SMALL MODULAR REACTORS AS ENERGY SOURCE IN FUTURE

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as Energy Source in Future

A Comprehensive Educational Guide

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Small Modular Reactors as Energy Source in Future:

A Comprehensive Educational Guide

A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation

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Preface

This textbook, *Small Modular Reactors as Energy Source in Future: A Comprehensive Educational Guide*, was conceived to provide a thorough and accessible introduction to SMR technology for students, researchers, policymakers, and energy professionals. While much has been written about nuclear power in general, few resources present SMRs in a structured, educational format that combines fundamental principles with the latest technological, economic, and policy developments. Our aim is to bridge that gap.

The chapters are organized to guide the reader from the basic physics of nuclear energy and the evolution of advanced energy systems, through the technical specifics of SMR design, safety, and applications, to the broader economic, regulatory, and environmental context. We also present global case studies, highlighting successes, challenges, and lessons learned from diverse SMR projects. Special attention is given to the role SMRs could play in Armenia's energy strategy, reflecting the national relevance of the topic.

This work has been made possible through the support of the International Science and Technology Center (ISTC) within the microgrant **SMR PR-132.3.1.4**. The financial and institutional support from ISTC has allowed us to devote the necessary time and resources to produce a comprehensive, up-to-date, and pedagogically valuable resource. We also gratefully acknowledge the assistance of **EDIT print**, whose collaboration has ensured the professional quality of this publication.

It is our hope that this textbook will serve not only as an academic reference but also as an inspiration for the next generation of nuclear scientists and engineers. By understanding the principles, challenges, and potential of SMRs, readers will be better equipped to contribute to a sustainable, secure, and technologically advanced energy future.

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Acknowledgements

We wish to express our deep gratitude to all those who have contributed to the realization of this textbook, *Small Modular Reactors as Energy Source in Future: A Comprehensive Educational Guide*.

First and foremost, we extend our sincere thanks to the **First Foundational Infrastructure for Responsible Use of SMR Technologies** and **International Science and Technology Center (ISTC)** for providing financial support through the microgrant **SMR PR-132.3.1.4**. This support was instrumental in enabling the research, writing, and preparation of the material presented in this work.

We are grateful to the **A. Alikhanyan National Science Laboratory (AANL)** for providing the institutional environment and resources that facilitated our work. Our colleagues at AANL have offered valuable insights, technical expertise, and encouragement throughout the project.

Special thanks go to **EDIT print**, whose professional skills in design, layout, and production ensured that this textbook meets the highest standards of publication quality.

We also acknowledge the broader community of scientists, engineers, and policymakers working in the field of nuclear energy, whose research and open exchange of knowledge have enriched the content of this book. The examples, data, and case studies presented here are built upon decades of collective effort in advancing nuclear science and technology.

Finally, we wish to thank our families for their patience, understanding, and unwavering support during the long hours dedicated to the completion of this work. Their encouragement has been an invaluable source of motivation.

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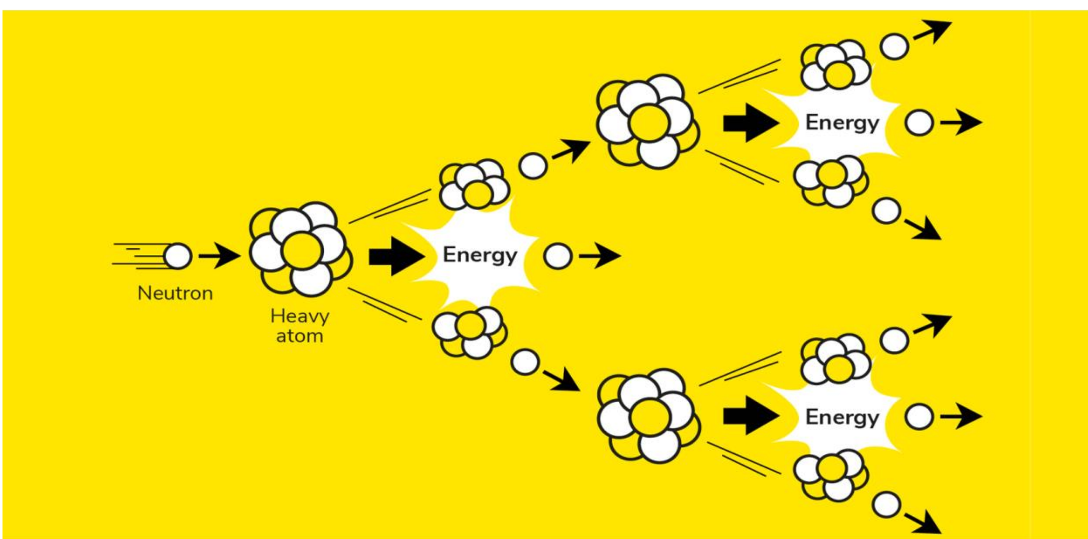
Chapter 1. Development of new generation energy sources

1.1 Basic principles of nuclear fission.

Nuclear fission is one of the most remarkable processes in modern science, a discovery that changed the world and gave humanity a new and incredibly dense source of energy. At its heart, fission is a process in which the nucleus of a heavy atom splits into two or more smaller nuclei. This splitting releases an extraordinary amount of energy, far greater than anything we can obtain from conventional chemical fuels such as coal, oil, or natural gas. The reason for this enormous release of energy lies in the structure of the atom itself and in the famous equation by Albert Einstein, $E=mc^2$, which tells us that even a very small amount of mass can be converted into a very large amount of energy. For instance, one kilogram (about 2.2 pounds) of matter is equivalent to

$$E = 1 \text{ kg} \times (3 \times 10^8 \text{ meters/sec})^2 = 1 \times 3 \times 10^8 \times 3 \times 10^8 \text{ joules} = 9 \times 10^{16} \text{ joules}$$

This is a huge of amount of energy, equivalent to the energy content of over three million metric tons of coal.



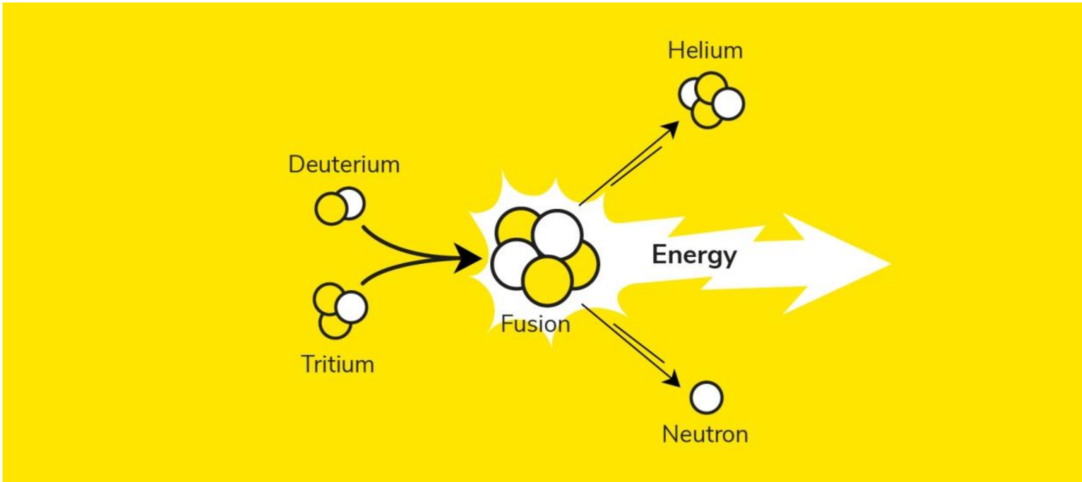
The atoms that are most useful for fission are called fissile isotopes. These are heavy elements, such as uranium-235 and plutonium-239, that can be induced to split when they absorb a neutron. When such a nucleus captures a neutron, it becomes unstable. This instability causes it to deform and eventually break apart into two lighter nuclei, known as fission fragments. At the same time, it releases two or three additional neutrons and a large amount of energy, both in the form of the kinetic motion of the fragments and in electromagnetic radiation such as gamma rays.

A typical example of a fission reaction can be seen with uranium-235. When a uranium-235 nucleus absorbs a neutron, it might split into barium-141 and krypton-92, while releasing three neutrons and roughly two hundred million electron volts (200 MeV) of energy. This number may not sound very large at first, but it is millions of times greater than the energy released in a single chemical reaction, such as burning a molecule of coal or gasoline. This is why nuclear fuel is so energy-dense: a small amount can power entire cities for months.

One of the most fascinating aspects of fission is that it can lead to a chain reaction. The neutrons released during one fission event can collide with other fissile nuclei, causing them to split as well, releasing more neutrons, and so on. If conditions are right, this becomes a self-sustaining process. Controlling this chain reaction is the central challenge and achievement of nuclear reactor design. If the reaction produces more neutrons than are lost or absorbed, the process speeds up, leading to what is called a supercritical state. If it produces exactly the right amount to sustain itself steadily, the reactor is said to be critical, which is the goal in power generation. If fewer neutrons are available, the reaction slows and eventually stops.

The energy released in each fission event is not all the same kind. Most of it, which is about 170 MeV, is carried as kinetic energy by the fission fragments, which quickly slow down and transfer their energy as heat to the surrounding material. Smaller amounts of energy are carried by the fast-moving neutrons and by gamma radiation. A portion is also released later, as the unstable fission products undergo radioactive decay. In a nuclear reactor, all of this energy ultimately becomes heat, which is absorbed by a coolant, used to produce steam, and finally converted into electricity through turbines and generators.

It is worth noting that nuclear fission is quite different from nuclear fusion, another process that also releases large amounts of energy. While fission splits large, heavy nuclei into smaller ones, fusion combines small, light nuclei, such as isotopes of hydrogen, into heavier ones, releasing even more energy per reaction. Fusion powers the Sun and other stars, but on Earth it requires extreme temperatures and pressures, making it far more challenging to harness for practical power generation. Fission, by contrast, has been mastered and used in power plants for decades.

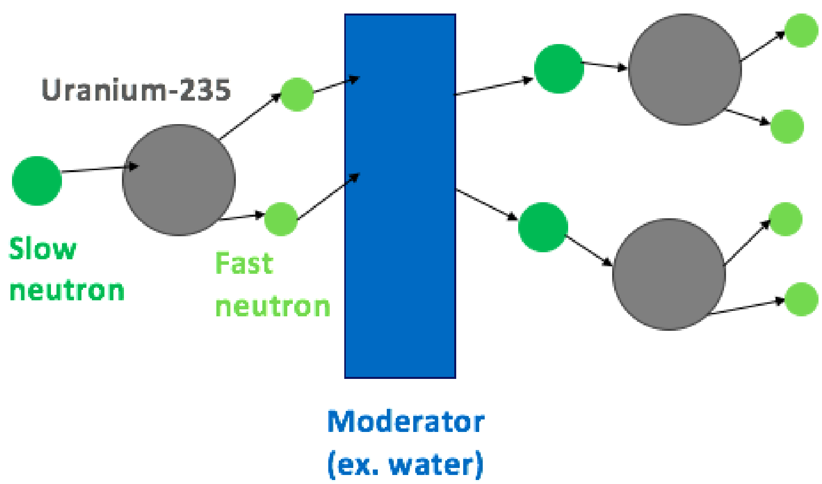


Understanding the basic principles of nuclear fission is the foundation for exploring all forms of nuclear reactor technology, including Small Modular Reactors. These principles explain why nuclear energy is so powerful, why it requires careful control, and why it remains a leading contender for providing reliable, low-carbon energy in the future.

1.2 Neutron moderation and thermal reactors.

When a nuclear fission reaction occurs, the newly released neutrons leave the splitting nucleus at tremendous speeds - often traveling at several percent of the speed of light. These are called *fast neutrons*. While they are highly energetic, fast neutrons are actually less likely to cause further fission in certain key nuclear fuels, especially uranium-235, which is the primary fuel used in most commercial reactors.

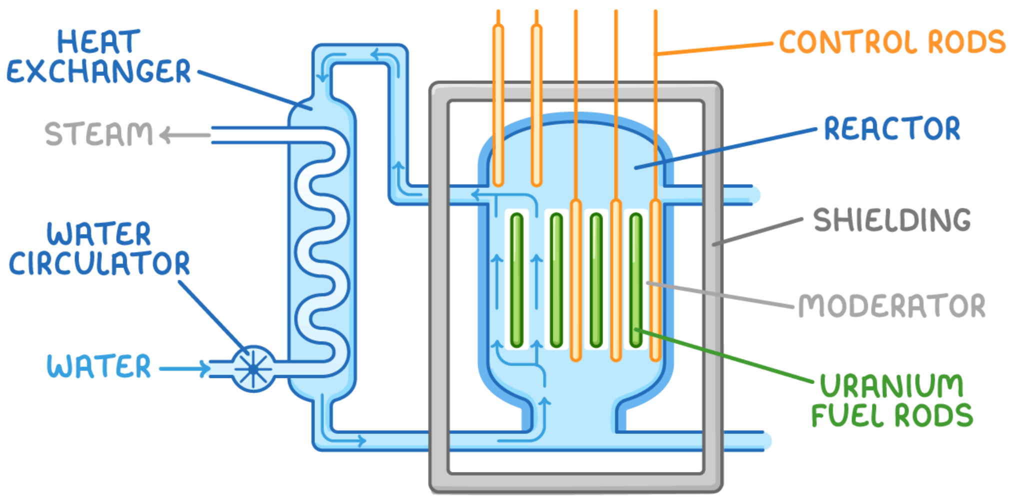
The reason lies in nuclear physics. The probability that a neutron will cause a fissile nucleus to split is measured by a quantity called the *fission cross section*. For uranium-235, this cross section is much larger for *slow* neutrons than for fast ones. Slow neutrons, often called *thermal neutrons*, move at speeds similar to the random motion of particles in a warm gas - roughly 2,200 meters per second at room temperature. This slower pace gives them more time to interact with the nucleus and be absorbed, greatly increasing the chance of fission.



Because of this property, most reactors are designed to slow down, or *moderate*, the fast neutrons produced by fission. This is the job of a **neutron moderator** - a material placed in and around the reactor core whose atoms are light enough to transfer a significant fraction of the neutron's energy in collisions, but which do not absorb too many neutrons.

Neutron moderation essentially consists of elastic and inelastic scattering of fast neutrons produced in a fission reaction by the nuclei in the surrounding media until their energy is reduced to a level where they are in thermal equilibrium with the media. Fractional loss of energy of a neutron per collision is related to the scattering angle and the mass number of the target nuclei. The lower the mass number of the moderating atom, the greater the fractional loss of energy per collision.

The most common moderators are **ordinary light water (H_2O)**, **heavy water (D_2O)**, and **graphite**. Light water, used in the vast majority of power reactors, is an excellent moderator but also has the drawback of absorbing some neutrons, meaning the reactor must use fuel enriched in uranium-235 to compensate. Heavy water, in which hydrogen atoms are replaced with the heavier isotope deuterium, absorbs far fewer neutrons, allowing reactors to operate with natural (unenriched) uranium. Graphite, a crystalline form of carbon, also absorbs very few neutrons and was used in some of the earliest large-scale reactors.



The process of moderation is essentially like playing billiards at the atomic scale. Imagine a fast neutron as a cue ball smashing into another ball. If the cue ball hits something with a similar mass - like hydrogen, which has almost the same mass as a neutron - it transfers a large fraction of its energy in just a few collisions. This means that hydrogen-rich materials, such as water, are excellent at slowing down neutrons quickly. Heavier atoms, like carbon in graphite, require more collisions but still accomplish the job without removing too many neutrons from the chain reaction.

Once neutrons are slowed to thermal energies, they are far more effective at causing additional fission events in uranium-235 or plutonium-239. This dramatically increases the efficiency of the chain reaction, allowing the reactor to operate steadily and produce energy in a controlled way.

This brings us to the concept of a **thermal reactor**, which is any nuclear reactor designed to use thermal neutrons to sustain its chain reaction. Almost all of the world's nuclear power plants today are thermal reactors, including pressurized water reactors (PWRs), boiling water reactors (BWRs), and heavy-water moderated CANDU reactors. In each of these, the moderator plays a critical role in making the most of the fuel and ensuring that the reactor can run reliably for long periods before the fuel needs to be replaced.

The design of a thermal reactor must carefully balance the presence of the moderator with other key factors. If the moderator absorbs too many neutrons, the chain reaction might stall. If there is too little moderation, the neutrons remain too fast and the fission probability drops. The geometry of the fuel rods, the arrangement of the moderator, and the temperature of the system all influence how effectively moderation occurs. Temperature is especially important: as the moderator gets hotter, it becomes less dense, and neutrons travel farther between collisions. This change can slightly reduce moderation and, in many reactor designs, provides a natural *negative feedback* that helps regulate power output - a useful safety feature.

Moderation is not just about efficiency; it is also central to reactor safety and stability. By ensuring that most neutrons are slowed to the right energies, the reactor can be designed to remain in a controlled, self-sustaining state without sudden, dangerous increases in reactivity. This principle has guided nuclear engineers for decades and is one of the reasons modern thermal reactors have such strong safety records when operated properly.

In contrast, there are also **fast reactors**, which deliberately avoid moderation and use fast neutrons to sustain the chain reaction. These reactors can use different fuels, such as uranium-238 or even thorium, and have the potential to produce more fuel than they consume. While fast reactors are an exciting part of nuclear research and development, the vast majority of the reactors currently operating in the world, including many proposed Small Modular Reactors, are based on the thermal principle because of its proven reliability and relatively straightforward engineering.

Neutron moderation may seem like a simple idea - just slow the particles down, but in reality it is the product of decades of careful study, experimentation, and design. Without moderation, the efficiency of most nuclear reactors would drop dramatically, making them far less practical. With it, nuclear energy becomes one of the most concentrated, controllable, and dependable sources of power we have, setting the stage for more advanced designs like the SMRs that will be explored in later chapters.

1.3 Reactor kinetics and control mechanisms.

Once we understand the basics of nuclear fission and how neutron moderation makes the chain reaction more efficient, the next step is to explore how this reaction is managed inside a reactor. Nuclear fission is a powerful process, but without precise control, it could either die out completely or grow too quickly to handle safely. The science of reactor kinetics - how the chain reaction changes over time, and the engineering of control mechanisms are at the heart of making nuclear energy practical and safe.

Reactor kinetics begins with the concept of the multiplication factor, often symbolized by k. This number tells us how the neutron population changes from one generation to the next. If k equals exactly 1, the reactor is in a critical state, meaning the chain reaction is steady - each fission event, on average, causes exactly one more. This is the ideal condition for producing a constant level of heat and, therefore, steady electricity output. If k is greater than 1, the reactor is supercritical - the neutron population and power level are rising. If k is less than 1, the reactor is subcritical, and the chain reaction is dying out.

Maintaining the desired value of k is one of the primary goals of reactor operation, and it requires a deep understanding of how neutrons behave in the system. This behavior is influenced by many factors: the arrangement of fuel and moderator, the temperature of the core, the presence of any materials that absorb neutrons, and the buildup of fission products over time.

One important concept in reactor kinetics is the presence of delayed neutrons. Most neutrons produced in fission are “prompt” neutrons, released within a tiny fraction of a second after the nucleus splits. But a small fraction - less than 1 percent, are delayed, coming from the radioactive decay of certain fission fragments seconds or even minutes later. While this fraction seems small, it is crucial for control. Delayed neutrons slow down the pace of changes in reactor power, giving operators and automatic systems time to respond to fluctuations and adjust control systems. Without delayed neutrons, a reactor would be much harder, if not impossible, to control safely.

So how is the chain reaction actually controlled? The most well-known method is the use of control rods - long, slender rods made of materials that readily absorb neutrons, such as boron, silver-indium-cadmium alloys, or hafnium. By inserting these rods deeper into the reactor core, more neutrons are absorbed before they can cause fission, reducing k and lowering power. By withdrawing the rods, fewer neutrons are absorbed, allowing k to increase. In emergency situations, control rods can be fully inserted almost instantly, a process known as a scram, which rapidly shuts down the reactor.

Another way to influence reactivity is by adjusting the moderator. In some reactor designs, especially those using heavy water or graphite, the moderator's position or amount can be changed to alter how effectively it slows down neutrons. More moderation increases the chance of fission in uranium-235, while less moderation reduces it.

Temperature itself is a natural control mechanism, providing what engineers call reactivity feedback. As the reactor gets hotter, the fuel and moderator often expand or change density in ways that slightly reduce the neutron population. For example, in water-moderated reactors, higher water temperatures cause the water to become less dense, which means neutrons travel farther before colliding with hydrogen atoms, reducing the moderation effect. This is known as a negative temperature coefficient of reactivity and is one of the most important safety features of modern reactors, as it helps prevent overheating.

