Energizing the future:

Exploring the promise of small modular reactor technologies

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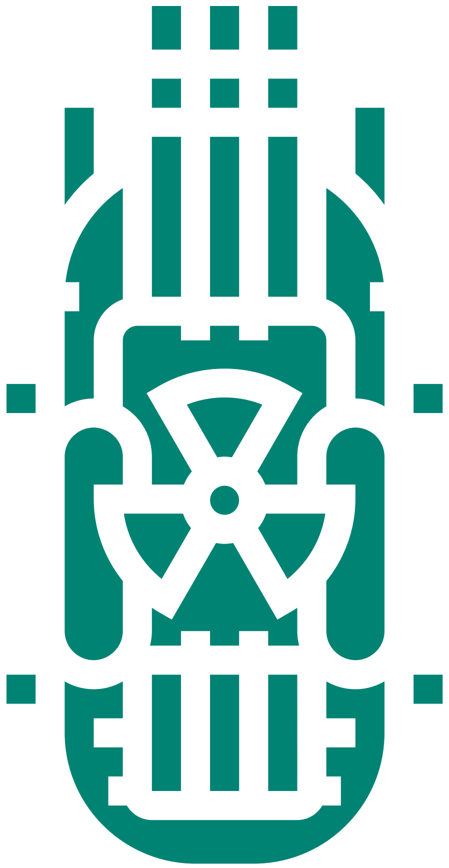
Small modular reactors are a transformative technology with the potential to revolutionize the global energy landscape.

As the demand for clean, reliable, and sustainable energy sources continues to rise, small modular reactors (SMRs) offer a solution to meet these challenges while addressing the growing need for decarbonization and energy security. This white paper surveys SMR technologies, exploring their historical development, key characteristics, benefits, challenges, and prospects. By delving into the intricacies of SMRs, their role in shaping the future of nuclear energy and advancing sustainability in the 21st century becomes clear.

What is a small modular reactor?

SMRs are a type of nuclear reactor characterized by compact size, typically producing less than 300MW, and modular design. SMRs hold significant importance in the energy sector for several reasons. First, their smaller size allows for more flexible deployment, enabling power generation in remote areas or regions with limited grid infrastructure. Second, SMRs offer the potential for cost savings and reduced financial risk compared to traditional large-scale nuclear power plants, as their modular design allows for incremental capacity additions and more accessible financing. SMRs also have the potential to play a crucial role in decarbonizing the energy sector by providing low-carbon baseload power that complements intermittent renewable sources like solar and wind.



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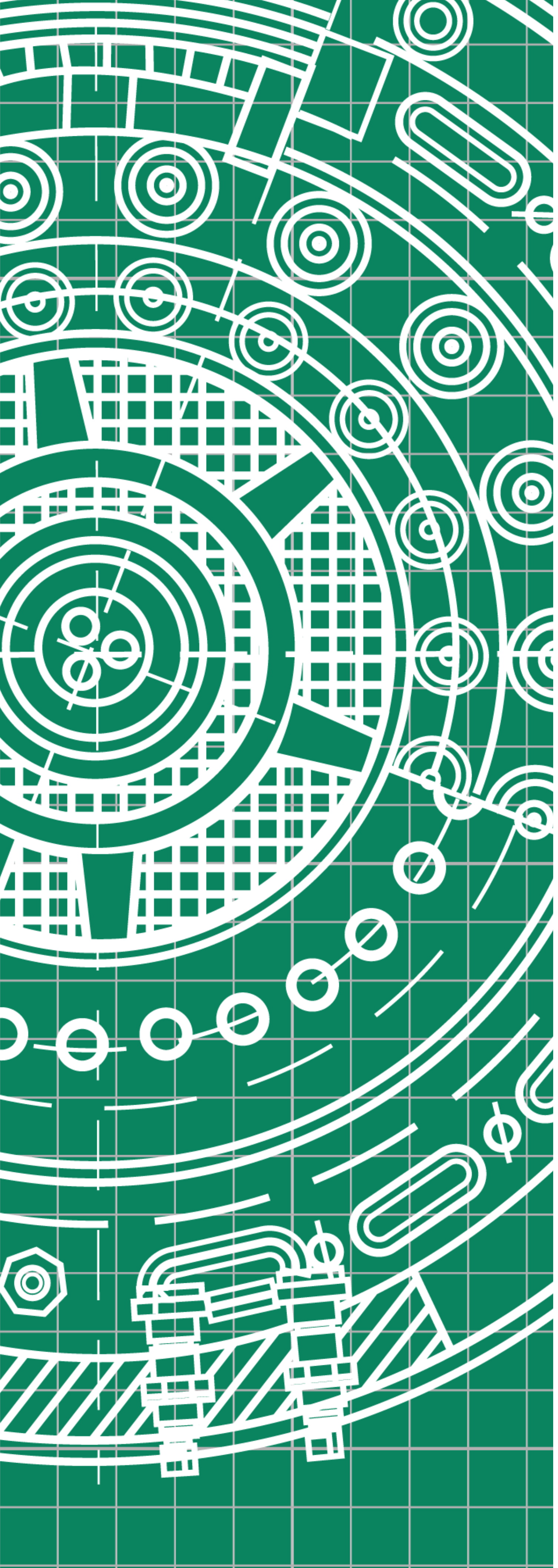


