demands, such as powering data centres or supporting local grids.

This trend supports the development of innovative financing approaches to address the unique aspects of SMR deployment, including through public-private partnerships, risk-sharing arrangements, and collaborations with international financial institutions. Engagement from high-profile private investors may also help accelerate regulatory harmonisation and public confidence, further strengthening the global business case for SMRs.

One promising deployment model involves co-locating SMRs with critical infrastructure, such as data centres, hospitals, or food processing facilities, to deliver stable, low-carbon power directly to users.

These integrated energy hubs could operate under long-term power purchase agreements, helping to offset capital costs and attract private investment. While beneficial globally, this approach could be particularly valuable in developing countries, where it may reduce financial risk and align clean energy deployment with industrial development goals.

Conclusion

SMRs offer a transformative pathway to clean, reliable energy, particularly in contexts where large-scale nuclear is less practical, such as remote communities, emerging markets, or energy-intensive industries. Their success will depend not only on technical innovation and investment but also on inclusive partnerships, transparent governance, and effective public engagement. SMRs can complement renewables, drive industrial decarbonisation, and play a central role in tripling global nuclear capacity by 2050 – helping to secure a just, inclusive, and resilient energy future for all.

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Vienna Center for Disarmament and Non-Proliferation

The VCDNP is an intenational non-governmental organisation that promotes peace and security by conducting research, facilitating dialogue, and building capacity on nuclear non-proliferation and disarmament.

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