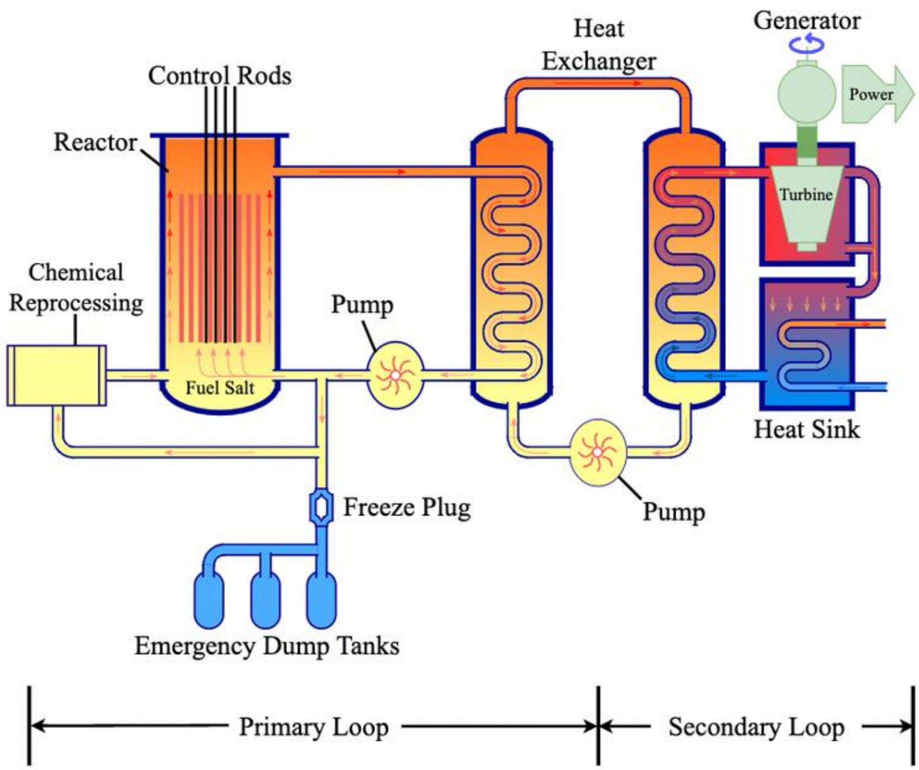
Chemical adjustments to the coolant or moderator can also be used for fine-tuning. Many reactors dissolve boric acid in the coolant water. Boron atoms are excellent neutron absorbers, so changing the concentration of boron changes the reactivity of the core. This method is often used for slow, long-term adjustments in pressurized water reactors, complementing the faster mechanical movement of control rods.

Reactor kinetics and control are not just about keeping the chain reaction going - they are also about ensuring that it behaves predictably under all operating conditions. This means anticipating how the reactor will respond to changes in load demand, fuel burnup, coolant flow, or even the buildup of certain fission products that act as neutron absorbers, known as neutron poisons. One famous example is xenon-135, a fission product with an extremely high neutron absorption cross section. After a sudden reactor shutdown, xenon-135 levels can temporarily rise, making it harder to restart the reactor until the isotope decays. This phenomenon, known as xenon poisoning, is a classic challenge in reactor operation and must be carefully managed.

The engineering of control systems, both mechanical and electronic, has advanced greatly over the decades. Modern reactors are equipped with layers of safety systems, from computer-controlled rod drives to passive mechanisms that shut down the reactor if certain physical conditions are exceeded, without needing any external power or operator action. This level of precision and redundancy is one of the reasons nuclear power has maintained a strong safety record when properly managed.

In the context of Small Modular Reactors, reactor kinetics and control mechanisms are just as important, though often implemented with even greater reliance on passive safety features and simplified designs. Many SMRs are designed so that their physical characteristics naturally stabilize the reaction, even without operator intervention. This makes them not only more flexible in deployment but also more inherently safe - a point that will be explored in later chapters.

Understanding the principles of reactor kinetics and the various control mechanisms used to manage the chain reaction is essential for anyone working in nuclear energy. These are the tools and concepts that allow us to harness the immense power of the atom not as a destructive force, but as a reliable and controllable source of clean energy for the modern world.



Chapter 2. Small Modular Reactors (SMRs)

2.1 Overview of SMRs and their role in the energy sector.

Small Modular Reactors, or SMRs, represent a new generation of nuclear power technology designed to be more flexible, scalable, and cost-effective than traditional large reactors. Unlike conventional nuclear power plants, which can require a decade or more to design and build, SMRs are conceived as compact, factory-manufactured units that can be transported to a site and installed much more quickly. Their modular nature means that energy producers can start with a single reactor and add more modules as demand grows, making them particularly attractive for countries or regions with limited grid capacity or fluctuating energy needs.

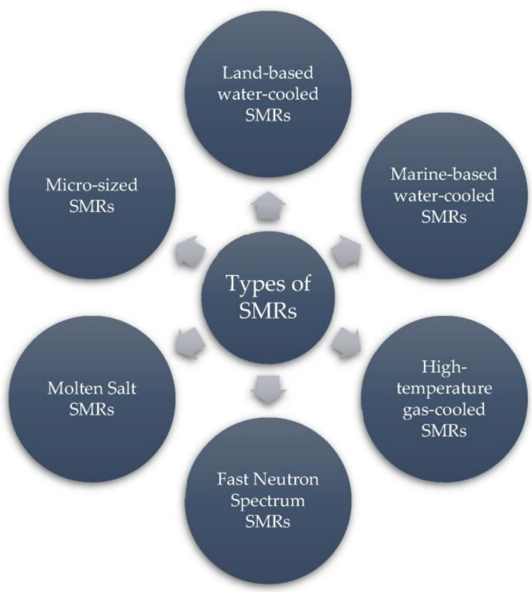
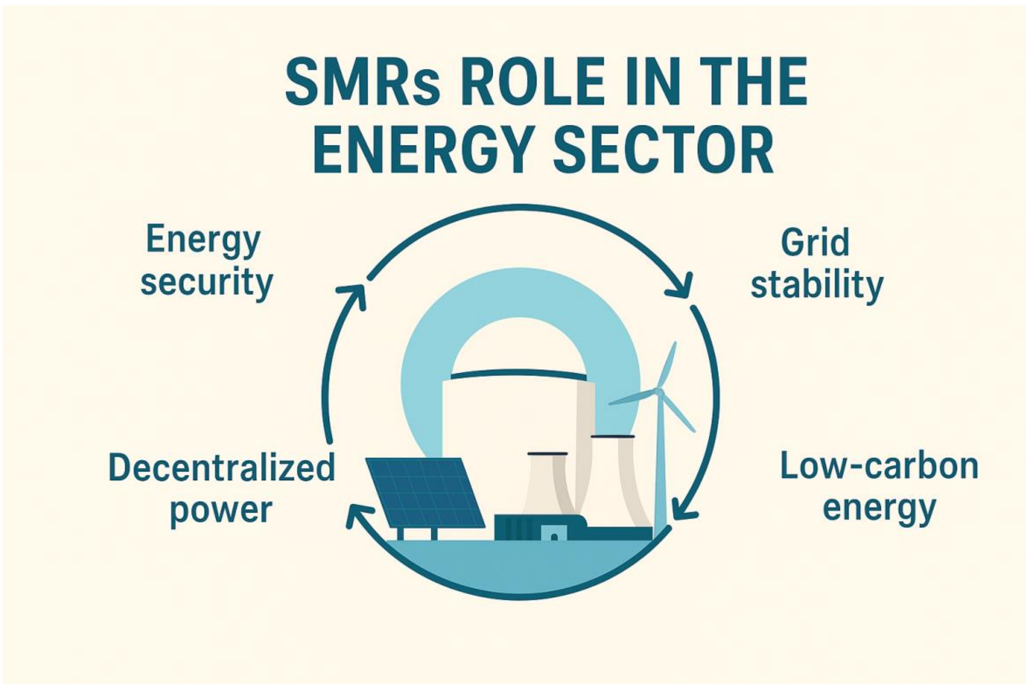


Figure 5. SMR classification scheme (IAEA)

One of the defining advantages of SMRs is their size. Typically producing between 50 and 300 megawatts of electricity per module, they can serve communities, industrial facilities, or even remote locations where a large power plant would be impractical. Their smaller footprint also allows for installation in areas where space is limited or where infrastructure constraints would make a large reactor unfeasible.

From a safety standpoint, SMRs often incorporate advanced passive safety systems that rely on natural processes, such as gravity or convection, rather than complex mechanical or electrical systems. This greatly reduces the risk of accidents and enhances public confidence in nuclear technology. In addition, the use of standardized designs and modular construction allows for better quality control during manufacturing, which can further improve operational safety and reliability.



For regions seeking to reduce dependence on fossil fuels, SMRs offer a pathway to cleaner energy without the massive upfront investment required for conventional nuclear plants. By lowering both financial and logistical barriers, SMRs have the potential to democratize access to nuclear power, enabling more nations to benefit from its stable, low-carbon output. As technology matures and deployment scales up, SMRs may well become a cornerstone of the global clean energy portfolio.

2.2 Advantages of SMRs compared to traditional large reactors.

The appeal of Small Modular Reactors lies not only in their technological novelty but in the concrete advantages they offer over conventional large-scale nuclear power plants. While large reactors have been the backbone of nuclear electricity generation for decades, they are complex, expensive to build, and often require significant time before they can begin delivering power. SMRs aim to address these challenges while retaining the benefits of nuclear energy - high reliability, low-carbon output, and long operating lifetimes.

Perhaps the most obvious difference is in size and scalability. A single large reactor can produce over 1,000 megawatts of electricity, which is ideal for supplying power to vast, interconnected grids. However, for smaller or less developed grids, this is often too much capacity all at once. SMRs, typically ranging from 50 to 300 megawatts per unit, allow energy providers to start with a manageable amount of generation and expand gradually as demand increases. This modular approach reduces financial risk because each new module can be funded and built independently, instead of committing to one massive project upfront.

Construction timelines are another significant advantage. Large nuclear plants often take ten years or more to design, license, and build, partly because each one is essentially a unique, site-specific project. SMRs are designed to be manufactured in factories, transported to the installation site, and assembled more like prefabricated building components. This not only shortens the time from investment to operation but also improves quality control by standardizing production in a controlled environment.

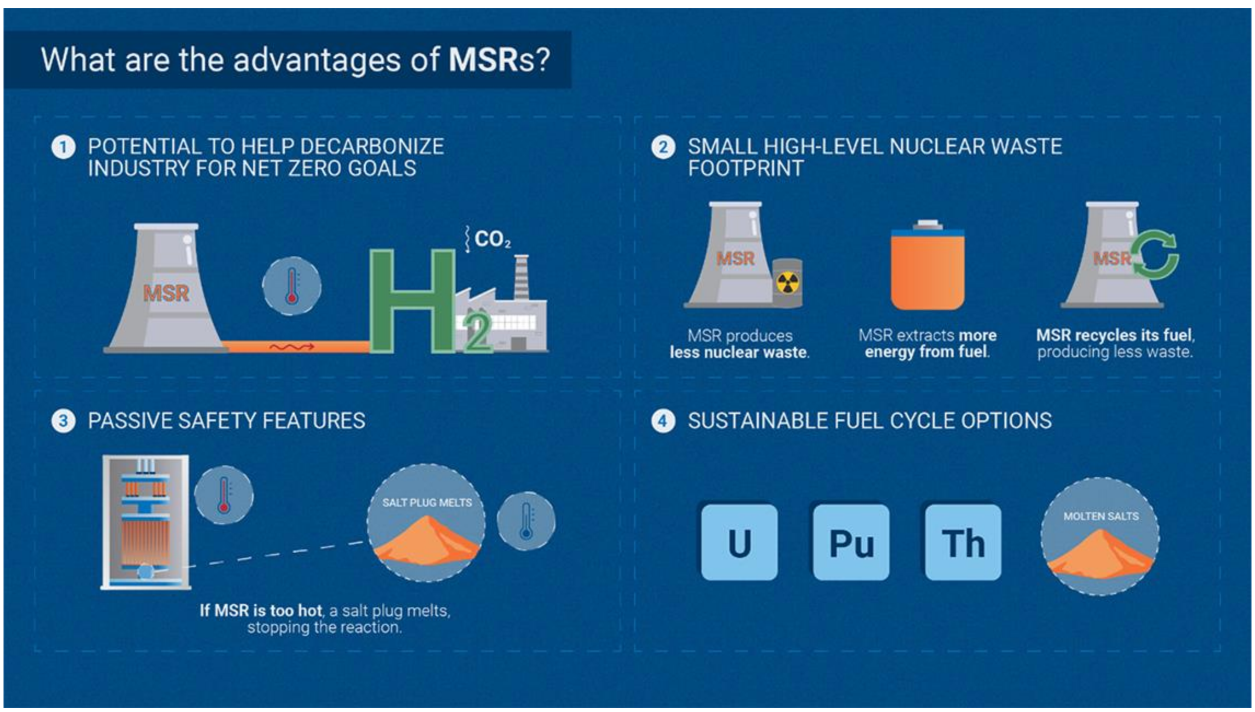
Safety is another area where SMRs have a strong edge. Many designs incorporate passive safety systems that do not require external power or operator intervention to function in an emergency. In some cases, the reactor can safely shut down and cool itself for days or even weeks without human input. The smaller size of the reactor core also means there is less heat to manage in the event of a problem, further reducing potential risks.

Flexibility in siting is a practical advantage. Large nuclear plants require vast amounts of land, robust cooling water supplies, and heavy infrastructure. SMRs can be installed in more diverse environments - on smaller sites, in industrial zones, near remote communities, or even on barges for floating power stations. This flexibility opens up opportunities for nuclear energy in places where it was previously impractical.

Economically, SMRs can be more accessible to a wider range of countries and utilities. Their smaller capital requirements make financing easier, especially for nations with limited budgets or developing power markets. Over time, mass production could drive costs down further, making SMRs competitive not only with traditional nuclear plants but also with some fossil fuel and renewable options.

Finally, SMRs open the door to a broader set of applications beyond electricity generation. Because of their size and design, they can supply heat for industrial processes, desalinate seawater for fresh water production, or generate hydrogen for use as a clean fuel. This versatility strengthens their role in the transition toward a more sustainable and diversified energy mix.

In short, SMRs offer a combination of scalability, safety, flexibility, and economic accessibility that makes them a promising addition to the energy landscape. They are not intended to replace all large reactors, but to complement them - filling roles and meeting needs that traditional plants cannot always address effectively.



2.3 Current global status and deployment of SMRs.

Small Modular Reactors are no longer just theoretical designs on paper, but they are steadily moving from concept to reality in various parts of the world. While still in the early stages of commercial deployment, SMRs have gained significant attention from governments, industry leaders, and research institutions as a strategic part of the future energy mix. Several prototypes, demonstration units, and early commercial reactors are already being built or operated, offering valuable lessons for wider adoption.

In the United States, several SMR projects are in advanced stages of planning and licensing. The most notable is NuScale Power's VOYGR design, which has received U.S. Nuclear Regulatory Commission (NRC) design certification - making it the first SMR design approved in the country. A planned multi-module NuScale plant in Idaho is expected to supply power to several utilities in the western United States, serving as a key demonstration for commercial SMR deployment.

Other countries, including the United Kingdom, South Korea, are actively pursuing SMR projects, each tailored to their national energy needs. The UK's Rolls-Royce SMR program is leveraging the nation's aerospace and engineering expertise to create a reactor optimized for rapid manufacturing and deployment.

International collaboration is another defining feature of SMR development today. Many nations are working together through organizations such as the International Atomic Energy Agency (IAEA) to share research, harmonize safety standards, and develop licensing frameworks that could accelerate cross-border deployment.

While commercial-scale SMR fleets have yet to become widespread, the pace of development suggests that the 2030s could see a significant increase in operational units worldwide. As demonstration projects prove their performance, economics, and safety, SMRs are likely to become an important complement to renewables, large nuclear plants, and other clean energy sources.

Chapter 3. Design and Technology of SMRs

3.1 Types of SMRs: Light Water Reactors (LWRs), High-Temperature Gas-Cooled Reactors (HTGRs), Molten Salt Reactors (MSRs), and others

Small Modular Reactors are not defined by a single design or technology; rather, they represent a family of advanced nuclear systems, each with unique characteristics, strengths, and potential applications. While all SMRs share the advantages of compactness, modular construction, and enhanced safety features, they differ in how they generate and manage heat, what kind of fuel they use, and how they transfer that heat to produce electricity or industrial energy. Understanding the major SMR types helps explain why this technology can serve such a diverse range of needs.

Light Water Reactors (LWRs)

The Light Water Reactor is the most common type of nuclear power plant operating today, and many SMR designs build upon this proven foundation. LWRs use ordinary water as both coolant and neutron moderator, slowing down neutrons to sustain the fission chain reaction. In SMR form, these reactors can be pressurized water reactors (PWRs) or boiling water reactors (BWRs), but scaled down for easier manufacturing and deployment. Their key advantage is familiarity: decades of operational experience, established regulatory frameworks, and a global supply chain make LWR-based SMRs relatively straightforward to license and operate. This familiarity also eases public acceptance, as the underlying technology is already well understood.

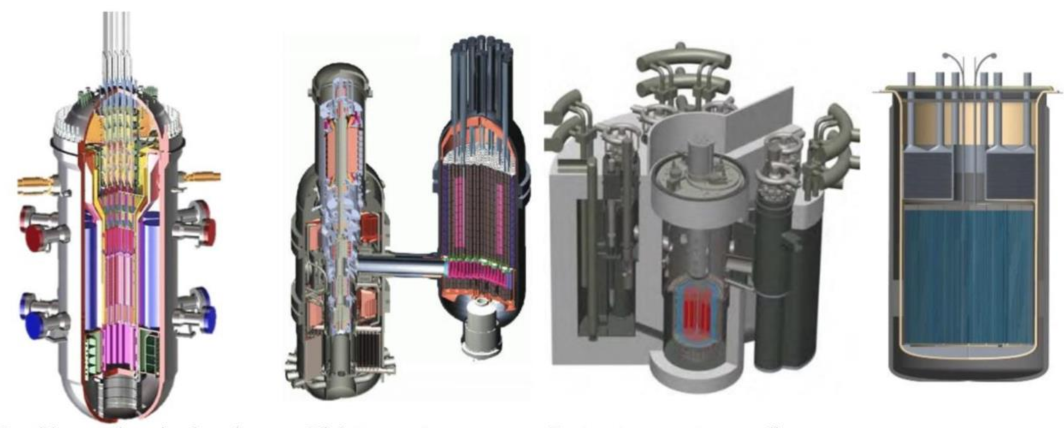
Molten Salt Reactors (MSRs)

Molten Salt Reactors take a very different approach, using liquid fluoride or chloride salts as both coolant and, in some designs, as the fuel carrier itself. Operating at atmospheric pressure and high temperatures, MSRs offer significant safety and efficiency advantages. The liquid fuel form in certain designs allows for continuous removal of fission products and refueling without shutting down the reactor. This technology also opens the door to using thorium as a fertile material, potentially expanding the world's nuclear fuel resources. MSR-based SMRs are still largely in the experimental or prototype stage, but their ability to operate at high efficiency, produce industrial heat, and reduce certain types of nuclear waste makes them a promising option for future deployment.

Other Emerging SMR Types

Beyond LWRs, HTGRs, and MSRs, several other innovative SMR designs are under development. Lead-cooled fast reactors (LFRs) use molten lead or lead-bismuth eutectic as coolant, offering excellent heat transfer and high-temperature operation. Sodium-cooled fast reactors (SFRs) have a long history in experimental settings and promise high fuel efficiency and the ability to recycle spent nuclear fuel. Microreactors—producing less than 50 MW—are also gaining attention, particularly for defense installations, Arctic communities, and off-grid industries. These ultra-compact units can be transported by truck or even aircraft, and operate for many years without refueling.

Each SMR type comes with its own balance of maturity, cost, efficiency, and suitability for specific tasks. Some are ready for near-term deployment, leveraging existing reactor technology, while others push the boundaries of nuclear innovation and may take longer to reach commercial readiness. Together, they demonstrate the flexibility and adaptability of the SMR concept—one of the main reasons it is attracting such broad international interest.



Land-base and marine-based Water-cooled reactor technology | High temperature gas-cooled reactors | Fast neutron spectrum, sodium- or other liquid metal-cooled reactors | Molten salt reactors

3.2 Key components: Reactor core, coolant systems, containment structures

Although Small Modular Reactors vary widely in design, fuel type, and operating principles, they all share a set of essential components that enable them to produce power safely and reliably. At the heart of every SMR lies the reactor core, surrounded by a coolant system to remove heat, and enclosed within containment structures to ensure that radiation and radioactive materials remain securely isolated from the environment. Understanding these components is essential to appreciating how SMRs work and why they are considered a safe and viable energy source.