A short history of SMRs

The historical development of SMRs traces back to the early years of nuclear energy research and development. While the concept of smaller, more flexible nuclear reactors has been around for decades, concerted efforts to design and develop SMRs gained momentum in the late 20th and early 21st centuries.

In the 1970s, interest emerged in smaller nuclear reactor designs for various applications, laying the groundwork for SMR development. A significant milestone was the development of the Integral Fast Reactor concept by Argonne National Laboratory in the U.S. in the 1980s. Several countries, including the U.S., Canada, Russia, China, and the U.K., developed SMRs in the 2000s to tackle challenges such as high costs, long construction times, and safety concerns in the nuclear industry.

In the 2010s, several SMR designs advanced to licensing and demonstration stages. NuScale Power in the U.S. developed a PWR SMR design that received approval from the NRC in August 2020. Similarly, Rolls-Royce in the U.K. and Canadian Nuclear Laboratories also made significant progress in SMR development.

General characteristics of SMRs

SMRs have several distinct features and design principles that set them apart from traditional large-scale nuclear reactors. In addition to their compact size and modular design, SMRs incorporate advanced safety features to reduce the risk of accidents and improve overall safety performance. Light water reactor SMRs are dominated by pressurized water reactor (PWR) designs, the most common type of SMR under development globally.

GE Hitachi Nuclear Energy's BWRX-300 is a significant boiling water reactor (BWR) SMR currently under development, with NRC pre-licensing activities underway.

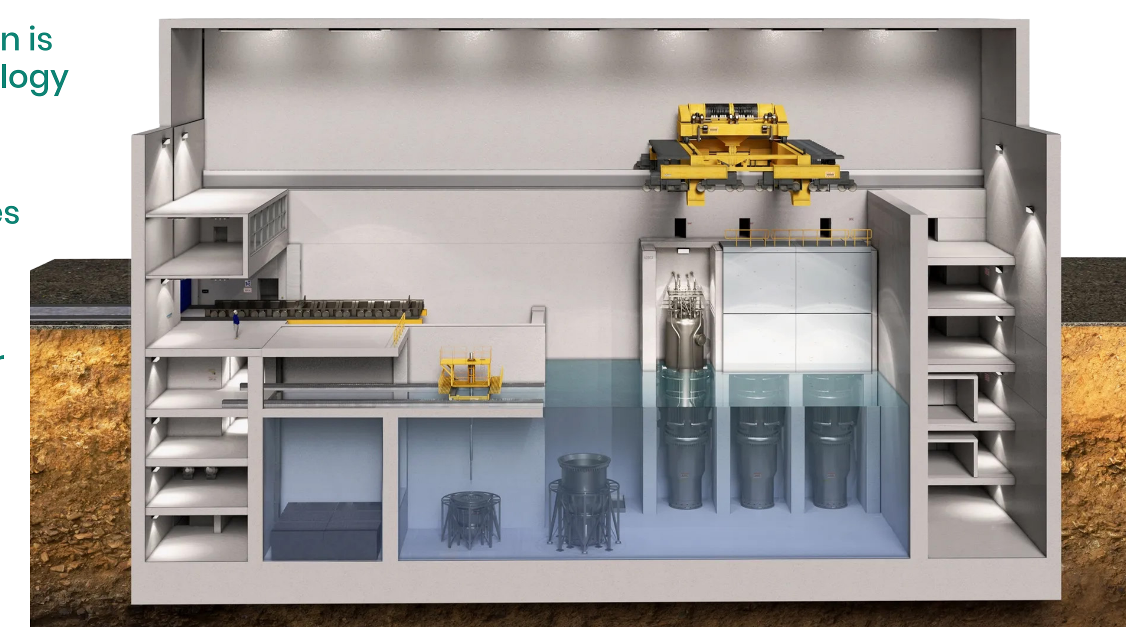
Ontario Power Generation (OPG) has contracted with GE Hitachi to build four units of its BWRX-300 SMRs at the Darlington Nuclear Generation Station in Ontario, Canada. The reactor design is estimated to reduce capital cost by up to 60% per MW installed using common construction techniques. Construction lead times are expected to average 24 – 36 months. Site preparation is underway with a planning goal of the first SMR operational by the end of 2028.

SMR, LLC, a wholly owned subsidiary of Holtec International, is developing the SMR-300. The reactor design features a passive safety system and underground containment structure. It incorporates integrated spent fuel storage, reducing the need for separate storage facilities. SMR, LLC has filed a Construction Permit Application with the Nuclear Regulatory Commission (NRC) for two SMR-300s to be installed on the site of the 800-MW Palisades Nuclear Power Plant (which ceased operations in May 2022 but is currently being recommissioned). The SMRs are slated to begin operation in mid-2030. The U.S. Department of Energy (U.S. DOE) conditionally approved a $1.52 billion loan guarantee for the project in March 2024.

Notably, Westinghouse unveiled its AP300 SMR in May 2023, a scaled-down version of its AP1000 reactor operating in China. Westinghouse expects to receive NRC certification of the AP300 by the end of 2027. The AP1000 design is already licensed in the U.K.

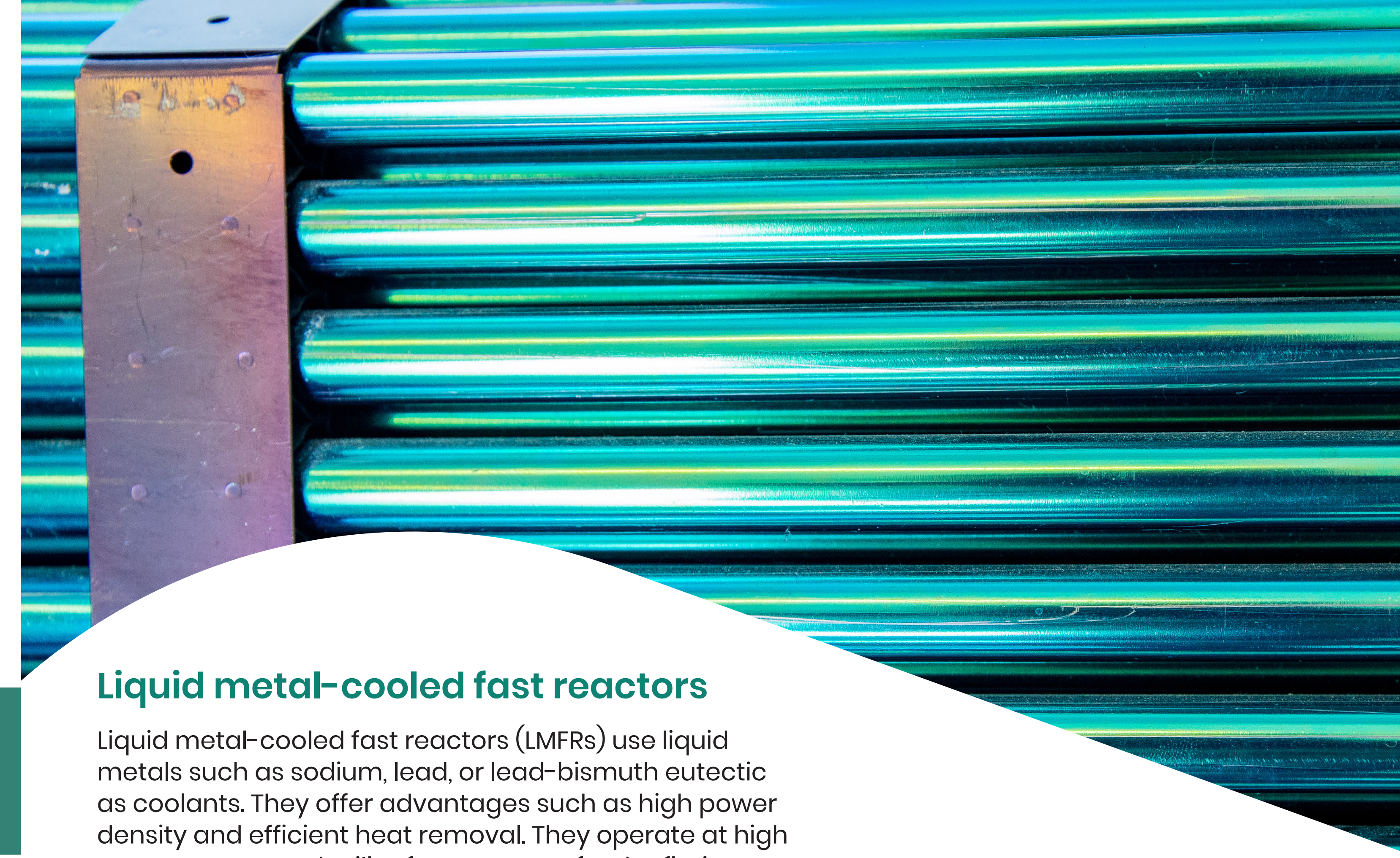
NuScale Power Corporation is developing its SMR technology in the United States.