Reactor Core

The reactor core is the central part of the SMR where nuclear fission occurs. It contains the fuel—typically uranium, though advanced designs may use thorium, mixed-oxide (MOX) fuels, or specialized fuel forms such as TRISO particles. When a fissile nucleus absorbs a neutron, it splits into smaller nuclei, releasing both energy and more neutrons. This chain reaction, if carefully controlled, produces a steady heat output that can be harnessed for electricity or other applications.

In SMRs, the core is often more compact than in traditional large reactors, enabling closer integration of safety systems and sometimes allowing the entire core and coolant loop to be housed in a single pressure vessel. The compactness also supports modular manufacturing, where cores are built in factories under strict quality control before being shipped to their operating site.

Coolant Systems

The coolant system is responsible for transferring heat away from the reactor core and delivering it to the power conversion system, where it is transformed into electricity or used for industrial purposes. The choice of coolant varies by SMR design: light water in LWR-based SMRs, helium in HTGRs, molten salts in MSRs, and liquid metals such as lead or sodium in certain advanced reactors.

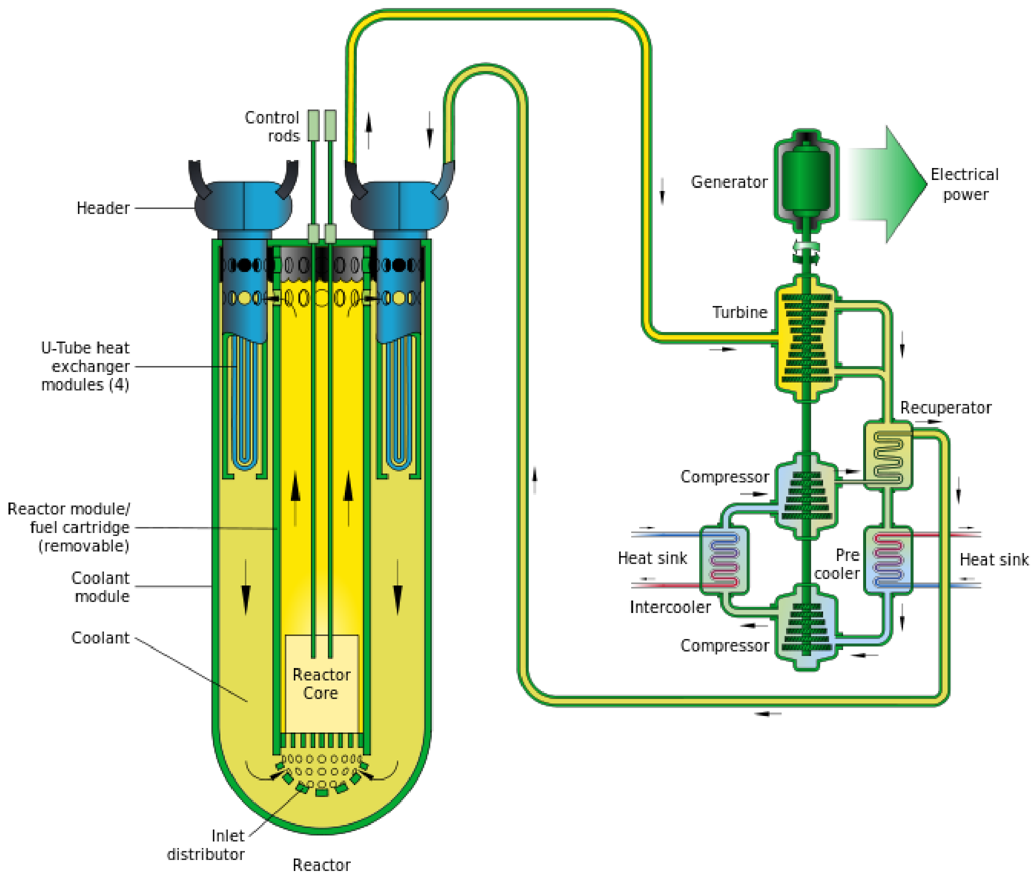
A major advantage of many SMR designs is the inclusion of passive cooling features, where natural convection or gravity can circulate the coolant without relying on mechanical pumps. This significantly improves safety by ensuring that even if power is lost, the reactor can continue to remove decay heat. Some SMRs also use an integral reactor vessel, where the core, steam generators, and sometimes pressurizers are all contained within one sealed unit, reducing the risk of leaks and simplifying maintenance.

Containment Structures

The containment structure is the final physical barrier that prevents the release of radioactive materials into the environment. It encloses the reactor vessel and associated systems, shielding workers and the public from radiation during normal operation and in the unlikely event of an accident.

In SMRs, containment designs often take advantage of the reactor's small size, allowing for more robust structures without excessive cost. Some designs even place the entire reactor module underground, providing natural protection against both environmental hazards and external threats. Advanced containment concepts may combine reinforced concrete with steel liners, or use double-wall containment for additional safety.

Together, the reactor core, coolant systems, and containment structures form the technological backbone of SMRs. Their integration in a compact, factory-built module not only streamlines construction and reduces cost but also enhances safety and reliability. By combining tried-and-tested engineering principles with innovative design features, SMRs are positioned to meet diverse energy needs while maintaining the highest standards of nuclear safety.



3.3 Modular construction and scalability

One of the defining characteristics of Small Modular Reactors is captured in the name itself: they are modular. This concept goes far beyond simply making reactors smaller. It represents a shift in how nuclear plants are designed, built, and expanded over time, aiming to reduce costs, shorten construction schedules, and give operators greater flexibility in meeting energy demands.

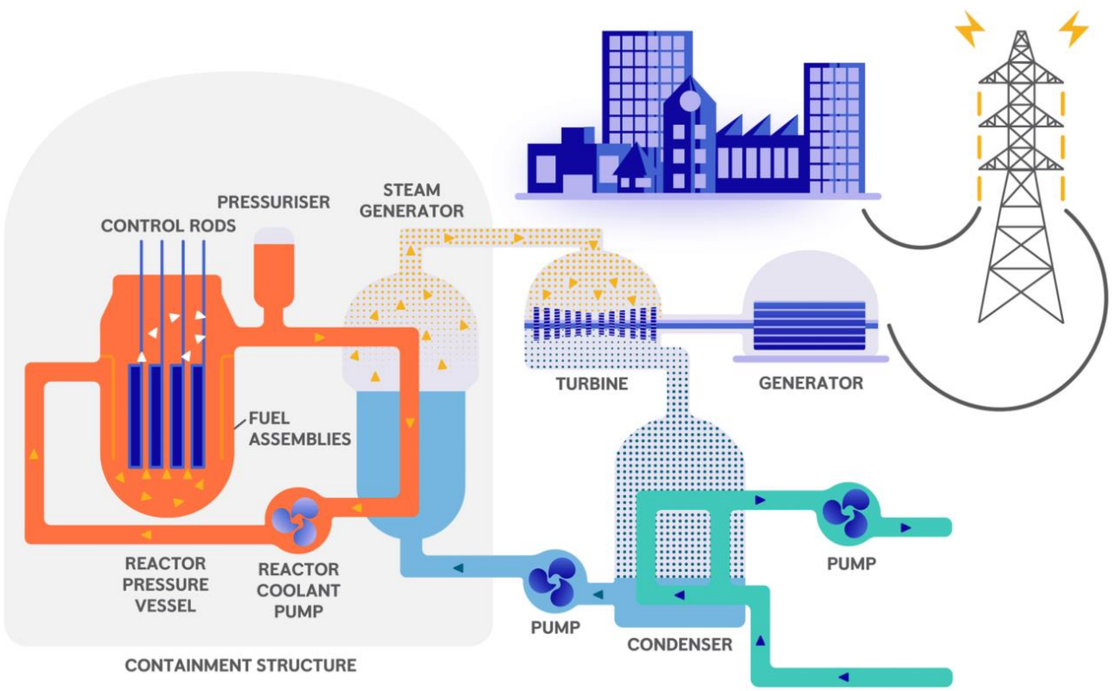
In a modular construction approach, the reactor and its supporting systems are manufactured in a controlled factory environment, often as large, transportable sections or complete sealed modules. These factory-built components are then shipped to the installation site, where they can be assembled with much less on-site construction work compared to traditional large nuclear plants. This approach offers several advantages. First, it allows for higher quality control, since components are produced under standardized conditions with consistent oversight. Second, it reduces the potential for costly delays caused by weather, supply chain disruptions, or site-specific challenges. Third, it allows for parallel activities—while the site is being prepared, the reactor modules are being built elsewhere—shortening the overall timeline from project initiation to power generation.

Scalability is another key benefit of this approach. Instead of committing to a massive, multi-gigawatt plant all at once, utilities or governments can start with a single SMR unit and add more modules as demand grows or financing becomes available. For example, a single SMR might serve as the initial power source for a small community or industrial complex, with additional modules added later to supply electricity to a growing population or expanding facilities. This incremental expansion helps spread out capital costs, making nuclear energy more accessible to countries and organizations that cannot commit to the high upfront investment of a large reactor.

The modular philosophy also opens opportunities for diverse deployment configurations. Multiple SMRs can be combined in one site to form a "nuclear park," sharing infrastructure such as cooling systems, control rooms, and grid connections. Alternatively, they can be distributed across multiple locations, bringing reliable electricity to remote or isolated regions without the need for large transmission infrastructure.

In addition to electrical generation, scalability allows SMRs to be tailored to specific applications. For instance, one site could operate a few modules for grid power and dedicate others to industrial heat production, desalination, or hydrogen generation. This flexibility makes SMRs attractive in integrated energy systems that combine nuclear with renewable sources, ensuring both stability and adaptability in the power supply.

By combining factory-based manufacturing with a build-as-you-need expansion strategy, modular construction and scalability position SMRs as a practical and versatile solution for the energy challenges of the future. They break away from the traditional "all or nothing" model of nuclear power and instead offer a step-by-step path toward reliable, low-carbon energy.



Chapter 4. Safety and Security of SMRs

4.1 Inherent safety features of SMRs

Safety is the foundation of all nuclear power plant design, and the emergence of Small Modular Reactors (SMRs) represents not only a reduction in reactor size but also a fundamental shift in safety philosophy. Traditional reactors have relied heavily on engineered, active systems - pumps, control electronics, and rapid operator intervention - to maintain safe conditions. While SMRs still employ these engineered protections, they also build safety directly into the physics, geometry, and material properties of the system. These are known as inherent safety features - characteristics that function automatically to maintain stability, without the need for external action.

One of the most important inherent safety attributes of SMRs is their small core size. Because the total heat generated during operation is lower than in large reactors, the amount of residual decay heat following a shutdown is also significantly reduced. In the event of a cooling interruption, this smaller heat load can be removed more easily through natural processes such as conduction, convection, and thermal radiation, rather than requiring high-capacity active cooling. This gives operators valuable time to respond and reduces the probability of fuel overheating.

Closely related to small core size is the fact that many SMRs operate with a low power density. Power density refers to the amount of heat produced per unit volume of the reactor core. Lower power density means the generated heat is distributed over more mass, allowing the system to absorb and dissipate temperature increases more slowly. This naturally extends the safe grace period in which temperatures remain within acceptable limits after shutdown, even without active cooling.

Another central aspect of SMR inherent safety lies in their negative temperature and void coefficients. In reactors with a negative temperature coefficient, an increase in coolant temperature leads to a natural decrease in reactivity. In water-moderated SMRs, heating causes the water to expand, reducing its density and its ability to slow down neutrons. This makes the nuclear chain reaction less efficient, automatically lowering the power output. Similarly, in designs with a negative void coefficient, the formation of steam bubbles in the coolant reduces moderation and slows the reaction. These effects provide a built-in, self-regulating mechanism that stabilizes reactor power without human or mechanical intervention.

Many SMRs also rely on passive heat removal through natural circulation. In such systems, heated coolant becomes less dense and rises, while cooler coolant descends to replace it, creating a continuous flow driven entirely by buoyancy forces. This thermosiphon effect allows decay heat to be removed without the use of pumps, electrical power, or moving parts. As long as there is a heat sink - such as a water pool or atmospheric cooling surface - the reactor can maintain safe temperatures indefinitely, even during a complete loss of external power.

The physical arrangement of components also contributes to inherent safety. Several SMR designs use an integral reactor vessel, where the core, steam generators, pressurizer, and primary coolant loop are all housed within a single sealed structure. This greatly reduces the number of external connections and piping systems that could potentially leak, and it also provides a compact, robust containment that is easier to monitor and protect.

In some designs, the entire reactor module is installed underground or underwater. An underground location offers natural shielding against radiation and protection from external hazards such as severe weather, aircraft impact, or deliberate attack. In submerged installations, such as offshore SMRs, the surrounding water serves both as a passive heat sink and as a physical security barrier.

Finally, SMRs inherently carry a smaller inventory of radioactive material compared to large reactors. This not only limits the maximum possible release in the event of an accident, but also allows for unique operational strategies, such as replacing the core as a sealed module, thereby reducing the handling of spent fuel on-site.

All of these inherent safety characteristics work together to form the first line of defense in SMR safety philosophy. They do not replace engineered safety systems, but rather complement them, creating a layered approach - often referred to as defense in depth, where natural physical responses work alongside mechanical and procedural safeguards to ensure that accidents are both highly unlikely and easily contained if they do occur.

4.2 Passive safety systems

Passive safety systems are an essential feature of modern Small Modular Reactor (SMR) design, complementing the inherent safety characteristics built into the reactor's physics and materials. While inherent safety features act automatically as a consequence of the reactor's physical design, passive safety systems are engineered mechanisms that operate without the need for active controls, external electrical power, or human intervention. Instead, they rely on natural forces such as gravity, buoyancy, and heat transfer to maintain safe conditions under both normal and accident scenarios.

In conventional large nuclear plants, safety systems often depend on electrically powered pumps, valves, and control circuits to keep the reactor stable and cool in emergencies. This dependency can create vulnerabilities if the power supply is interrupted, as was observed in past incidents where loss of power impaired cooling. SMRs address this challenge by using passive safety systems capable of functioning indefinitely or for extended periods without any external support. This resilience is particularly valuable in scenarios where a facility might be isolated from grid power for days or even weeks.

One of the most fundamental passive safety mechanisms in SMRs is passive decay heat removal. After a reactor shuts down, the nuclear fission process stops, but the fuel continues to produce heat from the decay of radioactive fission products. In many SMR designs, this residual heat is transferred away from the reactor core through natural circulation of the coolant. The heated coolant rises naturally toward heat exchangers, where it releases heat to a secondary medium - often a large pool of water or an atmospheric air-cooled condenser - before cooling and descending back toward the reactor core. This circulation is continuous and requires no pumps or moving parts, making it highly reliable even during complete station blackouts.

Gravity plays a central role in several passive safety functions. For instance, in some designs, emergency coolant or borated water for shutdown reactivity control is stored in elevated tanks above the reactor vessel. If additional cooling is needed, valves can open automatically, and gravity will drive the coolant downward into the reactor core without any pumping equipment. The same principle can apply to containment cooling systems, where water stored in elevated reservoirs flows down over the containment walls to remove heat in the event of high internal temperatures.

Thermal expansion and material properties are also leveraged to trigger safety responses without electrical or mechanical signals. In some SMRs, rising temperatures cause metal components to expand or fusible plugs to melt, mechanically opening safety valves or initiating coolant injection. This approach ensures that critical safety actions occur automatically in response to the actual thermal conditions inside the reactor, not just to external sensors or operator commands.

Another widely adopted passive feature is the use of large pools of water, often located inside or adjacent to the containment structure, which serve both as an immediate heat sink and as a radiation shield. In the event of an accident, these pools can absorb and dissipate heat for several days or even weeks without the need for replenishment. Some SMR designs submerge the reactor pressure vessel directly into such pools, ensuring that the core is constantly surrounded by a passive cooling medium.

Air is another important passive cooling medium for certain SMR configurations. Systems that incorporate natural draft air cooling use temperature-induced density differences to draw cooler outside air in through ducts, pass it over heat exchangers, and then allow the warmed air to rise and exit through exhaust chimneys. This process continues indefinitely as long as there is a temperature difference between the reactor systems and the surrounding environment, eliminating dependence on powered fans or compressors.

Passive safety systems are also integrated into containment and isolation strategies. In some SMRs, the containment structure itself is designed to be partially or fully underground, surrounded by soil or water that passively absorbs and dissipates heat. This configuration reduces the likelihood of containment failure during severe accidents and limits environmental impact even if multiple active systems are unavailable.

The underlying philosophy behind passive safety systems in SMRs is to ensure that the reactor will naturally move toward a safe, stable condition without requiring rapid human response or complex active interventions. By exploiting physical laws that operate reliably under all conditions, SMRs achieve a high level of resilience against both foreseeable and unforeseen events. In practice, this means that even in the most extreme scenarios—loss of power, loss of communication, natural disasters, or operational errors—the reactor's fundamental safety functions can be maintained until active measures are restored or the situation is resolved.

4.3 Nuclear security and non-proliferation concerns

Nuclear security and non-proliferation are critical considerations in the development, deployment, and operation of Small Modular Reactors (SMRs). While these reactors are smaller in scale and often benefit from enhanced safety features compared to traditional large nuclear plants, they remain part of the nuclear fuel cycle and therefore require rigorous measures to prevent the misuse of nuclear materials, unauthorized access, or diversion for weapons purposes. The dual challenge is to make SMRs widely accessible as a clean energy solution while ensuring that their deployment does not contribute to the spread of nuclear weapons technology or materials.

From a security standpoint, SMRs must be protected against both physical and cyber threats. Physical security involves preventing sabotage, theft of nuclear materials, or attacks that could lead to the release of radioactive substances. The compact and often modular nature of SMRs can provide some advantages in this area: their smaller size allows for highly integrated and robust containment structures, and many designs place the reactor underground or underwater, creating natural barriers to intrusion. However, SMRs also present unique challenges, especially if they are deployed in remote or less secure regions where traditional security infrastructure is limited. In such cases, security strategies must be tailored to the site's specific vulnerabilities, ensuring continuous monitoring and rapid response capability.

Cybersecurity is equally important in the modern nuclear landscape. Even though many SMR designs aim to minimize reliance on digital control systems for core safety functions, operational monitoring, grid integration, and auxiliary systems still depend on computerized controls. This creates potential entry points for malicious actors. Ensuring the resilience of these systems requires not only robust technical safeguards - such as secure network architectures, encryption, and intrusion detection - but also strong organizational policies and continuous personnel training.

On the non-proliferation side, SMRs must comply with international safeguards administered by bodies such as the International Atomic Energy Agency (IAEA). These safeguards include material accounting, containment, and surveillance measures that allow inspectors to verify that nuclear fuel is being used exclusively for peaceful purposes. The challenge with SMRs is that their deployment model may differ from traditional large plants. Some designs propose factory-fueled modules that operate for many years without refueling, after which the entire reactor module is returned to the manufacturer or a centralized facility. While this approach can reduce proliferation risks by limiting on-site fuel handling, it requires careful oversight during transport and storage of both fresh and spent fuel to ensure no diversion occurs.

Fuel type is another factor influencing proliferation risk. Low-enriched uranium (LEU), which is below 20% enrichment in the isotope uranium-235, is the preferred fuel for most SMR designs, as it is unsuitable for direct use in weapons. However, some advanced SMR concepts may employ fuels with higher enrichment levels or alternative fissile materials such as uranium-233 bred from thorium or plutonium from recycled fuel. In these cases, additional safeguards and transparency measures are essential to reassure the international community that these materials are not being diverted for military purposes.

Remote deployment, one of the key potential advantages of SMRs, can also present proliferation concerns. In isolated regions, regulatory oversight and physical protection may be more difficult to maintain, especially if political stability is uncertain. This makes robust, tamper-proof design features particularly valuable - sealed reactor cores, self-contained fuel cycles, and built-in monitoring technologies can all help mitigate these risks.

Ultimately, maintaining nuclear security and preventing proliferation in the SMR era will depend on a combination of technical innovation, strong international cooperation, and consistent regulatory enforcement. The goal is to create a deployment model where SMRs can fulfill their promise as a clean, flexible energy source while ensuring that their presence in any country or region does not undermine global non-proliferation objectives. As the technology matures and spreads, integrating security and safeguard measures from the earliest stages of design will be essential to building public trust and international confidence in SMRs as a safe and responsible part of the future energy mix.

Chapter 5. Economic and Environmental Aspects

5.1. Cost Analysis and Economic Feasibility of Small Modular Reactors

The development of small modular reactors (SMR) technologies is one of the most promising areas of modern nuclear power engineering. Unlike traditional large-capacity nuclear power plants, SMRs have a number of unique economic characteristics that require detailed analysis to understand their commercial potential.

Over 90% of the world's power plants are low-power - less than 300 MW. Low-power nuclear power plants do not require large sites for reactors, huge capital costs for construction, they are safer, since they use less nuclear fuel than large nuclear power plants. Currently, several commercial projects of low-power nuclear power plants are being developed in the world.