The PWR SMR design utilizes natural circulation and passive safety features and is the first and only SMR to receive U.S. Nuclear Regulatory Commission (NRC) design approval and certification.



Right: NuScale Power 6-Module Reactor Building Cross Section *(Source: NuScale Power)*

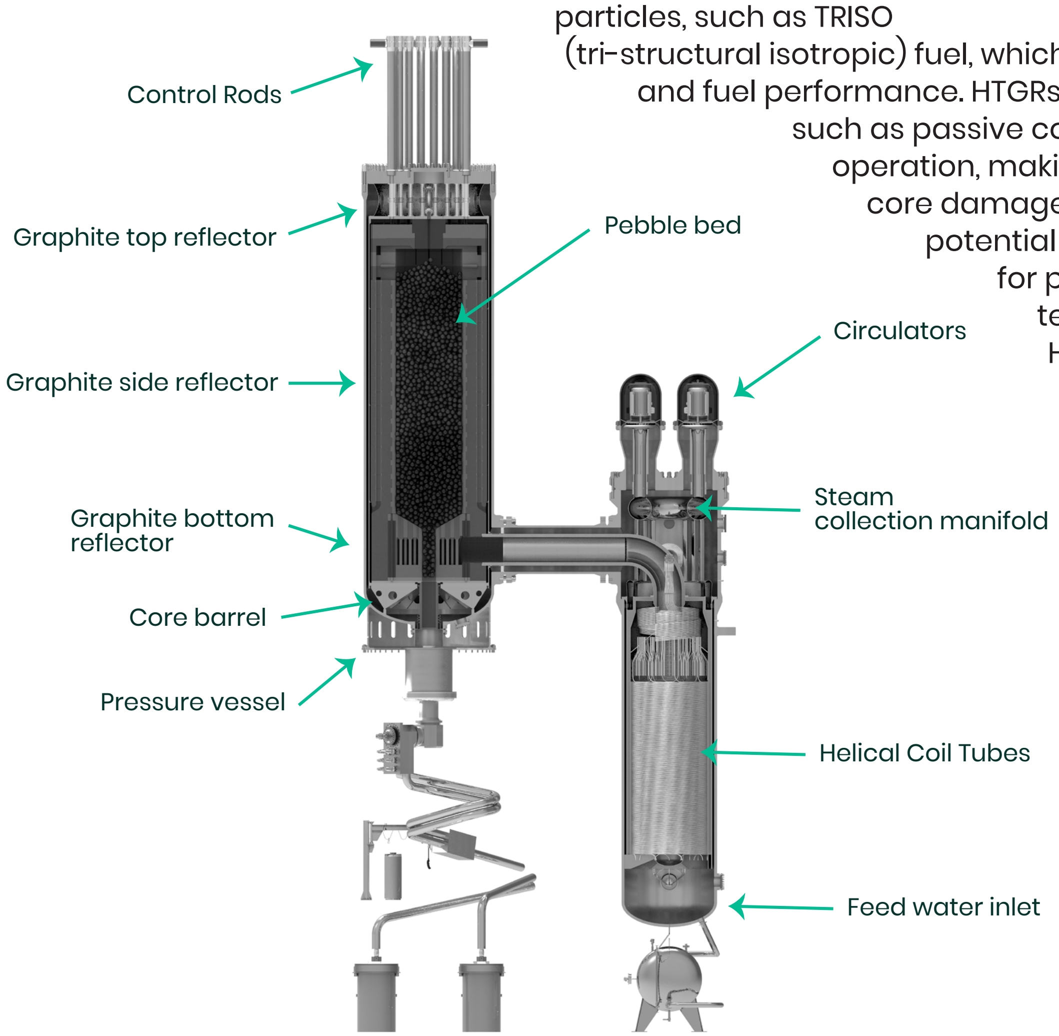
In addition to light water reactors (LWRs) several other SMR technologies are under active development.