The economic evaluation of SMRs projects includes a comprehensive analysis of capital and operating costs, as well as consideration of factors affecting the total life cycle cost of a power plant. This Chapter is devoted to a systematic study of the main economic aspects of the construction and operation of small modular reactors.

SMRs Financial Cost Structure

The total financial cost of developing and introducing SMRs technology into production with the goal of becoming an industry component in the long term consists of capital and operating costs (operating expenses). The sum of capital expenditures (CAPEX) and operating expenses (OPEX) constitute the expenses of a company that are not included in the direct cost of the products or services that the company offers to the market.

1) Capital expenditures (CAPEX) - one-time investments in the creation of long-term assets, including the purchase of equipment, construction of facilities and implementation of technology.
2) Operating Costs (OPEX) - running costs associated with the day-to-day operation of a power plant.

Operating Costs of SMRs

Operating costs (OPEX) are the running costs required for the day-to-day operation of a power plant. For small modular reactors, the structure of operating costs has a number of specific features due to technological solutions and the scale of production.

- **Operating expenses structure**

- ✓ Personnel costs. SMRs are expected to have lower operating costs due to more efficient technology, process automation and smaller scale. Automation of management and control processes in SMRs allows to significantly reduce the need for operating personnel. Modern technological solutions can ensure a 30-50% reduction in the number of staff compared to traditional NPPs.

  Specific features of SMR staffing include:

- The need for specialized training of personnel to work with new technologies;
- Possibility of remote control of several modules from a single control panel;
- Increased requirements for operator qualifications within a high degree of automation.

- ✓ **Fuel costs**. The cost of fuel plays an important role, which can be reduced by using new technologies, more efficient fuel cells or waste recycling. The fuel component of the operating costs of SMRs is characterized by a number of technological features:

Nuclear fuel enrichment. SMRs use fuel with a higher degree of uranium enrichment (up to 19.75% versus 3-5% for traditional NPPs), which increases the specific cost of the fuel, but ensures longer operating cycles.

Fuel Cycles. Increased operating time between refueling (3-7 years versus 12-18 months for traditional reactors) reduces the frequency of costly fuel replacement operations. Some SMR designs envisage a 20-year fuel cycle without refueling.

- ✓ **Maintenance and Repair.**

The modular design of the SMRs offers significant maintenance advantages:

- Module reusability and rapid maintenance: the small size allows easier and cheaper reactor maintenance and faster response to technical failures;
- Simplified maintenance due to standardized modular design;
- Possibility of complete replacement of modules at the manufacturing plant;
- Reduction of power plant downtime;
- Increased utilization rate of installed capacity;
- Possibility of scheduled maintenance at factory.

✓ **Quantitative estimates of operating costs**

Modern estimates of operating costs of SMRs include the following (per MWh):

- Total operating costs: $15-25 per MWh.
- Fuel costs: $8-12 per MWh.
- Operation and maintenance: $12-18 per MWh.
- Labor costs: $5-10 per MWh.

Economic analysis of small modular reactors demonstrates their potential advantages over conventional nuclear power plants in terms of capital and operating costs. The key factors in the economic efficiency of SMRs are standardization of production, modularity of design, automation of control processes, and reduced construction time. At the same time, the commercial success of SMR technology will largely depend on achieving serial production and creating sustainable supply chains for components. High initial costs for the development and certification of new technologies require significant investment and a long-term strategy for the development of the industry.

Financial affordability and economic advantages of modularity

✓ **Prefabrication savings**. Prefabrication of modules can provide significant cost reduction compared to traditional on-site construction. Standardization of production processes helps to reduce production costs by optimizing technological operations and reducing time costs. Accelerated installation of ready-made modules significantly reduces the overall construction time of the power plant, which leads to a faster return on investment compared to large nuclear power plants. This factor makes small modular reactor projects especially attractive to potential investors.

✓ **Lower financial barriers/costs**. The lower initial investment required to implement SMRs projects significantly expands the range of potential customers. This advantage is especially important for developing countries and companies with limited financial resources that cannot afford to invest in larger-scale nuclear projects. The phased introduction of capacities allows to significantly reduce the financial risks associated with one-time large capital investments. The modular approach creates opportunities for attracting private investors, which contributes to the diversification of sources of financing for energy projects.

Scaling and scaling flexibility: Scaling and adaptability of energy systems

Flexibility of power ramp-up at SMRs

The modular architecture of the SMRs provides unique flexibility in ramping up generation capacity to meet changing energy demand. The ability to add modules in stages allows energy companies to adapt production capacity to the current needs of regional energy systems without overinvestment.

- **Series production strategy**

The long-term goal of SMRs technology development is to achieve large-scale serial production with the aim of commissioning hundreds of reactors. The implementation of this strategy requires the creation of a specialized production infrastructure and standardization of all technological processes.

Adaptation to the needs of regional energy systems can be achieved through the integration of SMRs into existing energy networks and ensuring compatibility with renewable energy sources. The relative mobility of the modules allows for the optimal placement of generating capacities in accordance with the geographical and economic characteristics of the regions.

Application areas and target markets for SMRs

SMRs demonstrate economic feasibility in the following application areas:

Remote areas and isolated power grids. Small modular reactors are the optimal solution for supplying power to remote areas, island states and small power grids where it is not economically feasible to build a large reactor.

Diversification of the energy sources . The use of SMRs helps to reduce dependence on fossil fuels and ensures diversification of energy sources in national energy systems.

Long-term competitiveness. When large-scale production is achieved and advanced technological solutions are implemented, the cost of energy produced by SMRs can become competitive with alternative energy sources.

5.2.2. Regulatory and Market Factors for the SMRs

Regulatory and certification processes have a significant impact on the timeframe and overall cost of SMR projects. The need to go through complex licensing procedures can significantly increase the time frame for project implementation and associated costs.

Normative regulation simultaneously creates opportunities for obtaining government subsidies and various forms of support for innovative energy technologies. Government stimulations and incentive programs can significantly improve SMR projects economic indicators and accelerate their commercial implementation.

Calculation of the normalized cost of electricity

- Theoretical basis for calculating the cost of electricity

Levelized Energy Cost (LEC) or Levelised Cost of Energy (LCOE), is a key economic indicator that describes the average estimated cost of electricity generation over the life cycle of a power plant. This indicator takes into account all capital expenditures, operating costs and revenues at present cost.

The mathematical formula for calculating the LEC is presented below:

$$\mathrm{LEC} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

, where

- LEC = Average cost of normalized electricity production
- n = Life cycle of the energy system
- t = Specific year of the life cycle
- I_t = Investment costs in year t
- M_t = Operating and maintenance costs in year t
- F_t = Nuclear fuel costs in year t
- E_t = Volume of Electricity Production in year t
- r = Discounting rate

- **Peculiarities of LCOE calculation for SMRs**

The normalized cost of electricity is usually calculated for a life cycle period of 20-40 years and is expressed in monetary units per kWh or MWh. When comparing the LCOE of different energy technologies, it should be taken into account that the resulting cost depend significantly on the assumptions made, financial conditions and technological development projections.

Of particular importance are the assumptions regarding the installed capacity utilization rate. For example, solar power plants can have an installed capacity utilization rate of about 10% depending on geographic location, which has a significant impact on the resulting LCOE.

- **Projected LCOE estimates for SMRs**

When large-scale mass production is achieved and the benefits of the modular approach are fully realized, the cost of electricity generated by the SMRs could drop significantly, making nuclear power more affordable for a wide range of consumers. Below are the current LCOE estimates for SMRs for commercial projects in the case of mass production:

- First commercial projects: $80-120 per MWh
- At mass production: $50-80 per MWh (forecast values).

For comparison, we present LCOE indicators for conventional NPPs, TPPs /gas plants/ and alternative technologies (renewable energy sources):

- Conventional NPPs: $60-90 /MWh
- Gas-fired power plants: $40-70 /MWh
- Wind power plants: $25-60 /MWh

Comparison with alternative energy technologies

An objective comparison of different energy technologies requires a comprehensive approach that takes into account both positive and negative aspects of each technological solution. For small modular reactors, this analysis includes an assessment of economic, environmental, and technical performance.

Competitive advantages of the SMRs

Stability of power supply. SMRs high installed capacity utilization rate ensures stable power supply regardless of weather conditions and time of day, which is a critical factor for energy security.

Environmental characteristics. The low level of carbon emissions (10-15g CO_2/kWh) allows to classify SMRs as an environmentally friendly technology, which meets modern requirements for decarbonization of the energy sector.

Longevity of infrastructure. A design life of 60-80 years ensures long amortization of capital costs and stability of energy supply for decades.

Cogeneration capabilities. The ability to simultaneously generate electricity and heat increases the overall efficiency of nuclear fuel utilization and expands the applications of the technology.

Limitations and Challenges of SMRs Development

High initial investments. Significant capital costs during the construction phase create financial barriers to project implementation, especially in the context of limited access to long-term financing.

Regulatory barriers. Imperfect regulatory framework and complicated licensing procedures for new technologies can significantly increase the time and cost of implementing SMRs projects.

Public perception. The social aspects of nuclear technology deployment, including public perceptions of the safety of small modular reactors, can affect the feasibility of projects in different regions.

Competing with renewable energy sources. Continued cost reductions in wind and solar power create additional competitive pressure on SMR technologies.

Table 1.

Advantages of SMRs	**Disadvantages of SMRs**
Stability of electricity supply (high utilization rate)	High initial costs
Low carbon emissions (10-15g CO_2 / kWh)	Regulatory barriers - imperfect regulatory framework
Long lifetime (60-80 years)	Public perception of nuclear power small modal rectors
Possibility of cogeneration (heat + electricity).	Competition with cheapening renewable energy sources (RES-renewable energy sources).

The economic benefits of SMRs from an environmental perspective

Small modular reactors offer a number of economic advantages from an environmental perspective. The modular design of projects helps to reduce waste and improve safety, which in turn leads to a reduction in the associated costs of environmental impacts. This approach allows to optimize economic performance by minimizing negative external impacts.

Associated Risks: Economic, Investment Risks and Opportunities

✓ *Current Economic Constraints*

The development of small modular reactors faces a number of significant economic barriers:

Investment Challenges:

- The need for significant capital investment in project development
- High costs for certification and licensing of innovative technologies
- Excessive cost of electricity in the first commercial projects compared to conventional sources

Market constraints:

- Uncertainty in achieving economies of scale in production
- Lack of a worked out supply chain for mass production
- Intense competition with low-cost renewable energy and storage systems

✓ *Technical risks*

The technical component of SMRs projects is characterized by the following risk factors:

- Uncertainty of performance of new technological solutions
- Potential technical challenges in transitioning to mass production
- Difficulties of integration with existing energy systems

✓ *Regulatory aspects*

The regulatory framework for SMRs requires substantial adaptation:

- Necessity to modify existing regulations for new technologies
- Lengthy licensing procedures (5-10 years), which increases costs and project timeframes
- Differences in regulatory requirements between jurisdictions
- Need to develop appropriate infrastructure and ensure security

✓ *Political and social risks:*

- Dependence on political support and changes in energy policy
- Impact of geopolitical factors on industry development
- Public perception of nuclear power and possible changes in regulatory policy

Optimal Applications of SMRs

Small modular reactors demonstrate the greatest efficiency in the following areas:

- Isolated energy systems and regions with limited energy infrastructure
- Replacement of decommissioned coal-fired power plants
- Power supply for data centers and industrial plants with high energy consumption

- Developing countries with dynamically growing energy consumption

Global SMRs Market and Outlook

➢ *Market Development Forecasts*

Projected global SMRs market size:

- 2025: US$5-8 billion
- 2030: US$25-40 billion
- 2040: US$ 150-300 billion

➢ *Regional Market Share*

- North America: 35-40% of the global market
- Asia Pacific: 30-35%
- Europe: 20-25%
- Other regions: 5-10%

➢ *Leading Developing Countries*

- USA: NuScale Power with VOYGR project (market leader)
- UK: Rolls-Royce SMR
- South Korea: national SMR projects

Technology developing countries have significant export potential in the world markets.

Economic feasibility of implementing the SMRs

➢ **Key economic factors**

A central factor raising interest in small modular reactors is the claimed potential savings from their factory mass production off construction sites. However, studies from different countries show that the capital costs of SMRs can be equivalent to those of larger reactor plants. The economic feasibility of the costs of producing and deploying small modular reactors includes:

✓ *Competitive advantages*

- Competitiveness with gas-fired power plants when carbon taxation is introduced
- Potential savings of 30-50% compared to conventional NPPs
- Possibility to locate SMRs near consumers with reduction of power transmission costs
- Multipurpose use: power generation, heat supply, water desalination, green hydrogen production.

At the same time, the economic challenges of the initial phase include:
In the initial stages of deployment, the cost of electricity from SMRs may exceed the cost of electricity from plants with conventional energy sources due to:
- Technology development and certification costs;
- Costs of establishing mass production;
- Lack of economies of scale.

At the same time there are factors of economic feasibility, as well as economic efficiency of SMR construction, which are determined by:
- Specific conditions of the region of location;
- Cost of technology development and implementation;
- Prices for traditional and alternative energy sources;
- Safety and environmental sustainability requirements;
- Level of technological readiness;
- Scope of government support

Thus, the main obstacles to the cost-effectiveness of the SMR remain:
1. **Rising costs of the first projects** - as NuScale's experience shows, real costs significantly exceed initial estimates;
2. **Need for mass production** - only mass production can provide economies of scale;
3. **Regulatory obstacles** - lengthy licensing procedures increase costs and risks.

Practical examples of SMR project implementation in terms of financial costs

Some examples of the economic costs and feasibility of small modular reactors (SMRs) include:

1.NuScale Project (USA)

NuScale Power's VOYGR project represents one of the leading cases in the field of SMR. The economic analysis of the project demonstrates the typical challenges of the industry (actual costs far exceed initial estimates):

- Construction cost increased from $5.3 billion to $9.3 billion
- Target electricity price increased by 53% from 2021
- Unit cost of NuScale SMR became comparable to conventional NPPs

2. Open100 Project (Europe)

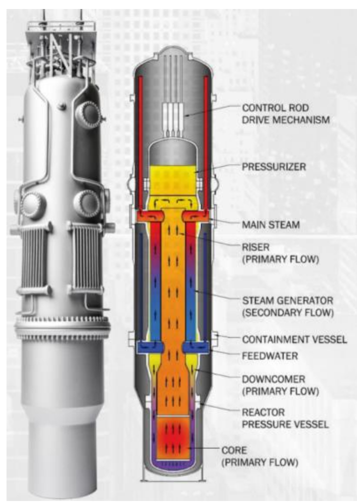
European Innovation Council (EIC) study on the Open100 project (114 MW capacity):

- Project cost: 303 million dollars
- For comparison: a 1,144 MW reference plant costs $5.5 billion dollars
- Demonstrates potential to reduce absolute costs while maintaining unit costs

3. UAMPS targets

Utah Associated Municipal Power Systems (UAMPS) is a full-service interlocal agency that provides comprehensive wholesale electric energy services on a non-profit basis to community-owned power systems throughout the Intermountain West. The UAMPS membership represents 50 members from Utah, Arizona, California, Idaho, Nevada, New Mexico, and Wyoming, is targeting a generation cost of $55 per MWh for the Carbon-Free Power Project, which would be competitive, but current cost escalation issues cast doubt on the achievability of this goal.

4. Prospects for Developing Countries



Design of the VOYGR mini-reactor

Environmental aspects of small modular reactor operation.

General environmental impact of SMRs

Small Modular Reactors (SMRs), like any industrial plant, have a certain impact on the environment. Environmental pollution is the contamination of the environment by harmful substances, disrupting the natural balance and affecting living organisms. Environmental pollution is the impact of substances, microorganisms and energy over natural environment and has negative impact on ecological systems through their properties, location or quantity.

As a result of anthropogenic impact, polluting products accumulate in air, landscapes, soils, geological environment, natural waters and living matter in concentrations exceeding natural background values. Pollution levels are controlled through a system of regulations, including maximum allowable concentrations (MACs) and maximum allowable emissions (MAEs).

The SMRs has its own environmental features and potential problems associated with spent fuel - the handling of already spent fuel, and the risks of accidents.

SMRs, like any industrial plant or facility, have an impact on the environment. Environmental monitoring, a system of collecting information on the state of environmental components, including observation, assessment and forecasting of pollution, serves as a tool for studying the state of ecology. Environmental impact management is realized through a set of scientific, technical, economic and legal measures. It is possible to change the current situation of global, regional and local anthropogenic pollution by moving to a fundamentally different level of engineering and technology, by creating low-waste or waste-free production, by equipping all enterprises with highly efficient purification devices that eliminate the dispersion of harmful substances in the environment.

The environmental impact of small modular reactors: positive and negative aspects.

Positive environmental aspects of SMRs

Efficient use of fuel resources

SMRs are characterized by reduced requirements for the amount of fossil fuel resources needed. Fuel loading or refueling at SMRs power plants is carried out every 3-7 years, while traditional plants require refueling every 1-2 years. Increased fuel efficiency helps reduce the volume of radioactive waste generated.

Substitution of carbon-based energy sources

Low-capacity nuclear power plants are an optimal solution for stable and environmentally friendly energy supply to consumers in areas remote from centralized power grids. This is especially important when replacing outdated power plants with high CO_2 emissions that traditionally use coal or gas fuel.

Reduction of greenhouse gas emissions: decarbonization of the energy sector:

SMRs, like other nuclear power plants, do not produce greenhouse gas emissions during electricity generation, which contributes to the fight against global warming.

- Energy decarbonization is the process of reducing carbon dioxide emissions from the energy sector, mainly by shifting from fossil fuels to renewable energy and other low-emission sources.

Decarbonization is a set of measures to reduce the amount of greenhouse gases emitted into the atmosphere from the combustion of fossil fuels. At the same time, it is a range of technologies to extract already emitted gases from the atmosphere in order to reduce their concentration and slow down the processes of global warming on the planet. Decarbonizing the economy is considered as one of the main ways to combat climate change. In a broader sense, decarbonization is a set of measures aimed at reducing the overall level of carbon in the economy or in specific sectors.

The principle of decarbonization is called the 3R principle: reduce, reuse, recycle.

For a successful decarbonization process, certain technological steps must be taken:

- reducing the energy intensity of product manufacturing;
- improving the efficiency of energy generation;
- making the transition to low- and no-carbon energy sources;
- using low-carbon and wear-resistant materials, as well as materials from renewable raw materials.

The need for deep decarbonization of the energy sector stimulates the development of innovative nuclear power. SMRs play a key role in this process, as they represent a virtually carbon-free energy source.

5.3 Impacts of SMR on natural resources

Impact on water resources

Some types of SMRs use water as a heat transfer medium, which can affect water resources and ecosystems in the plant area. The impact of SMRs on water resources is twofold and depends on the specific technology and operating conditions. In general, SMRs that use water as a heat transfer medium can consume significant amounts of water for cooling, which can lower water levels in reservoirs and affect ecosystems. On the other hand, some SMRs projects are considering the use of more efficient cooling systems, such as air cooling, which can significantly reduce water consumption. In addition, SMRs can have an indirect impact on water resources through climate change and increased reservoir temperatures.

Positive aspects:

- *Reducing greenhouse gas emissions*: No greenhouse gas emissions slows climate change and reduces negative impacts on aquatic ecosystems;
- *Desalination feasibility*: Possibility of integration with desalination systems to provide access to fresh water in arid regions;
- *Localization of energy production* near consumers reduces risks of transmission accidents as SMRs can be installed near consumers, which reduces the need to transport electricity and reduces the risk of transmission accidents.

Negative aspects:

- *Significant water consumption* of SMRs that use water as a heat transfer medium may lead to lowering of reservoir levels;
- *Thermal pollution* from discharging heated water negatively affects aquatic organisms;
- *Radioactive pollution*: potential risk of radioactive contamination of water in case of emergency situations;
- *Contamination during construction and operation*: construction and operation of SMRs can lead to soil and water contamination as a result of construction activities and industrial waste discharges.

Here are examples of small reactor technologies and their impact on water:

Technological solutions:

- **fast neutron reactors** using molten salts or liquid metals as coolant reduce water consumption and improve safety;
- air-cooled **mini-reactors or micro-NPPs** have minimal impact on water resources. Small reactors - micro-NPPs, used for example in food, pharmaceutical, chemical and other industry segments, can use air cooling and have minimal impact on water resources.

The impact of small modular reactors on water resources depends on the specific technology and operating conditions. All possible risks and benefits associated with the use of SMRs should be carefully assessed and strategies should be developed to minimize negative impacts on water resources. It is important to consider both direct water consumption and indirect factors such as climate change and thermal pollution.

Impact on land resources

The construction of small modular reactors (SMRs) requires a certain amount of land area (as with large nuclear power plants), which can have an impact on the local environment: SMRs have a smaller impact on land resources than conventional nuclear power plants due to their compact size and modular design. SMRs take up less space, allowing them to be built in areas unsuitable for large NPPs and reducing potential environmental impacts.

Let's take a closer look at the impact of SMRs on land resources:

Advantages:

- **Reduced space requirements**
  - Compared to conventional nuclear reactors, SMRs have lower energy capacity output and, consequently, smaller physical dimensions, which reduces the space required to accommodate them.

- **Possibility of construction in areas unsuitable for large NPPs**
  - The need for a smaller construction area makes it possible to build SMRs in areas where it is inappropriate to build large NPPs, such as near small towns or industrial plants, without occupying large land areas.

- **Integration into existing infrastructure**
  - SMRs can be integrated into existing infrastructure, minimizing additional land use.

- **Minimal impact on soil, vegetation and landscape**
  - Due to the smaller size of SMRs, their impact on the environment, including land resources, is generally considered to be lower: negligible impacts on soil, vegetation and wildlife, and landscape.

- **Possibility of use for rehabilitation of degraded areas**

- In some cases, SMRs can be used to rehabilitate degraded land or to create energy facilities on previously abandoned industrial sites.

- **Reduced risk of accidents** and their consequences related to environmental impact due to compactness and simpler design.

Overall, SMRs represent a promising technology that can provide reliable energy supply with a lower impact on land resources than traditional energy plants.

Functional benefits of SMRs

Localization of energy production

SMRs can be installed close to consumers, which reduces transmission losses and reduces the need for expensive transmission lines and increases energy security especially in remote areas.

The modular design of the SMR allows for easy scaling of capacity according to demand, avoiding the over-building of large energy facilities. This results in more efficient use of resources and a lower overall environmental impact.

The modular design allows power to be scaled according to demand, resulting in efficient use of resources and reduced environmental impact.

Integration with renewable energy sources

SMRs can be paired with renewable energy sources such as solar and wind farms to provide stable power supply with variable renewable generation. This ability to create hybrid systems allows for a more sustainable and cleaner energy infrastructure. The flexibility of integration allows SMRs to be used in a variety of settings where large nuclear power plants are inefficient or infeasible, providing clean energy in remote regions. SMRs provide energy system flexibility by working in conjunction with solar and wind farms to stabilize electricity supply with variable generation of renewable sources. This integration facilitates:

- ✓ support development of clean technologies;
- ✓ creation of sustainable energy systems;
- ✓ development of clean hydrogen production.

Environmental problems and risks associated with SMRs operation

Spent Fuel Management Challenges

The main environmental challenges of small modular reactors and the environmental risks associated with SMRs are those related to spent fuel.

SMRs, like other nuclear reactors, produce radioactive waste, the management of which requires strict safety precautions. SMRs spent fuel is the main environmental problem associated with the generation of radioactive waste. It is characterized by high radioactivity, heat generation and radiotoxicity, requiring specialized handling and storage practices. Depending on the design of SMRs, the composition and amount of waste can vary, but in general, SMRs can produce both less and more waste than conventional reactors, depending on fuel burnup and efficiency.

Thus, SMRs spent fuel is an important aspect to be considered in the design and operation of these reactors. Understanding the characteristics of spent fuel and developing effective fuel management practices are key factors in ensuring the safety and sustainability of SMR-based nuclear power.

SMRs waste peculiarities.

Radioactive waste: Critics argue that smaller reactors pose a higher risk, requiring more transportation of nuclear fuel and leading to increased waste generation. Although each individual SMR produces less radioactive waste than a large nuclear power plant, the mass deployment of many such reactors could increase the total volume of waste and complicate its management. The problem of spent nuclear fuel utilization remains relevant for all types of nuclear reactors, including SMRs.

Here are some of the difficulties associated with radioactive waste in case of mass use of SMRs:

- waste composition and quantity varies depending on reactor design
- mass deployment of multiple SMRs can increase total waste
- complicating logistics for managing waste from multiple sources
- lack of long-term solutions for safe storage and treatment.

Transportation risks: The modular design of the SMR involves factory manufacture and subsequent transportation to the site, which creates additional risks related to:

- transportation of nuclear materials and equipment;
- increased transportation security requirements;
- increased frequency of transportation operations in mass deployments.

Nuclear proliferation or nonproliferation risks

The simplified design and smaller size of SMRs can facilitate access to nuclear technology for countries with limited expertise, which increases nuclear nonproliferation risks and requires increased international control.

Accident Risks

Despite enhanced safety standards, SMRs are not without accident risks:

- the possibility of radioactive contamination of the environment;
- impact on the public in the immediate vicinity of the reactors;
- the need for evacuation measures in case of serious incidents.

High construction costs.

Small Modular Reactors (SMRs), like traditional NPPs, are not without risks. Despite the fact that SMRs, like any NPP, are designed with higher safety standards in mind, there is still a risk of accidents that could lead to radioactive contamination of the environment. The main risks are related to radioactive waste, high construction costs, political risks, and the possibility of accidents. Although modern nuclear reactors, including SMRs, are designed with high levels of safety and are considered safe, accidents cannot be completely ruled out: accidents are still possible and their consequences can be serious. Accidents at SMRs, although smaller than at large reactors, can still result in radiation releases and other adverse consequences.

Despite these risks, SMRs can be an attractive option for power generation, especially in regions without access to large power plants or as a supplement to existing energy sources. However, before deciding to build an SMRs, it is necessary to carefully assess all potential risks and develop robust strategies to mitigate them. Despite the smaller size of SMRs compared to large reactors, their construction still requires significant investment. This may make them less affordable for some countries or companies, especially in times of political and economic instability.

Political risks

The payback periods of SMRs can be long, up to 20-25 years, making them vulnerable to political changes in the country where they are located. Changes in regulations, laws or political will can affect the operation of SMRs and their safety.

Location in vulnerable communities:

SMRs, like any other nuclear facilities, may be located near populated areas, which could put local residents at risk in the event of an accident.

SMR Safety and Security Systems

The safety and security of small modular reactors (SMRs) is a critical aspect of their development and operation. Despite their smaller size and the use of innovative technologies, the primary goal remains to protect the population and the environment, as well as to minimize the risks of accidents and radiation exposure. Let us consider the main aspects of SMR safety:

• **Built-in safety features:**

SMRs are designed with multiple built-in safety features aimed at preventing accidents and mitigating their impact on the environment.

• **Passive safety systems:**

SMRs widely use passive safety systems that do not require an external energy source or operator intervention to operate in the event of an emergency. These systems rely on physical phenomena such as natural circulation of the coolant, convective processes and gravity effects. These systems allow to eliminate many safety class components (valves, pumps, piping, cables), limiting the risk of their failure.

- **Thorough regulation and licensing:**

Strict SMR licensing and regulatory processes should be in place to ensure safety at all stages of their project lifecycle:

  - Detailed risk assessment and management;
  - Nuclear material control;
  - Radioactive waste management protocols.

- **Risk Assessment and Management:**

SMR developers and operators conduct detailed risk assessment and management to identify and address potential threats.

- **Protection against external impacts**:

SMRs are designed to withstand external hazards such as earthquakes, floods and other natural disasters. Some SMRs designs provide for the reactor module to be located underground, which provides protection against man-made threats such as missile attacks or terrorist attacks.

- **Nuclear Material Control:**

Robust nuclear material control systems are essential to prevent unauthorized access and use.

- **Radioactive waste management:**

There are strict protocols and procedures for the safe management of radioactive waste. The management of waste generated from SMRs operations should also be subject to strict protocols.

Overall, the safety and security of SMRs is a priority, and modern technology and stringent regulatory standards are aimed at ensuring the safe and reliable use of these new types of nuclear reactors.

SMRs draw on experience with conventional large reactors as well as experience with small reactors on nuclear submarines and other nuclear-powered vessels such as icebreakers. SMRs have passive or internal safety systems, a simpler design, a reactor core with lower core power and larger coolant fractions. All of these combine to significantly increase the time available for specialist operators to respond to incidents or accidents.

SMRs safety principles are generally based on known phenomena such as natural circulation to cool the reactor core even in incident or accident situations, requiring very limited or even no operator action to bring the reactor to a safe state if necessary. These passive safety systems also allow the elimination of a number of components, valves, safety class pumps, pipes and cables, effectively limiting the risk of failure.

Small modular reactors are an important technology for achieving climate sustainability goals and the transition to sustainable energy, providing a clean, reliable and flexible energy supply.

SMRs represent a promising technology for low-carbon energy production. However, their environmental impacts require careful study and monitoring. It is necessary to develop reliable safety systems, address the problem of spent fuel management and minimize environmental impact. It is important that the introduction of SMRs takes place within a balanced approach that takes into account both the benefits and potential risks of the technology.

Small modular reactors represent a new trend in nuclear power that promises to be a safer and more cost-effective solution. However, this technology faces a number of environmental challenges that require careful consideration.

Economic benefits taking into account environmental aspects of SMRs

Small modular reactors have a number of economic advantages from an environmental point of view. The modular design of the projects helps to reduce waste and improve safety, which in turn leads to a reduction in associated costs of environmental impact. This approach allows for the optimization of economic indicators by minimizing influence of negative external effects.

Technical solutions to environmental problems of SMRs

Developers of small modular reactors are actively working to solve environmental problems through innovative technological approaches, such as:

- ✓ Advanced safety systems

The introduction of advanced passive safety systems based on natural physical processes ensures that the reactor is automatically brought to a safe state without operator intervention.

- ✓ Optimization of fuel cycles

The development of more efficient fuel cycles is aimed at maximizing the use of nuclear fuel and minimizing the formation of radioactive waste.

- ✓ Integration with renewable sources

Creation of hybrid energy systems combining SMRs with renewable energy sources ensures stable and environmentally friendly energy supply.

- ✓ Development of closed fuel cycles

Development of closed fuel cycle technologies allows for the processing of spent fuel, significantly reducing the volume of long-lived radioactive waste.

Thus, the environmental aspects of SMRs represent a complex issue that requires a balanced approach between the potential benefits of decarbonising the energy sector and the risks associated with the handling of radioactive materials and waste.

SMRs represent a promising technology for achieving climate sustainability goals and the transition to sustainable energy by providing clean, reliable and flexible energy supply. However, their environmental impact requires careful study and monitoring at all stages of the life cycle.

The introduction of SMRs should take place within the framework of an integrated approach that takes into account both the environmental benefits and potential risks of this technology, with mandatory compliance with the strictest environmental safety standards.

5.2. Comparison of small modular reactors with renewable energy sources

Renewable energy sources (RES) are becoming the cornerstone of the modern energy transformation. Renewable energy sources play an increasingly important role in the modern world, providing clean and sustainable energy for future generations. RES are energy sources that are constantly renewed in nature and are inexhaustible, unlike traditional fossil fuels such as coal, oil and gas. Renewable energy sources include solar, wind, hydropower, geothermal and bioenergy. The use of renewable energy sources has a number of advantages, including being environmentally friendly and reduced dependence on non-renewable resources. However, in the context of increasing load on energy systems, renewable energy sources alone are not always able to guarantee the stability and predictability of generation. In this context, small modular reactors (SMRs) are considered as an important addition to renewable energy sources within the framework of a balanced and flexible energy balance.

Cost of Electricity (LCOE) Comparison: Current LCOEs for Renewables and SMRs

Table 2

Current LCOE figures	
Renewable energy sources (RES)	**Small modular reactors (SMR):**
1) Solar: $30-60 per MWh (down 56% since 2010) 2) Wind power: $25-60 per MWh 3) Hydropower: $40-80 per MWh 4) Geothermal energy: $70-120 per MWh	1) Current estimates: $50-120 per MWh 2) Forecast for serial production: $36-50 per MW/h 3) Real Projects: NuScale Shows Cost Increases That Increase LCOE

The dynamics of cost changes for renewable energy sources and SMR

Table 3

Renewable energy sources (RES)	Small modular reactors (SMR):
a) **Solar energy: a stable reduction in cost by 10-15% per year** b) **Wind power: 5-8% decline per year** c) **Technological improvements and economies of scale continue to drive down costs**	a) **So far, they are showing an increase in costs on the first projects** b) **Potential for reduction when reaching serial production** c) **High uncertainty in forecasts**

📌 Note: Data is based on the Lazard 2025 report and industry estimates of project initiatives. According to the Lazard 2025 report, renewables remain the most competitive form of new generation excluding subsidies. In 2024, the LCOE for renewable technologies such as wind and solar in the Asia-Pacific region fell by 16%, thanks to a 21% drop in capital costs.

System Costs and Grid Integration

Here are some characteristics of renewable energy sources and small modular reactors.

- Renewable Energy Sources (RES)

Additional System Costs:

- Energy Storage Systems: $200-400/kWh for Li-ion batteries
- Backup Power: Need for Fast, Flexible Generators
- Network modernization: adapting infrastructure to integrate variable generation
- Load and demand management: intelligent metering and control system, load balancing system.

Intermittency issues:

Intermittency or discontinuity of operation is typical for renewable energy sources. For solar energy installations, the utilization factor is 15-35%, and for a wind installation, the utilization factor is 25-50%. For reliability, it is necessary to be able to reserve capacity up to 80-90% of the peak generation of renewable energy sources.

RES integration challenges

• **Growing grid connection queues**: More than half of all storage capacity in queues is offered in hybrid configurations with generation (525 GW). Interest in hybrid projects is particularly strong in CAISO (the California Independent System Operator, which manages the electric power system of California and parts of Nevada) and in the West outside the ISO*[1], where 98% and 81% of all proposed solar projects, respectively, are in a hybrid configuration.

Storage System Functions: Energy storage systems have many applications including energy arbitrage, generation deferral, ancillary services, load control, transmission and distribution deferral.

- **Small Modular Reactors**

Benefits of system integration:

- Stable generation: 85-95% utilization;
- Predictability: scheduled shutdowns for routine maintenance and reliability;
- Low system costs: minimal redundancy requirements;
- Inertia: maintains grid stability.

Limitations:

- Less flexibility in power control
- Long start/stop times
- Requirements for qualified personnel.

Comparing SMRs and RES, we see that these technologies complement each other. Renewables demonstrate steady cost reduction and rapid deployment, but require significant investments in storage and balancing systems, while small modular reactors, despite current problems with cost growth, can play an important role in providing stable baseload generation in power systems with a high share of RES. The LCOE for SMRs is about $50-100 per MWh, which is slightly higher than large reactors, but SMRs are competitive due to good scalability and lower financial risks. At the same time, traditional reactors take 8-15 years to build, while SMRs are expected to be built in 3-5 years.

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*[1] An Independent System Operator is an organization responsible for ensuring the reliable and efficient operation of the electric power system in a particular region. An ISO does not own power plants or transmission lines, but is responsible for their coordination and management, as well as for ensuring competition in the electricity market

- **Performance and Reliability: Comparison of Small Modular Reactors and Renewable Energy Sources**

Below are some key technical characteristics and comparison of the reliability of SMR and RES:

Table 4

Small modular reactors (SMR)	Renewable energy sources (RES)
Power utilization factor	
Utilization rates: 85-95%	• Solar energy: depending on the region and season 15-35% • Wind energy: depending on wind conditions 25-50% • Hydro energy: depending on water content 40-60% • Geothermal: is the most stable of the renewable energy sources 70-90%
Small modular reactors (SMR)	**Renewable energy sources (RES)**
Service life and reliability	
✓ Design life of SMR: 60-80 years ✓ High reliability: industrially proven technologies ✓ High predictability: planned maintenance ✓ Predictable degradation: planned replacement of components ✓ Planned shutdowns: 4-6 weeks every 18-24 months	✓ Solar panels: 25-30 years (0.5-0.8% degradation per year) ✓ Wind turbines: 20-25 years ✓ Hydroelectric power plants: 50-100 years with proper maintenance ✓ Geothermal power plants: 30-50 years

- ✓ **Environmental aspects of SMR and RES**

Table 5

Small modular reactors (SMR)	Renewable energy sources (RES)
Carbon footprint	

1) Life cycle: 10-15 g CO_2 per kWh 2) Emission stages: uranium mining, construction, decommissioning 3) Long-term waste: radioactive waste requires long-term storage	1) Solar: 20-50 g CO_2 per kWh (depending on technology) 2) Wind: 10-20 g CO_2 per kWh 3) Hydro: 10-50 g CO_2 per kWh (depending on region) 4) Geothermal: 15-30 g CO_2 per kWh
Environmental Impact	
1) Land use: compared to large NPPs, small footprint (1-5 km²) per module /increases depending on capacity and number of modules/ 2) Water resources: cooling requirement 3) Radiation safety: strict safety requirements	1) Solar: large land resources (5-10 km²/GW) 2) Wind: impact on birds and landscape 3) Hydro: alteration of aquatic ecosystems 4) Geothermal: minimal impact on surface

✓ Economic flexibility and scalability of SMR and RES

Table 6

Small modular reactors (SMR)	Renewable energy sources (RES)
Investment volume	
✓ Single investment: o $300-900 million per module - Scalability: modularity allows for phased introduction of capacities - Financial risks: medium (due to technology still under development)	✓ Solar energy: Amounts to $800-1,200 per kW of installed capacity ✓ Wind energy: $1,200-2,000 per kW - High scalability: from kilowatts to gigawatts - Low financial risks: proven technologies
Speed of deployment	
✓ Licensing time: 5-10 years ✓ Construction time: 3-5 years ✓ Total period before commercial operation: 8-15 years	- Solar: 6-18 months - Wind: 12-24 months - Hydro: 3-8 years (depending on scale) - Geothermal: 2-5 years

✓ **Geographical and climatic factors**

Table 7

Small modular reactors (SMR)	Renewable energy sources (RES)
Regional Applicability/Placement Requirements	
- Universality: applicable in any climate - Independence from natural conditions: independent of sun, wind, water - Placement features: seismic safety requirements / seismic resistance/, water supply	- Solar: optimal in sunny regions (insolation >1,400 kWh/m²/year) - Wind: requires stable wind conditions (>6 m/s average annual speed) - Hydro: dependent on water resources - Geothermal: limited to geothermally active regions
Seasonal variability	
- Stability: constant generation all year round - Planned shutdowns: usually during periods of low demand	- Solar: strong seasonal variability (winter/summer) - Wind: moderate seasonal variability - Hydro: dependent on water availability (spring maximum) - Geothermal: stable generation

✓ Synergies and hybrid solutions

Table 8

Combined systems	
SMR + RES	RES + storage
• Baseload + variable generation: optimal combination of stability and flexibility • Cogeneration: SMR for heat, RES for electricity • Regional optimization: SMR in some regions, RES in others	• Solar + batteries: improving generation predictability • Wind + pumped storage: long-term energy storage • Hybrid wind-solar parks: smoothing out daily fluctuations
Role in the energy system	
SMRs as base generation:	RES as variable generation:
• Ensuring power system stability • Frequency and voltage support • Backup for peak loads	• Maximize the use of renewable resources • Reduce system operating costs • Decarbonize energy

✓ Development prospects and competition in the energy sector

Table 9

Technological breakthroughs	
Small modular reactors (SMR)	Renewable energy sources (RES)
▪ Generation IV reactors: higher efficiency and safety ▪ Prefabrication: cost reduction through standardization ▪ Hydrogen integration: hydrogen production during periods of low demand	▪ Perovskite solar cells: potential for 30-50% cost reduction ▪ Floating wind turbines: exploiting new wind resources ▪ Advanced storage: reducing storage costs
Energy development scenarios	
Balanced development scenario:	Renewable energy dominance scenario:
o SMRs: 15-25% in the energy balance (base generation) o Renewable energy sources: 60-70% in the energy balance (variable generation) o Accumulators: 10-15% to balance the system	o Advantages: rapid cost reduction, broad support o Challenges: Need for Mass Energy Storage o System costs: may exceed generation costs.

✓ Regional features of competition

Table 10

Developed countries	Developing countries
❖ Focus on RES: existing infrastructure, high support ❖ The role of SMR: replacing decommissioned nuclear and coal-fired power plants ❖ System integration: advanced networks and electricity markets	❖ Base Power Generation Needs: Rapid Growth in Energy Consumption ❖ Infrastructure limitations: weak power grids ❖ Financial constraints: preference for less capital-intensive projects
Isolated systems	
❖ Advantages of SMR: stability, independence from natural conditions ❖ Limitations of RES: need for backup and storage ❖ Economic feasibility: high costs of organic fossil fuels make SMR competitive	

✓ Competitive advantages and areas of application of SMR and RES

Table 11

Competitive advantages	**Small modular reactors (SMRs)**	**Renewable energy sources (RES)**
Predictability of electricity generation	✓	✕
Generation stability	✓	✕
Deployment speed	✕	✓
Electricity cost	✕	✓
Low cost systems	✓	✕
Scalability	✓	✓
Modularity	✓	✓
Long term reliability	✓	✕
Independence from natural conditions	✓	✕
Environmental friendliness	✓	✓
Optimal areas of application	**(SMRs)**	**(RES)**
Base generation in power systems	✓	✕
Isolated areas	✓	✕
Mass power supply	✕	✓
Rapid deployment of capacities	✕	✓
Industrial application with cogeneration	✓	✕
Decentralized systems	✕	✓
Regions with high renewable resources	✕	✓
Regions with limited renewable resources	✓	✕

The most likely development scenario assumes the complementary coexistence of SMR and RES:

- **RES** will dominate the total generation volume due to low cost and rapid deployment;

- **SMR** will occupy the base generation niche, ensuring the stability of the power system;

- **Energy storage** will play a key role in the integration of variable generation of RES.