High-temperature gas-cooled reactors

High-temperature gas-cooled reactors (HTGRs) use helium as a coolant and graphite as a moderator. They operate at higher temperatures than traditional water-cooled reactors, typically between 600°C and 950°C. HTGRs usually use ceramic-coated fuel particles, such as TRISO (tri-structural isotropic) fuel, which provides enhanced safety and fuel performance. HTGRs offer inherent safety features, such as passive cooling and high-temperature operation, making them less susceptible to core damage in accidents. They also have potential cogeneration applications for producing electricity and high-temperature process heat. China Huaneng reports its 210MWe HTR-PM plant was operational in December 2021 and reached full power on December 9, 2022.

X-energy is developing its Xe-100 modular HTRG that uses its proprietary TRISO-X tri-structural fuel. (Bottom Left)



Xe-100 reactor specifications	
Thermal Output:	**200MW**
Steam Temp:	**565°C**
Steam Pressure:	**16.5 MPa**
Electric Output:	**~76MW**

Liquid metal-cooled fast reactors

Liquid metal-cooled fast reactors (LMFRs) use liquid metals such as sodium, lead, or lead-bismuth eutectic as coolants. They offer advantages such as high power density and efficient heat removal. They operate at high temperatures and utilize fast neutrons for the fission process. LMFRs typically use metallic or ceramic fuel forms that withstand high temperatures and fast neutron flux. LMFRs offer high neutron efficiency, allowing for the efficient use of fuel and the transmutation of long-lived nuclear waste. They also have the potential for closed fuel cycles, where plutonium and other actinides can be recycled. Russia's Atomenergoprom reports its 300MW BREST-OD-300 lead-cooled fast reactor is under construction, with commissioning slated for 2028.

Molten salt reactors

Molten salt reactors (MSRs) use a liquid fluoride salt mixture containing uranium or thorium as fuel and coolant. They operate at atmospheric pressure and high temperatures. The fuel in MSRs is dissolved in the molten salt coolant, allowing for continuous online reprocessing and removing fission products. MSRs offer inherent safety features like passive cooling and low coolant pressure. They also have the potential for thorium fuel cycles, which could provide a more abundant and sustainable fuel source than uranium. China Nuclear Power Corporation reports its 10MWe TMSR-LF1 plant is under construction, with operation scheduled for 2026.

SMR design characteristics

Enhanced safety features

SMRs prioritize safety by using passive safety systems that require no external power or operator intervention to function. These systems rely on natural processes like gravity, convection, and chemical reactions to shut down the reactor and remove excess heat in an emergency. Redundant safety systems and diverse safety barriers are also incorporated to mitigate the consequences of potential accidents or equipment failures. Further, SMRs are designed to maintain inherent reactor stability under various operating conditions, reducing the likelihood of accidents or unplanned shutdowns. Advanced control systems and feedback mechanisms help stabilize reactor operation and prevent instabilities or power excursions.

Modular construction

Modular construction involves fabricating reactor components in a factory setting and assembling them onsite. This approach offers several advantages, such as standardized modules that can be replicated and mass-produced, rigorous quality control measures, parallelization of activities, and significant cost savings due to reduced construction times, lower labor costs, and minimized onsite work.

Scalability

SMRs offer scalability in size, capacity, and configuration. They can be deployed individually or in clusters to meet varying energy needs. SMRs are designed to integrate seamlessly with existing grid infrastructure and can be adapted for various applications beyond electricity generation.