The success of each technology depends on specific regional conditions, including natural resources, energy infrastructure, regulatory environment and economic priorities.

5.3 Role of SMRs in reducing carbon emissions

The challenge of reducing global carbon emissions is one of the most pressing issues of our time, with energy production at the center of the problem. The majority of the world's electricity is still generated from fossil fuels such as coal, oil, and natural gas, all of which release significant amounts of carbon dioxide (CO_2) and other greenhouse gases into the atmosphere. Small Modular Reactors (SMRs), as a form of nuclear power, present a viable pathway toward deep decarbonization by providing consistent, low-carbon energy that can replace or significantly reduce reliance on carbon-intensive generation.

Nuclear power, by its nature, produces electricity without direct carbon emissions during operation. Unlike coal or gas plants, which emit CO_2 as a result of burning fuel, nuclear fission in an SMR releases energy by splitting atomic nuclei, a process that does not involve combustion. While the full life cycle of an SMR - from construction and fuel fabrication to decommissioning - does involve some indirect emissions, these are relatively small compared to fossil fuel plants and even comparable to the life-cycle emissions of many renewable technologies. This makes SMRs an important tool for achieving substantial emissions reductions across power systems.

The carbon reduction potential of SMRs is particularly significant in regions where fossil fuels dominate the energy mix. In such cases, deploying SMRs to replace aging coal or oil-fired plants can result in immediate and dramatic drops in emissions. Because SMRs are capable of delivering continuous, baseload power, they can directly displace fossil fuel capacity without requiring the large-scale energy storage or backup systems that variable renewables often need to ensure reliability. This stable, 24/7 operation ensures that low-carbon electricity is available at all times, reducing the need for carbon-emitting "peaker" plants that are brought online during periods of high demand or low renewable generation.

Beyond electricity generation, SMRs can contribute to decarbonization in sectors that are traditionally hard to electrify. Many industries - such as steel production, chemical manufacturing, and oil refining - require high-temperature process heat, which is often supplied by burning fossil fuels. Certain SMR designs, particularly high-temperature gas-cooled reactors and molten salt reactors, can produce the necessary heat directly and with zero operational carbon emissions. This opens up opportunities to decarbonize industrial processes that currently account for a substantial share of global greenhouse gas emissions.

SMRs can also support the production of clean hydrogen through high-temperature electrolysis or thermochemical processes. Hydrogen is increasingly seen as a critical energy carrier for decarbonizing transportation, industry, and even heating systems. Producing hydrogen without carbon emissions requires a low-carbon energy source, and SMRs, with their ability to run continuously and provide both electricity and heat, are well-suited to this role.

In hybrid energy systems, SMRs can work alongside renewables to further drive down emissions. For example, during periods of high wind or solar output, SMRs could operate at reduced power or redirect their output to hydrogen production, desalination, or district heating. During periods of low renewable availability, SMRs can return to full power, ensuring that electricity demand is met without resorting to fossil fuels. This ability to act as a clean, flexible backup greatly enhances the carbon reduction potential of renewable-heavy grids.

It is also worth noting that SMRs can play a role in enabling carbon reductions in remote or isolated communities. Many such locations rely on diesel generators for power, which are not only expensive to operate but also highly carbon-intensive. Deploying SMRs in these regions can eliminate the need for diesel entirely, providing a clean and steady source of power while also reducing local air pollution.

The contribution of SMRs to carbon reduction will depend on how quickly they can be deployed, the scale at which they are adopted, and the extent to which they replace high-emission sources rather than competing with other low-carbon technologies. Policy frameworks, market incentives, and public acceptance will all influence their impact. Nonetheless, from a technical standpoint, SMRs are capable of making substantial contributions to carbon neutrality goals, both directly by replacing fossil generation and indirectly by enabling clean solutions in other sectors of the economy.

In the broader context of climate strategy, SMRs are not a silver bullet but a powerful complementary tool. When combined with renewable energy, energy efficiency measures, and emerging carbon capture technologies, they can form part of a diversified portfolio of solutions aimed at achieving net-zero emissions. Their ability to provide reliable, scalable, and low-carbon energy positions them as a crucial asset in the decades-long effort to decarbonize global energy systems.

Chapter 6. Applications of SMRs

The permanent energy crises of various countries prove the need for additional strategic energy resources for any state. In the context of growing demand for environmentally friendly energy and the need to ensure energy security, interest in small and medium-power reactors, also known as small modular reactors (SMRs), is growing.

Small modular reactors are defined as advanced reactors for power generation with module capacity up to 300 MW. These reactors feature advanced engineering features, can be used in single-module or multi-module plants, and are designed to be delivered fully factory-ready to power companies for subsequent installation as needed.

The IAEA coordinates the efforts of its Member States to develop different types of SMRs, taking a systematic approach to identify and develop promising technologies to ensure the competitiveness and reliable operation of such reactors.

As of 2023, there were more than eighty modular reactor projects under development in 19 countries, demonstrating the scale of interest in this technology worldwide. SMR development is taking place in four main directions:

1. **Commercialization** - transition from demonstration projects to serial production
2. **Standardization** - creation of unified technical standards for various types of SMR
3. **Integration** - inclusion of SMR into existing energy systems
4. **Specialization** - development of SMR for various types of applications (Arctic conditions, offshore platforms, industrial complexes, etc.).

6.1. Energy generation for remote areas

- **Main areas of application of SMR in remote areas**

Small modular reactors have unique characteristics that make them particularly suitable for power supply in remote areas. Examples of SMRs used in remote industrial facilities include:

- Power supply for mines, especially in the Arctic and other hard-to-reach regions;
- Power supply for oil and gas fields in remote areas;
- Power supply for mining complexes in isolated areas.

Regional and distributed energy:

- Remote regions with limited energy infrastructure;
- Island states and territories;
- Regions with unstable energy supply.

- **Advantages of SMR for remote areas**

SMR have the following advantages:
1. **Modularity** - the ability to increase capacity as demand grows.
2. **Compactness** - placement of units closer to consumers.
3. **Passive safety** - built-in safety systems of modern designs.
4. **Cogeneration** - simultaneous production of electricity and heat.
5. **Low cooling requirements** - expansion of construction geography.

Practical examples of project implementation

a. **USA (Tennessee):** Google with Kairos Power, has selected Tennessee as the site of an advanced nuclear power plant that is expected to supply electricity to the Big Tech company's data centers in the U.S. southeast starting in 2030. Tennessee reactor will be first to be deployed under Google's corporate agreement. Would support 500 megawatts of advanced nuclear capacity, which is enough to power about 350,000 homes, to be developed by California-based nuclear company Kairos. The 50-gigawatt small modular nuclear power plant will be built in Oak Ridge, Tennessee, under a long-term power purchase agreement with utility Tennessee Valley Authority to deliver electricity to Google data centers locally and in the state of Alabama.

6.2. Desalination and industrial heating

Desalination of water using small modular reactors is one of the most promising ways to solve the problem of fresh water shortage. SMRs generate both electricity and heat, which are used to power desalination plants. This technology combines nuclear energy with water treatment processes, ensuring efficient use of energy resources.

SMRs in water desalination processes. Technological principles of desalination

SMRs generate both electricity and heat, which are used to power desalination plants. The main technological methods of desalination include:

1. **Reverse osmosis** is a water purification process in which water under pressure passes through a semipermeable membrane that retains various impurities (salts, bacteria, viruses, organic compounds). The result is purified water (permeate) and a concentrate containing the removed impurities. Reverse osmosis is the most energy efficient method, using electricity to operate high-pressure pumps. SMRs provide a stable power supply for this process.
2. **Multi-stage flash distillation (MSF)** is a desalination technology widely used to produce large volumes of fresh water. Using MSF, the technology uses heat from a reactor to evaporate seawater. This method is particularly effective in cogeneration.

Technical solutions for integrating SMRs with desalination plants

There are several concepts for integrating modular reactors with desalination plants:

- **Direct coupling** - heat from the reactor's primary circuit is directly used for desalination via an intermediate heat exchanger
- **Electrical coupling** - the reactor generates electricity to power electric desalination plants
- **Hybrid systems** - combine both approaches for maximum efficiency.

Advantages of SMRs for desalination processes.

Small modular reactors have a number of characteristics that make them particularly attractive for use in desalination processes:

1. **Compactness** - allows installations to be placed in close proximity to consumers, reducing transportation costs for water delivery.
2. **Modularity** - provides the ability to increase capacity as the need for fresh water increases.
3. **Passive safety** - modern designs have built-in safety systems that operate without external power supply.
4. **Cogeneration** - simultaneous production of electricity and heat, which significantly increases the overall efficiency of the energy complex.

Economic aspects of desalination

The cost of desalinated water using SMR depends on:

- Capital costs of reactor construction;
- Cost of fuel and operation;
- Scale of production;
- Local conditions and requirements.

It is estimated that for large-scale production, the average cost could be between US$0.5 and US$2 per cubic meter of water.

Hydrogen production using SMRs

Small modular reactors represent a promising solution for the production of "green" hydrogen, an environmentally friendly energy source produced without greenhouse gas emissions, through the electrolysis of water. The advantages of this approach are:

- Stable energy source for continuous operation of electrolysers
- Use of SMR heat to improve electrolysis efficiency
- Promoting decarbonisation of industry and transport.

Technological foundations of hydrogen production

Green hydrogen is produced through water electrolysis, where an electric current splits water molecules into hydrogen and oxygen. SMRs can provide a stable source of energy for this process, providing:

· **Continuous operation of electrolyzers** - unlike renewable energy sources, which depend on weather conditions.

· **Increased efficiency of electrolysis** – by using the heat generated by SMRs.

· **Decarbonization of industry and transport** – by replacing hydrocarbon fuels with hydrogen.

Applications of hydrogen produced by SMRs

"Green" hydrogen can be used in various sectors of the economy:

- as a fuel for hydrogen transport (cars, buses, trains);
- for the production of electricity in fuel cells;
- in industrial processes (ammonia production, oil refining, metallurgy);
- for large-scale energy storage.

International experience in hydrogen production using SMRs: application examples

- **France** is considering building an SMR to produce green hydrogen as part of its national hydrogen strategy.
- **The US** has approved the use of the first NuScale small modular reactor that can be adapted to produce hydrogen.
- Research shows the cost-effectiveness of SMRs for green hydrogen production, especially in remote areas with limited infrastructure.

6.3. Integration with renewable energy systems

Reliability of power supply to consumers and high quality of supplied electricity are the main requirements for energy sources of centralized and decentralized energy systems.

The integration of small modular reactors with renewable energy systems represents an innovative approach to creating hybrid energy systems capable of providing a stable and environmentally friendly energy supply, offering a number of significant advantages.

Principles of integrating SMRs with renewable energy sources

SMRs, due to their relatively small capacity and high control flexibility, can effectively complement renewable energy sources such as solar and wind power plants. The main principle of integration is to compensate for the intermittent nature of the operation of renewable sources and to ensure a stable base load in the power system. Hybrid energy systems based on SMR and renewable energy sources allow optimizing the energy balance, ensuring continuous generation of electricity regardless of weather conditions and time of day.

Benefits of Integration

Increased reliability: SMRs can act as a backup energy source, compensating for fluctuations in renewable energy generation, especially during periods of low solar or wind activity. This ensures continuity of power supply and stability of power parameters in the grid.

Emissions reduction: Integrating SMRs with renewable energy sources can significantly reduce the use of fossil fuels to generate electricity in thermal power plants, which can significantly reduce CO_2 and other greenhouse gas emissions into the atmosphere.

Economic efficiency of the integrated system: In certain conditions, the combined operation of SMR and renewable sources can be more economically advantageous than using only one type of energy source. This is especially true for remote or isolated areas where the construction of large energy facilities is not economically feasible.

Flexibility of the integration system: SMRs can quickly adapt to changes in electricity demand, allowing them to work effectively in conjunction with variable renewable energy sources.

Technical solutions for integration: forms of SMR integration with renewable sources

1. **Combined heat and power (cogeneration):** Small modular reactors can be used to produce thermal energy that can be used for:

- heating residential and industrial buildings;

- ensuring technological processes in industry;
- production of additional electricity using thermal power plants operating in conjunction with renewable sources.

2. **Water Electrolysis to Produce Hydrogen**: Modular reactors produce electricity for the electrolysis of water to produce hydrogen, which is used as a fuel for various transport means/vehicles, in industrial processes as a reducing agent or feedstock, and for energy storage for subsequent conversion to electricity.
3. **Microgrids and autonomous power systems**: SMRs are integrated into microgrids - small autonomous power systems that provide electricity to remote communities or industrial facilities, which helps increase the reliability of energy supply and reduce dependence on the centralized power grid.

6.3.4. Technological aspects of integration

Modern SMR designs: Some modern SMR designs have special characteristics that make them more suitable for integration with renewable sources:

- Molten salt reactors have high thermal inertia and the ability to store thermal energy, which helps smooth out fluctuations in energy consumption.
- Gas-cooled reactors have high efficiency and fast response to load changes, which ensures optimal integration with variable energy sources.

Network infrastructure requirements: Integration of SMR and renewable energy sources requires the development of a modern network infrastructure capable of:

- efficiently transmit and distribute electric power from various sources;
- manage the operating modes of various types of energy sources;
- ensure real-time load balancing;
- maintain stable parameters of electric power quality.

Energy Storage Systems: The development of energy storage systems (batteries, hydrogen storage) is an important aspect of integration, allowing excess energy to be accumulated and used during periods of peak demand. Key storage technologies include:

1. Electrochemical storage

- **Lithium-ion batteries** provide rapid response to load changes and high efficiency of energy storage and release.

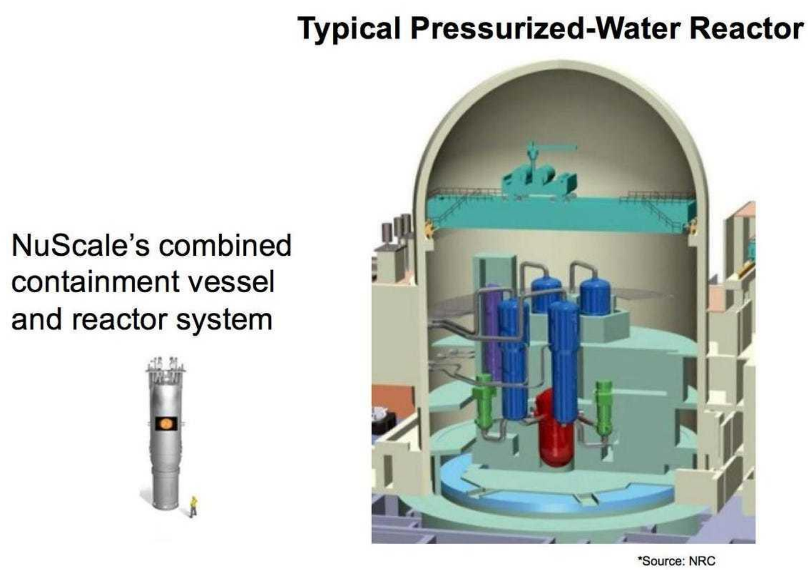
- **Flow batteries** are suitable for long-term storage of large volumes of energy.

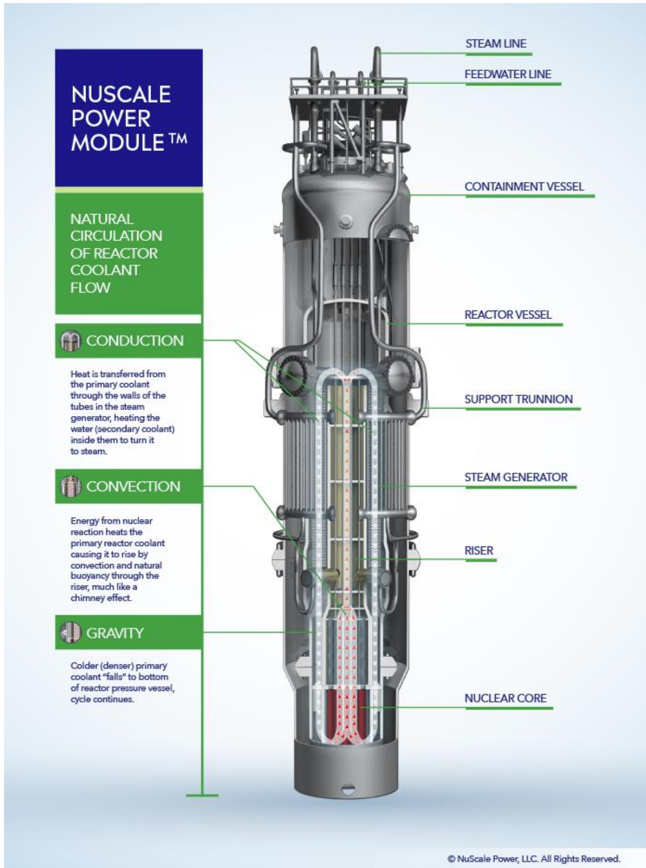
2. Mechanical Storage Systems

- **Pumped storage plants** use excess energy to pump water to an upper reservoir, which then generates electricity.
- **Compressed air systems** store energy in the form of compressed air in underground reservoirs.

3. Chemical energy storage

- **Hydrogen storage** allows the conversion of excess electrical energy into hydrogen for subsequent use in fuel cells or industrial processes.





AI Needs More Energy

The artificial intelligence (AI) sector is increasingly influencing global energy consumption. With AI advancing, demand for generation and grid capacities is growing. Key to AI implementation is a stable supply of low-carbon or, ideally, even zero-carbon electricity, which nuclear power can provide. This is what the Energy and Artificial Intelligence report by the International Energy Agency deals with.

How energy and information are linked

In today's technological landscape, information processing involves using energy. Physically, a 1 or a 0 means the presence or absence of energy. Machine learning is also energy-dependent. For example, in a Hopfield neural network, named after the Nobel laureate who received the prize for foundational discoveries and inventions in machine learning, reference values are programmed to achieve the lowest energy state, or "valley," towards which the system strives during training.

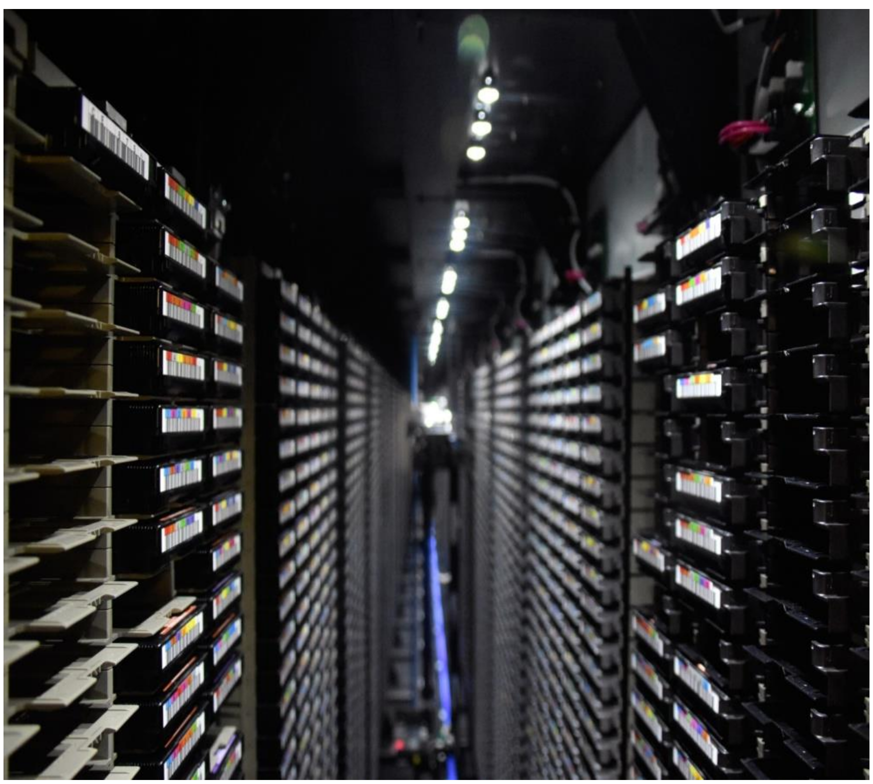
To date, technological breakthroughs, combined with lower computing costs and access to massive amounts of data, have propelled the growth of AI so dramatically that it has evolved from a scientific pursuit into an industry influencing production processes, everyday life, politics, art—and the energy industry.