Cost-effectiveness

SMRs are cost-effective and have reduced capital investment compared to large-scale nuclear reactors. Their modular design allows for standardized production of reactor components in factory settings, reducing manufacturing costs. The smaller size of SMRs enables more efficient use of materials and resources, further contributing to cost savings in construction. Additionally, SMRs can be built in stages, reducing the upfront capital investment required for project development. SMRs have a smaller scale and modular design, which lowers financing risks. This approach spreads financial risk over multiple project stages, increasing investor confidence.

Flexibility in deployment and grid integration

SMRs offer advantages due to their modular design, enabling standardized production, shorter construction times, and scalable deployment. Multiple units can operate in parallel, adjusting power generation to match fluctuating demand. The versatility of SMRs suits various locations and applications, including baseload, load following, and peaking power. Integrating well with existing grids, SMRs enhance stability and reliability as distributed resources, reducing reliance on centralized plants and long-distance transmission. Their modular, scalable nature facilitates efficient grid integration and load following while providing process heat for industrial, heating, and desalination needs.

SMR market trends upward

Rising global energy demand, coupled with the imperative to reduce greenhouse gas emissions and combat climate change, is fueling interest in nuclear power and SMRs as low-carbon energy solutions. Countries worldwide are setting ambitious decarbonization goals, spurring exploration of nuclear energy within clean energy strategies, and opening avenues for SMR deployment.

Governments globally are incentivizing the development and deployment of SMRs through policy support and financial incentives. Research funding, tax credits, loan guarantees, and regulatory reforms are among the measures to streamline licensing and permitting processes. Additionally, nuclear energy policies such as carbon pricing and renewable energy targets shape market demand for SMRs.

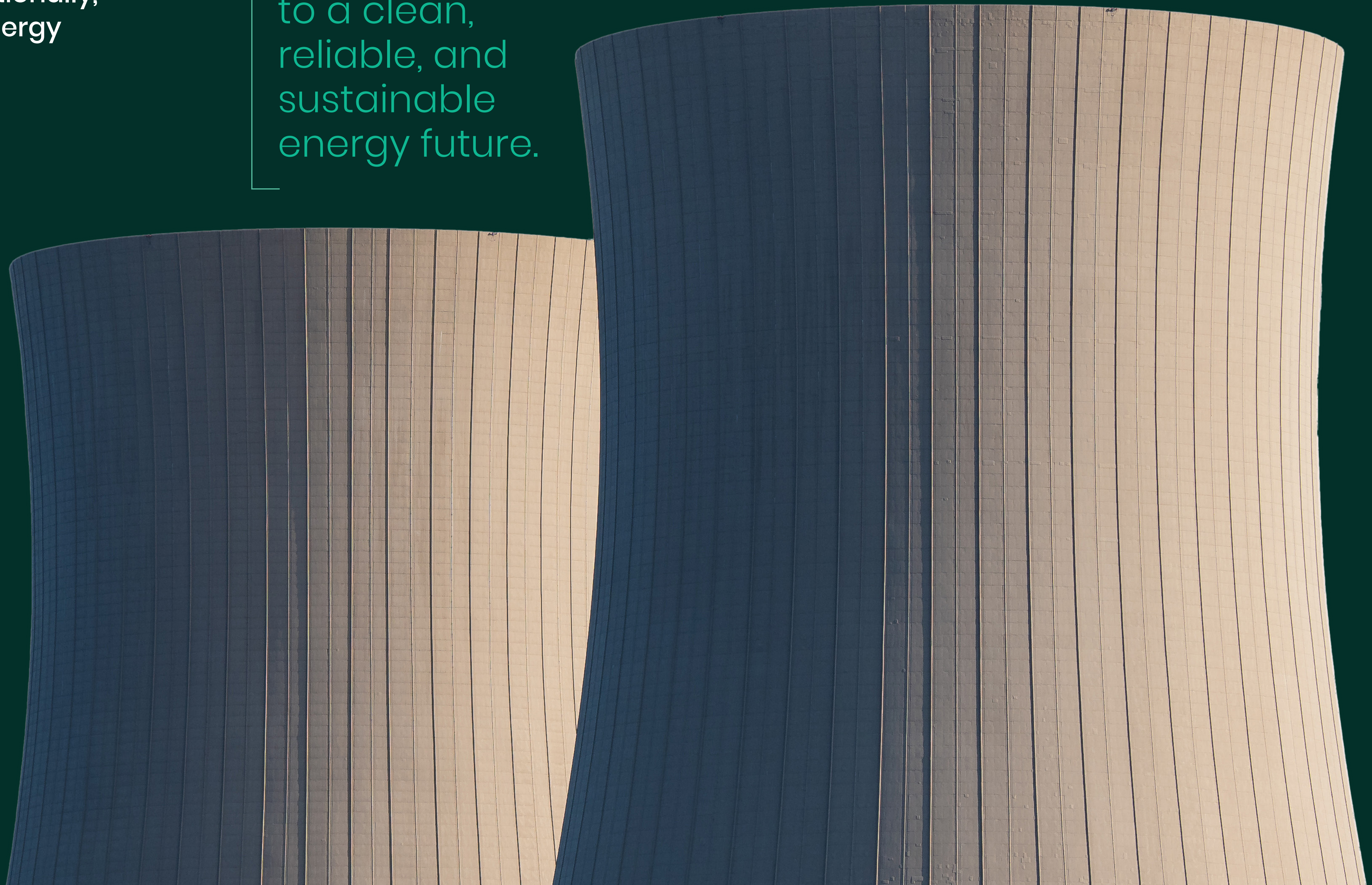
Ongoing research and development efforts propel technological advancements and innovation in SMR designs, materials, and manufacturing processes. Though commercialization remains uncertain, HTGRs and MSRs promise enhanced safety, efficiency, and flexibility. Innovations in modular construction, digitalization, and automation are concurrently driving cost reductions and expediting SMR deployment.

The SMR market presents a dynamic landscape with various reactor designs, technologies, and vendors vying for market share. Intense competition among developers and suppliers is fostering innovation, driving down costs, and elevating performance standards.

SMRs are expanding into novel markets and applications beyond traditional electricity generation, including district heating, desalination, industrial process heat, and remote off-grid power supply. These emerging sectors offer fertile ground for SMR deployment and market expansion.

Overall, the SMR market shows significant growth potential driven by increasing energy demand, decarbonization efforts, policy support, technological innovation, and emerging market opportunities.

As SMR technology continues to mature and gain acceptance, it will play a significant role in the global transition to a clean, reliable, and sustainable energy future.



Current research & development initiatives

Research and development (R&D) initiatives with SMRs encompass various activities to advance reactor technology, enhance safety, reduce costs, and accelerate commercial deployment.

Beyond the R&D efforts focused on developing and optimizing advanced reactor designs, several crucial ongoing R&D initiatives exist:

Materials science research is essential for developing reactor materials that can withstand high temperatures, neutron flux, and corrosive environments in SMRs.

Other R&D initiatives focus on testing and qualifying materials for reactor components, including fuel cladding, structural materials, coolant systems, and containment structures.

A significant R&D effort is underway to optimize modular construction techniques and manufacturing processes for SMRs, including factory fabrication, assembly line production, and quality control measures. Research aims to reduce construction costs, accelerate project schedules, and improve the efficiency and reliability of SMR manufacturing.

R&D initiatives are exploring digitalization, artificial intelligence, and automation technologies to optimize SMR operations, maintenance, and safety. Research focuses on developing digital twins, predictive maintenance algorithms, and advanced control systems to enhance reactor performance and reduce operational risks.

Grid integration studies, energy systems modeling, and techno-economic analysis to assess the role of SMRs in future energy systems is another area of active R&D. This research aims to evaluate the technical, economic, and environmental impacts of SMR deployment, identify optimal deployment scenarios, and inform policy and regulatory decisions.

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Conclusion

SMRs hold significant promise as a transformative technology that can be pivotal in shaping the future energy landscape. With growing energy demand, increasing concerns about climate change, and the need for reliable, sustainable, and affordable energy sources, SMRs offer a solution that aligns with the decarbonization, energy security, and global economic development goals of many nations.

As we look ahead to the future energy landscape, SMRs are poised to emerge as a critical component of the global energy mix, complementing existing energy sources and accelerating the transition to a low-carbon economy. By embracing SMRs and supporting their development, deployment, and commercialization, policymakers, industry stakeholders, and society can seize the opportunity to build a brighter, more sustainable energy future for future generations.

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