The report notes that determining AI's exact share in the overall data center loads is challenging since data centers handle more than just AI tasks. Conversely, AI is not limited to data centers. Nevertheless, the authors of the report use the term "data centers."

A look back at data centers' electricity needs

According to the IEA, data centers account for about 1.5% of global electricity consumption in 2024 (415 TWh). The United States led the data center sector (45%), followed by Europe (15%).

On average, electricity consumption growth by data centers accelerated from 3% annually between 2005 and 2015 to 10% between 2015 and 2024. Since 2017, global electricity consumption by data centers has grown by roughly 12% on the annual average. This is more than four times faster than the overall growth of electricity demand.



In developing economies where energy use is growing across various sectors, data centers contribute about 5% of total growth. In countries where energy consumption has long remained almost flat, data centers account for about 20% of growth.

However, it should be noted that data centers are not the fastest-growing electricity consumers globally. According to IEA estimates, they lag behind heavy industry and other manufacturing sectors, household appliances, space cooling, heating, and electric transport. Still, at the local level, data center connections can cause problems related to power generation and grid transmission capabilities.

Projecting data centers' electricity needs

The IEA outlines four scenarios, or cases, for electricity consumption by data centers by 2030. In the Base Case, electricity consumption will more than double compared to current levels, reaching 945 TWh. As noted in the report, this is slightly higher than Japan's current consumption of electricity.

In the Lift-Off Case, power consumption will exceed 1,260 TWh by 2030. The High Efficiency Case projects consumption to reach about 800 TWh by the same year thanks to energy conservation. The Headwinds Case forecasts around 670 TWh. The IEA also extended projections to 2035, but uncertainty was so high that estimates ranged from 700 TWh to 1,720 TWh depending on the case.

Energy savings from AI

Industries employing AI reduce their energy use by optimizing production processes. "The industry of the future will be increasingly digitalized and automated; countries and companies that take the lead in integrating AI into manufacturing will jump ahead. AI applications can accelerate product development, lower costs and increase quality. Widespread adoption of existing AI applications to optimize processes in industry can lead to energy savings equivalent to more than the total energy consumption of Mexico today," the report says. This translates to roughly 8 EJ (exajoules) by 2035, or over 222 TWh.

Thus, AI-driven efficiency gains may curb the overall growth in electricity demand but only partially. Some downward influence on electricity consumption by data centers is also achieved through improving server and cooling equipment energy efficiency.

30% of global data center electricity needs are met by coal-fired power plants.

Powering data centers

Data centers are comparable in electricity consumption to metallurgical plants, including energy-intensive ones like aluminum smelters. Moreover, data centers are a rapidly growing and increasingly significant electricity consumer. This raises the question: How can their power supply be reliably ensured? Locating a data center depends heavily on a reliable power source, competitive electricity prices, and adequate grid capacity.

Sufficient generation capacity is the most critical factor in making a decision to build a data center. As noted in the report, 30% of global electricity needs for data centers are met by coal-fired power plants, followed by renewable energy (27%), gas (26%), and nuclear (15%). After 2030, the share of coal generation in powering data centers will somewhat decline, gas will remain steady, while the shares of renewables and nuclear will grow.

The report says that grids are a challenge in many regions: "Grid connection queues for both supply and consumption projects, including data centers, are long and complex. Building new transmission lines can take four to eight years in advanced economies and wait times for critical grid components such as transformers and cables have doubled in the past three years."

To ensure reliable and manageable electricity supply, technology and energy companies are partnering. In the United States, several major data center operators have teamed with power generation and distribution companies building new gas-powered facilities.

In 2024, similar agreements were signed between large American tech companies and nuclear power plants. In September, Oracle announced plans to use three small modular reactors (SMRs) to power its 1 GW data center. In mid-October, Amazon reached an agreement with Energy Northwest to build four advanced power units in the state of Washington. The nuclear station will have a capacity of 320 MW expandable to 960 MW. Technology for the station will be provided by X-energy, a company in which Amazon also invests. The project is expected to be finished in the early 2030s. Additionally, Amazon is working with Dominion Energy on the plans to build a 300 MW unit. Google signed an agreement with Kairos Power to purchase electricity from its upcoming SMRs, with a 500 MW fleet planned by 2035. The company is developing a demonstration molten salt reactor, Hermes, in Oak Ridge (Tennessee), scheduled to become operational in 2027. The next step will be constructing a two-unit station. "To date, plans to build up to 25 GW of SMR capacity associated with supplying the data center sector have been announced worldwide, almost all of them in the United States, although projects are at varying stages of maturity and certainty. The first projects are expected to start to materialize only towards the end of this decade," the report says.

True sustainability

Many technology companies and major data center operators aim to cut emissions and use clean energy by purchasing electricity from renewable sources, as noted in the report. Often these are financial agreements. This means that other sources – natural gas or coal – are used in reality to satisfy actual electricity needs. However, some tech companies still strive for real emission reductions. Google and Microsoft sign agreements for electricity supplies from low-carbon energy sources – hydropower, nuclear power, geothermal power plants, and natural gas stations with carbon capture.

Interest in nuclear capacity of any size

Assessing the prospects of nuclear power plants supplying electricity to data centers, the authors of the IEA report focus attention on small modular reactors, but large plants are also in play. In addition to the restart of a unit at Three Mile Island, there is also a contract between Amazon Web Services and Talen Energy for providing 960 MW of capacity from the Susquehanna Steam Electric Station, a nuclear facility in Pennsylvania consisting of two units rated at 1,257 MW each. Furthermore, in May, Google announced partnership with Elementl Power on three nuclear projects due to a sharp rise in AI-driven electricity consumption. Google will provide finance, with each of the three projects to have a capacity of 600 MW and classified as medium-sized nuclear plants under the IAEA criteria. These examples show that nuclear power plants of all sizes can be employed for connecting AI-related data centers in the US and beyond.

Chapter 7. Regulatory and Licensing Issues

7.1 Overview of nuclear regulations for SMRs

Nuclear energy is one of the most heavily regulated sectors in the world, and for good reason: the operation of a nuclear reactor involves handling radioactive materials and managing processes that must be kept under precise control to protect human health, the environment, and national security. Regulatory frameworks are designed to ensure that nuclear facilities operate safely, securely, and in compliance with international standards, and Small Modular Reactors (SMRs) are no exception to this rule. While SMRs bring new design approaches and deployment models, they must still navigate a rigorous licensing and oversight process before they can be built and operated.

In most countries, nuclear regulations are administered by an independent national regulatory authority, such as the U.S. Nuclear Regulatory Commission (NRC), or the Office for Nuclear Regulation (ONR) in the United Kingdom. These bodies set requirements for all phases of a nuclear project's life cycle - siting, design, construction, operation, and decommissioning, and are empowered to enforce compliance through inspections, audits, and legal measures. For SMRs, this means that each project must demonstrate not only that it meets existing safety standards but also that any novel design elements do not introduce unforeseen risks.

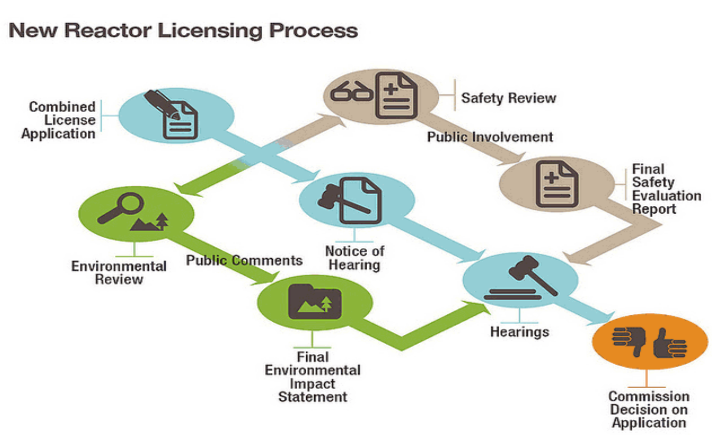
One of the distinctive challenges for SMRs is that existing regulatory frameworks were largely developed for large, conventional nuclear power plants. This can create mismatches between the regulatory requirements and the characteristics of SMRs. For example, some SMR designs incorporate factory-built modules that are transported to the site for assembly, a process not common in traditional plant construction. Regulators must determine how to adapt their oversight to cover both the manufacturing stage and the final installation. Additionally, the smaller size and lower power output of SMRs may call for adjustments in emergency planning zones, security staffing, and operator training requirements - issues that regulators are actively studying.

Internationally, organizations such as the International Atomic Energy Agency (IAEA) play a key role in harmonizing nuclear safety standards and providing guidance for emerging technologies. The IAEA develops safety requirements, technical documents, and review services that help national regulators establish clear and consistent rules for SMRs. This is particularly important because many SMR vendors plan to export their designs, and having regulatory alignment across borders can reduce duplication, speed up licensing, and build investor confidence. Collaborative initiatives like the IAEA's SMR Regulators' Forum facilitate the exchange of experience and best practices among countries pursuing SMR deployment.

Another layer of regulation concerns nuclear security and safeguards, which are often coordinated with international treaties such as the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). These frameworks ensure that nuclear materials are used solely for peaceful purposes and are not diverted to weapons programs. SMR operators must implement robust physical security measures and account for all nuclear materials in accordance with both national laws and international obligations.

In recent years, some countries have introduced regulatory innovations to better accommodate SMRs. The United States has explored performance-based regulations that focus on meeting safety outcomes rather than prescribing specific design solutions, providing more flexibility for advanced reactor concepts. These approaches aim to strike a balance between ensuring safety and encouraging innovation.

Ultimately, the regulatory environment for SMRs will continue to evolve as more designs mature and move toward commercial deployment. While the core principles of nuclear regulation, such as protecting people, the environment, and national security, will remain unchanged, the practical implementation of these principles will need to reflect the unique features of SMRs. Achieving this balance will require close cooperation between regulators, technology developers, and international bodies to ensure that safety and innovation progress hand in hand.



7.2 Challenges in licensing SMRs for commercial deployment

Licensing is one of the most critical and time-consuming steps in bringing any nuclear technology to market, and for Small Modular Reactors (SMRs), this process presents a mix of familiar hurdles and entirely new complexities. While the core objectives of licensing, such as ensuring that a reactor can operate safely, securely, and in compliance with environmental and non-proliferation requirements, are the same for both SMRs and large conventional plants, the distinctive features of SMRs often do not fit neatly within existing regulatory frameworks. This misalignment can lead to uncertainties, delays, and increased costs for developers and investors.

One of the primary challenges lies in the fact that nuclear regulatory systems in most countries were originally designed around gigawatt-scale reactors, with standardized assumptions about reactor size, power output, staffing levels, and emergency planning needs. SMRs, with their smaller footprint, lower generating capacity, and often different safety approaches, require rethinking these assumptions. For instance, some SMR designs incorporate passive safety features that greatly reduce the probability and severity of accidents, potentially allowing for smaller emergency planning zones. However, in many jurisdictions, regulatory requirements still mandate the same expansive emergency zones that apply to large plants. This mismatch can negate some of the siting advantages SMRs are meant to offer.

Another difficulty is the diversity of SMR designs themselves. While traditional reactors follow well-established design categories, SMRs span a wide spectrum, including light-water, high-temperature gas-cooled, molten salt, and fast neutron designs, each with its own cooling systems, fuel types, and operating conditions. Regulators must evaluate these technologies on a case-by-case basis, often without precedent. The absence of a licensing track record for many advanced SMR types means that regulators and developers alike must invest significant time in safety demonstrations, modeling, and testing to prove the design's robustness.

The modular nature of SMRs adds another layer of complexity. Many SMR concepts involve factory fabrication of reactor modules that are transported to the site for assembly. This introduces questions about how regulatory oversight should be divided between manufacturing facilities and the deployment site. Certifying quality and safety during off-site manufacturing requires inspectors to operate in different environments, potentially across international borders if modules are exported. Coordinating this oversight can be logistically challenging and may require new regulatory agreements between countries.

Licensing timelines and costs are also a major concern. Nuclear licensing is inherently lengthy and expensive, but SMR developers often have smaller budgets and shorter development cycles than large nuclear utilities. Lengthy regulatory reviews can erode the financial viability of projects, especially when competing with rapidly deployable renewable technologies. Developers have called for more predictable, staged licensing processes that allow non-safety-critical aspects of a project to proceed in parallel with safety reviews. Early engagement with regulators, sometimes years before a formal application, is becoming an important strategy to address this.

International deployment ambitions create further complications. Many SMR vendors hope to sell their technology in multiple countries, but each jurisdiction has its own regulatory regime, documentation requirements, and review processes. This fragmentation forces developers to duplicate licensing efforts, increasing costs and extending timelines. Efforts by organizations like the International Atomic Energy Agency (IAEA) and the SMR Regulators' Forum to harmonize safety standards and recognize equivalent certifications across borders are ongoing, but practical implementation remains limited.

Finally, there is the human factor. Licensing requires deep expertise in nuclear engineering, safety analysis, and regulatory law - skills that are in limited supply. Many regulatory bodies already face staffing shortages, and the influx of novel SMR applications could strain these resources further. Building regulatory capacity, particularly in countries new to nuclear power, will be essential if SMRs are to be deployed widely and on schedule.

In sum, licensing SMRs for commercial deployment is not simply a scaled-down version of licensing a large reactor, but it is a fundamentally different process that must account for new technologies, new business models, and often new operating environments. Overcoming these challenges will require proactive collaboration between developers, regulators, and international agencies, as well as regulatory innovation that preserves safety while enabling timely market entry. Without such adaptations, the promise of SMRs as a flexible, low-carbon energy solution could be slowed by procedural bottlenecks rather than technical limitations.

7.3 International cooperation and standards

The deployment of Small Modular Reactors (SMRs) is not merely a matter of national energy policy—it is increasingly a global endeavor that demands coordinated action across borders. Because nuclear technology involves complex safety, security, and environmental considerations, no single country can operate in isolation without affecting the broader international framework. This interconnectedness makes international cooperation and adherence to common standards essential for SMRs to realize their potential as a widely adopted energy solution.

At the heart of international nuclear cooperation lies the work of the International Atomic Energy Agency (IAEA), which serves as the primary forum for setting global safety, security, and non-proliferation guidelines. The IAEA publishes Safety Standards Series documents that cover all aspects of nuclear energy—from siting and design to operation, waste management, and decommissioning. While these standards are not legally binding, they are widely recognized as benchmarks of good practice and are often incorporated into national regulatory frameworks. For SMRs, the IAEA has also established specialized working groups, such as the SMR Regulators' Forum, to exchange technical insights, address licensing challenges, and encourage the alignment of regulatory approaches.

International standards play a particularly important role in facilitating the export of SMR technologies. Many SMR developers envision selling factory-built modules to multiple countries, which means that components, fuel, and operational support will cross national borders. Without harmonized technical requirements, a module approved in one country might need significant redesign to meet another country's regulations, adding cost and delays. Standardization can help avoid such inefficiencies by providing a consistent baseline for safety and performance expectations.

Non-proliferation commitments also underpin global cooperation in nuclear technology. Under the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), signatory states agree to use nuclear materials solely for peaceful purposes and to submit to safeguards inspections by the IAEA. For SMRs, this means that international trade in reactor technology and fuel must comply with strict accounting and verification measures. Many SMR designs use low-enriched uranium, but even in these cases, fuel cycle transparency and secure handling remain central to international trust.

Beyond safety and security, there is growing recognition that cooperation in SMR development can accelerate innovation and reduce costs. Multinational research programs, such as those coordinated through the Generation IV International Forum (GIF) or bilateral agreements between countries, allow shared access to test facilities, modeling tools, and operational data. Such collaborations can shorten development timelines by avoiding duplicated efforts and spreading the cost of large-scale experiments or prototype construction.

Regional cooperation is also emerging as a practical pathway for SMR deployment. Neighboring countries with smaller energy markets may find it economically viable to share licensing expertise, pool resources for fuel supply and waste management, or even operate joint SMR facilities under coordinated governance. For instance, discussions in parts of Europe, Asia, and the Middle East have explored the potential of regional SMR hubs serving multiple grids.

However, achieving true global alignment is not without obstacles. National sovereignty over nuclear safety regulation remains paramount, and political, economic, and strategic considerations can slow or limit the adoption of international standards. Differences in legal systems, infrastructure readiness, and public acceptance can also affect how and when countries choose to engage with cooperative frameworks. Despite these challenges, there is a strong consensus that early and sustained collaboration will be essential if SMRs are to be deployed at scale and across diverse geographic regions.

In essence, international cooperation and standards serve as the connective tissue that links SMR innovation to global deployment. Without them, each country would face a steep and costly learning curve in isolation. With them, the path toward safe, secure, and economically viable SMR adoption becomes not only faster but also more robust, ensuring that this emerging technology can contribute meaningfully to a sustainable and secure global energy future.

Chapter 8. Waste Management and Decommissioning

8.1. Strategy for managing nuclear waste from small modular reactors

Small modular reactors (SMRs) are a promising direction for the development of nuclear energy, characterized by increased safety, economic efficiency and flexibility of placement. However, like traditional nuclear facilities, SMRs generate radioactive waste (RW) that requires the development of specialized management strategies. The storage, disposal and environmental risks associated with the waste require special attention due to the potential hazards and negative impacts on human health and the environment.

Radioactive waste from small modular reactors is defined as a set of radioactive materials generated during the operation of SMRs and not subject to further use. This category includes:

- spent nuclear fuel (SNF);
- activated reactor structural materials;
- secondary radioactive waste of operational origin.

The management of radioactive waste from SMRs requires an integrated approach that takes into account potential risks to public health and the environment, as well as long-term radiation safety aspects.

Classification of radioactive waste

Scientifically based classification of radioactive waste is the basis for developing effective management strategies. In international practice, two main classification criteria are used: the level of radioactivity and the aggregate state of the waste.

✓ **Low-level radioactive waste (LLW)**. Low-level waste is characterized by a relatively low content of radionuclides and extremely low heat emission, which allows its transportation without the use of special radiation shielding. This category of waste is subject to disposal in near-surface disposal sites at a depth of up to 30 meters.

In accordance with American legislation (10 CFR Part 61), low-level waste is divided into four classes:

- **Class A:** waste with the lowest activity level that does not require stabilization;
- **Class B:** waste that requires stabilization or placement in stable packaging;
- **Class C:** waste with increased requirements for stabilization and protective barriers;

- **Class GTCC** (Greater Than Class C): waste exceeding the concentration limits for Class C, requiring special handling measures.

✓ **Intermediate-level radioactive waste (ILW).** Intermediate-level waste has an intermediate level of radioactivity, exceeding the characteristics of LLW, but not reaching the criteria for high-level radioactive waste (HLW). The heat emission of this waste category is significant, but does not require the use of active heat removal systems. Handling ILW requires the use of radiation shielding during transportation and special engineering barriers during disposal.

It should be noted that in the US legislation this category of waste is not distinguished as a separate class, whereas in European countries it is widely used in regulatory and legal acts.

✓ **High-level radioactive waste (HLW).** High-level waste poses the greatest radiation hazard and is characterized by significant heat generation, so intense that it requires the use of active cooling systems.

Management of HLW requires the use of a multi-barrier isolation system, including engineering and geological barriers, and placement in deep-seated geological formations.

✓ **Transuranic radioactive waste (TRW)**. The American classification system distinguishes a special category of transuranic waste, which is defined as materials contaminated with alpha-emitting transuranic radionuclides with a half-life of more than 20 years and a specific activity of more than 100 nCi/g (3.7 kBq/g), excluding high-level waste.

Particular attention to transuranic waste is due to the following factors:

- long half-lives of transuranic radionuclides;
- artificial origin of all transuranic elements;
- specific behavior in the biosphere and the human body;
- high radiotoxicity during internal irradiation.

Classification by state of aggregation

✓ **Solid radioactive waste.** Solid radioactive waste constitutes the largest share of the total volume of waste generated by SMRs. This category includes:

- spent fuel elements and their fragments;
- activated structural materials (reactor vessel, internal devices);
- contaminated materials and equipment;
- solidified liquid radioactive waste;

- used personal protective equipment and consumables.

✓ **Liquid radioactive waste**. Liquid radioactive waste is formed in various technological processes:

- primary circuit cooling systems;
- equipment decontamination processes;
- coolant and process media cleaning.

Liquid waste is subject to mandatory processing in order to reduce its volume and convert it into a solid state for subsequent disposal.

✓ **Gaseous radioactive waste**. Gaseous radioactive waste includes:

- radioactive noble gases (krypton-85, xenon-133);
- tritium in the form of water vapor;
- aerosols containing radioactive particles;
- gaseous fission products released from unsealed fuel elements.

Handling gaseous waste requires the use of special purification systems and emission control systems.

Terminology in the field of SMR radioactive waste

For a correct understanding of the problems of SMR radioactive waste management, it is necessary to clearly define the basic terms and concepts used in this area.

1. **Nuclear waste from SMRs** is the totality of all radioactive materials generated as a result of the operation of small modular reactors that cannot be reused in technological processes.
2. **Spent nuclear fuel (SNF)** is defined as nuclear fuel which, due to a change in isotopic composition and the accumulation of fission products, can no longer support a self-sustaining fission chain reaction in a given type of reactor with given neutron-physical parameters of the core.
3. **Contaminated components** include reactor structural elements such as fuel rods, reactor internals, structural materials and process equipment that have acquired radioactive properties as a result of neutron activation or surface contamination during operation.
4. **Radioactive waste (RW)** is liquid, solid or gaseous materials containing radioactive substances in concentrations exceeding the exemption levels established by regulatory documents, generated during the operation of SMRs.

Characteristics and features of spent fuel of SMR

Isotopic composition and quantitative characteristics

SMR spent nuclear fuel is a complex multi-component system, including:

- fission products of uranium-235 and other fissile isotopes;
- transuranic elements (plutonium, neptunium, americium, curium and others);
- residual amounts of unspent uranium-235 and uranium-238;
- activated impurities and corrosion products of structural materials.

The quantitative and qualitative characteristics of spent nuclear fuel are determined by the following factors:

- reactor type and fuel system design;
- initial enrichment in uranium-235;
- fuel burnup;
- irradiation time in the core;
- neutron-physical characteristics of the reactor.

Radiation characteristics of spent fuel

SMR spent fuel has high radioactivity due to the presence of short-lived and long-lived radionuclides. The main sources of radiation are:

- fission products with half-lives from seconds to millions of years;
- transuranic α-emitters with long half-lives;
- neutron-activated isotopes of structural materials.

The intense heat release of spent fuel is caused by the decay energy of radioactive isotopes and requires effective heat removal for a long time after removal from the reactor. The residual heat release decreases exponentially with time, but remains at a significant level for decades.

Radiotoxicity and environmental aspects of spent fuel

Radiotoxicity of spent fuel poses a serious danger to human health and the environment, manifesting itself in the form of:

- direct external irradiation of the body;
- internal irradiation when radionuclides enter the body;
- long-term impact on the genetic apparatus of living organisms;
- Disruption of the structure and functioning of ecosystems.

The long-term radiotoxicity of SMR spent nuclear fuel may differ significantly from that of conventional reactors depending on the content of long-lived transuranic elements and the fuel cycles used.

Spent Fuel Management Strategies

The following main strategies exist for handling SMR SNF:

- **Direct disposal** involves the placement of spent fuel in deep geological formations without prior processing, provided that long-term isolation from the biosphere is ensured.
- **Long-term intermediate** storage is the controlled placement of spent nuclear fuel in special storage facilities for a period of up to several centuries with the possibility of subsequent extraction.

Comparative analysis with traditional reactors (features of SMR waste)

Small modular reactors have a number of features that affect the characteristics of the resulting spent fuel:

- **Increased burnout depth** can lead to a decrease in the specific volume of waste generated, but at the same time increases the content of long-lived radionuclides.
- **Alternative fuel cycles** (e.g. thorium-uranium cycle) can significantly change the isotopic composition and radiation characteristics of SNF.
- **The use of liquid metal** coolants in some SMR designs can provide more efficient use of neutrons and reduce the volume of transuranic waste.

Spent Fuel Storage Systems.

Storing spent nuclear fuel is a fairly complex process. After processing, radioactive waste is stored in specially designated areas where it is isolated and localized, as well as allowing for easy retrieval at the end of the storage period.

International Standards and Guidelines

The International Atomic Energy Agency (IAEA) plays a key role in developing international safety standards for the management of radioactive waste and spent fuel. The Agency ensures:

- development of safety standards for radioactive waste and spent nuclear fuel management systems;
- technical support to Member States in the implementation of safe technologies;
- coordination of the activities of the Waste Safety Standards Committee;

- functions of the secretariat of the Joint Convention on the Safety of Spent Fuel and of Radioactive Waste Management.

The IAEA covers a wide range of radioactive waste management issues, including policy and strategy development, inventory assessment, economic analysis and waste minimization.

The choice of spent nuclear fuel storage method depends on many factors, including reactor type, fuel capacity, storage time, and technology availability.

Interim Storage

- ✓ **Wet Storage in Pools**

Primary storage of spent fuel is carried out in special pools filled with demineralized water, which performs the following functions:

- removal of residual heat from fuel elements;
- radiation protection of personnel and equipment;
- prevention of the spread of radioactive substances.

The wet storage system requires continuous monitoring and control of:

- radiation conditions in the storage area;
- temperature conditions of the water in the pool;
- chemical composition and purity of the water;
- integrity of the fuel element shells.

This method is temporary and is usually used for a period of several years to several decades.

- ➢ **Dry Intermediate Storage**

After sufficient reduction of heat generation, spent fuel is transferred to dry storage systems, which are characterized by the following features:

- placement of spent nuclear fuel in sealed metal containers;
- use of an inert gas environment (usually helium or argon);
- passive heat removal through natural convection;
- multi-barrier protection system (metal shells, concrete structures).

Dry storage provides increased safety and is seen as a longer term solution compared to wet storage.

Handling high-level waste

High-level radioactive waste requires the use of specialized storage systems with increased safety requirements:

- multi-level physical protection system;
- continuous radiation and environmental monitoring;
- redundant security systems;
- emergency response plans.

Strategic approaches to HLW management include:

- The process to recover valuable radioactive materials (uranium, plutonium) for reuse in the fuel cycle and to significantly reduce the volume of final waste.
- Conditioning by incorporating high-level waste into stable matrices (glass, ceramics, and synthetic minerals) to ensure long-term immobilization of radionuclides.

Problems and challenges of waste disposal

The development of safe technologies for the disposal of radioactive waste faces a number of serious problems:

➢ **Technical challenges:**
- the need to ensure the long-term integrity of engineered barriers;
- modeling the behavior of radionuclides in the geological environment;
- development of container materials with the required durability.

➢ **Economic aspects:**
- significant capital costs for the creation of geological repositories;
- the need for long-term financing of disposal programs;
- economic optimization of various waste management strategies.

➢ **Socio-political factors:**
- public perception of the risks associated with nuclear technologies;
- political resistance to the selection of sites for storage facilities;
- the need to ensure public participation in the decision-making process.

➢ **Transportation issues:**
- Ensuring safety during transportation of highly active materials;
- Development of specialized transport containers;
- Planning routes and emergency response procedures.

8.2. Long-term solutions for SMR waste disposal

Long-term solutions for radioactive waste management from small modular reactors

The development of small modular reactor (SMR) technologies is one of the most promising areas of modern nuclear energy. However, the widespread introduction of these technologies is impossible without solving fundamental issues of handling radioactive waste generated during the operation of SMRs.

The problem of long-term management of radioactive waste from SMRs is complex, combining technical, environmental, social and economic aspects. The specific design features of small modular reactors necessitate the development of adapted approaches to waste management that take into account both the general principles of radiation safety and the specific features of this type of nuclear installation.

Specifics of formation and characteristics of SMR waste

Design features of SMRs and their impact on waste composition

Small modular reactors are characterized by a number of design features that significantly affect the characteristics of the radioactive waste generated. The attributes of SMR nuclear waste show both similarities with pressurized water reactor (PWR) waste and significant differences due to specific technical features.

One of the key features of SMR is increased neutron leakage, which is due to the smaller size of the reactor core. This neutron-physical characteristic has a significant impact on the composition and volume of radioactive waste generated, requiring the adaptation of existing technologies for handling it.

Features of the SMR fuel cycle

The fuel cycle of small modular reactors has a number of specific characteristics. SMRs can use different types of nuclear fuel. Many advanced reactor designs, including small modular reactors (SMRs), will require fuel based on High-Assay Low Enriched Uranium (HALEU), which has a uranium-235 content of 5 to 20 percent, compared to the 5 percent content found in most operating nuclear power plant fuels. This requires the development of specialized methods for the processing and disposal of spent nuclear fuel (SNF).

Despite their smaller size compared to traditional nuclear power plants, SMRs can produce relatively large volumes of radioactive waste. This feature is due to the specific design of the reactors and their operating modes, which must be taken into account when planning waste management systems.

Utilization of SMR waste

Modular processing systems

A promising direction for the development of SMR waste management technologies is the creation of modular processing systems. This approach involves integrating processing units directly into the structure of modular reactors, which ensures minimization of waste generation and its efficient processing at the site of generation or origin.

Modular processing systems reduce the transport risks associated with the transportation of radioactive materials and ensure more efficient management of waste flows of various activity categories.

Radioactive Waste Disposal Technologies

Waste Classification and Disposal Methods

SMR radioactive waste is classified according to its activity level, which determines the choice of appropriate disposal technologies:

Very low-level waste (VLLW) is potentially hazardous for periods not exceeding several centuries. Surface backfill trenches equipped with a limited system of engineering barriers are used for VLLW disposal. This approach provides the required level of safety at relatively low economic costs.

Low-level waste (LLW) can also be safely stored in near-surface repositories less than 30 meters deep.
The technology of NAW burial is based on a combination of natural protective properties of the disposal site and engineering barriers, including specialized lining, concrete burial chambers and drainage systems. Currently, there are about 140 installations for near-surface burial of these waste categories in the world.

Intermediate-level waste (ILW) requires disposal in a stable geological environment capable of ensuring long-term safety without active human intervention for several thousand years. The technology for disposal of ILW is well developed and successfully used in a number of developed countries.

High-level waste (HLW) and spent fuel declared as waste pose a radiation hazard for hundreds of thousands of years. This category of waste requires disposal in a stable geological environment at significant depths, ensuring reliable isolation for several hundred thousand years.

Specialized storage facilities

The development of technologies for long-term storage of radioactive waste includes the creation of various types of specialized storage facilities:

Ground-based long-term storage facilities involve the design of safe geological or surface structures for temporary or long-term waste storage. These facilities must ensure reliable isolation of radioactive materials and the ability to monitor their condition throughout the entire storage period.

Geological containment ensures the placement of high-level waste in deep geological formations such as salt domes or stable rocks, which ensure long-term isolation from the environment. Deep geological disposal concepts include the development of underground repositories with increased reliability of a multi-barrier protection system.

International experience in geological disposal

Some countries have made significant progress in developing and implementing geological disposal projects for high-level waste:

International experience demonstrates that, from a technical point of view and from the standpoint of ensuring long-term safety, geological disposal is a technically feasible and scientifically sound solution. Various types of host rocks have been found to be suitable for safe geological disposal, including crystalline, sedimentary (clayey) and evaporitic (halite) rocks.

Innovative approaches and promising technologies for handling SMR waste

Modern materials and technologies. The development of technologies for handling SMR waste includes the development of modern materials for sealing and long-term protection of radioactive waste. Particular attention is paid to research in the field of transuranic elements and the development of technologies for their processing to significantly reduce the long-term radiotoxicity of waste.

Innovative materials for the creation of engineering barriers must ensure stability of properties under conditions of radiation exposure and aggressive chemical environments over extremely long periods of time.

Monitoring and research systems. Effective management of SMR radioactive waste requires continuous research into the behaviour of waste and its storage materials, including detailed analysis of their impact on the environment over decades. These studies constitute a critical component of a long-term waste management strategy.

The creation of modern monitoring and early warning systems is aimed at preventing emergency situations and ensuring long-term safety of radioactive waste storage. These systems must function automatically and ensure continuous monitoring of the storage facilities.

Principles of Radioactive Waste Management

The International Atomic Energy Agency (IAEA) has formulated fundamental principles for radioactive waste management aimed at ensuring the protection of human health and the environment without placing an undue burden on future generations:

1. **Protection of human health**. The radioactive waste management system must ensure an acceptable level of protection of human health at all stages of the waste life cycle.
2. **Environmental protection**. Waste management strategies should ensure an acceptable level of environmental protection, including the conservation of ecosystems and biological diversity.
3. **Protection beyond national borders**. Potential transboundary impacts on human health and the environment must be taken into account when developing waste management strategies.
4. **Protection of future generations**. Foreseeable health effects for future generations should not exceed relevant levels of effects that are acceptable at present.
5. **Minimize the burden on future generations**. Waste management strategies should not impose an undue burden on future generations in terms of maintenance and financial obligations.
6. **National legal framework**. Radioactive waste management should be carried out within an appropriate national legal framework with a clear division of responsibilities and provision for independent regulatory functions.
7. **Control of radioactive waste generation**. The generation of radioactive waste shall be kept at a minimal, practically feasible level.
8. **Consideration of interdependencies**. Due consideration shall be given to the interdependencies between all stages of radioactive waste generation and management.
9. **Safety of installations**. The safety of installations for handling radioactive waste must be ensured throughout their entire service life.

Environmental risks and implementation issues

Environmental risks of nuclear waste from SMRs

Management of radioactive waste from SMRs is associated with a number of potential environmental risks that require a comprehensive analysis and development of appropriate protective measures:

Radioactive contamination. Improper storage and disposal of radioactive waste may lead to radioactive contamination of environmental components, including soil, surface and ground water, and atmospheric air.
Biological risks. Ionizing radiation can cause genetic mutations, cancer, and other deterministic and stochastic effects that negatively affect human health and the state of the biota.
Long-term effects: Some radionuclides have extremely long half-lives, meaning radioactive contamination can persist for hundreds or thousands of years, requiring long-term waste isolation strategies.

Problems of Implementing Disposal Strategies

Despite significant technical advances in the field of radioactive waste management, the practical implementation of final disposal strategies remains one of the most complex modern problems in the field of spent fuel and radioactive waste management in many countries.

The main difficulties in the successful implementation of disposal projects are:

- High capital costs for the construction and operation of geological storage facilities;
- The complexity of long-term planning and ensuring institutional stability over centuries;
- The need to develop international coordination and harmonization of approaches to solve global waste management problems;
- Difficulties in public perception and ensuring social acceptability of large infrastructure projects in the field of nuclear energy.

Current status and development prospects for the disposal of SMR waste

Currently, there are no generally accepted international standards for the disposal of SMR waste, which is due to the relative novelty of this technology and ongoing research in the field of optimization of small modular reactor designs.

The field of SMR waste management is actively developing and requires intensification of international cooperation and development of uniform safety standards. Ensuring the safety of waste disposal is a priority in the development and industrial operation of SMR.

The creation of an effective SMR waste management system is a necessary condition for ensuring the sustainable development of nuclear energy and the formation of a positive public perception of this promising technology.

8.3. Decommissioning processes for Small Modular Reactors

Small modular reactors (SMRs) are a promising direction for the development of nuclear energy, characterized by compactness, modular design and increased safety. However, the end of the life cycle of these installations requires a special approach to decommissioning processes, taking into account their design features and technological characteristics.

The process of decommissioning SMRs is a complex interdisciplinary task requiring a deep understanding of nuclear technologies, radiation safety, environmental requirements, economic aspects, integration of advanced technologies, international cooperation and innovative approaches to address the unique challenges associated with the compact integrated design of these reactors.

The complete decommissioning cycle of SMRs can take 15-25 years, which is comparable to traditional nuclear power plants, but can be reduced due to the modular design and smaller scale of the plants. Successful implementation of SMR dismantling programs requires advance planning, creation of an appropriate technological base and training of qualified personnel.

General principles and stages of SMR decommissioning

Fundamental principles. The process of decommissioning small modular reactors is based on the following fundamental principles:

The safety principle implies ensuring radiation protection of personnel, the population and the environment at all stages of dismantling. This is achieved through the use of a safety barrier system, strict adherence to dose limits and the use of the ALARA (As Low As Reasonably Achievable) principle.

The principle of environmental sustainability requires minimizing the impact on the environment through the use of modern waste processing technologies, land restoration and compliance with environmental standards.

The principle of economic feasibility provides for the optimization of dismantling costs while maintaining a high level of safety and quality of the work performed.

Structure of the decommissioning process

The process of decommissioning of SMRs is structured in the form of successive stages, each of which has specific goals, objectives and completion criteria.

Stage 1. Planning and preparation (1-2 years).

The preparatory stage includes the development of a comprehensive dismantling strategy taking into account the design features of a specific type of SMR. At this stage, the following is carried out:

- Development of a detailed program for description of radioactive materials, including an inventory of all activated components and an assessment of their activity;
- Creation of a dosimetric monitoring system and planning of dose loads for personnel;
- Preparation of specialized equipment for working with compact modular structures;
- Development of remote dismantling methodology for integrated systems;
- Obtaining necessary licenses and permits from regulatory authorities.

Stage 2. Fuel unloading and systems preparation (2-3 years)

This stage is characterized by the implementation of operations for the safe removal of spent nuclear fuel and preparation of reactor systems for dismantling:

- Unloading spent nuclear fuel into on-site storage facilities, ensuring the required holding time to reduce residual heat generation
- Drainage and decontamination of coolant circuits using specialized decontamination solutions
- Flushing of steam generators, which is especially important for integral SMR structures
- Dismantling of control and protection systems while maintaining the necessary monitoring systems
- Modification of ventilation systems to ensure the safety of dismantling work.

Stage 3. Dismantling of in-reactor devices (3-5 years)

This stage is characterized by increased complexity of operations due to the high level of activation of components:

- Removal of control systems and emergency protection systems using remote technologies;
- Dismantling of internal structures taking into account their activation by neutron flux;
- Segmentation of the active zone with special attention to the compactness of the SMR design;
- Removal of the remaining coolant of the primary circuit and its processing;
- Processing of highly active components using robotic systems.

Stage 4. Dismantling the reactor vessel (5-8 years)

The most technically difficult stage, especially for integral SMR structures:

Technical features of dismantling the integral vessel:

Underwater cutting is carried out under conditions of maintaining water protection, which ensures radiation safety, but creates problems with visual control of the process and management of radioactive sludge.

Various cutting technologies are used: arc cutting in a water environment for large elements, mechanical cutting with circular saws for precision operations, laser cutting for particularly critical connections, water jet cutting with abrasive for complex profile parts.

Planning of cuts requires high precision to extract embedded components while minimizing the number of cuts and reducing personnel exposure.

Stage 5. Dismantling of auxiliary systems (3-4 years)

Includes dismantling of systems that ensure the functioning of the reactor:

- Coolant purification and water treatment systems;
- Emergency cooling and safety systems;
- Radioactive waste handling systems;
- Piping systems and auxiliary equipment.

Stage 6. Final decontamination (2-3 years)

The final stage includes:

- Decontamination of buildings, structures and remaining equipment;
- Comprehensive radiation survey of the territory;
- Work on restoration and reclamation of the site;
- Obtaining permission to be released from regulatory control.

Design features of SMR and their impact on dismantling processes

Integral design. Many modern SMRs are characterized by an integral design, where the main components of the primary circuit (reactor vessel, steam generators, pressurizer) are combined in a single sealed housing. This feature creates specific technological challenges:

Limited access to components is due to the fact that the steam generators are built directly into the reactor vessel, which excludes the possibility of their separate dismantling. This requires the use of specialized tools for working in a limited space and creates difficulties in visual control of the process.

The difficulties of segmentation are manifested in the impossibility of dismantling components separately, the need to simultaneously cut the housing and internal elements, and the increased risk of damage to adjacent components during cutting operations.

Modularity and transportability. The modular design of the SMR opens up the possibility of dismantling entire modules with subsequent transportation to specialized enterprises for final processing. However, this requires:

- Development of special containers for transporting activated modules;
- Solutions to logistics problems related to the movement of heavy integral units;
- Creation of specialized enterprises for processing SMR modules.

Typological features of various SMRs

Reactors with liquid metal coolant are characterized by problems with coolant solidification when the temperature decreases, which requires maintaining a high system temperature during dismantling and creating special technologies for handling sodium or lead.

High-temperature gas-cooled reactors create difficulties with dismantling graphite structures, problems with dust formation during graphite cutting and the need to use special gas cleaning systems.

Molten salt reactors are characterized by problems with equipment corrosion, difficulties in handling radioactive salts, and the need to develop special technologies for processing salt waste.

Management of radioactive waste during dismantling of SMRs

Classification of waste during dismantling of SMRs

Radioactive waste generated during dismantling of SMRs is classified by activity level:

- ❖ **High-level waste** includes components of the active zone and the most activated parts of the reactor vessel. It is characterized by high levels of β- and γ-radiation, significant heat generation and requires special handling conditions.
- ❖ **Medium-level waste** is represented by heat exchange equipment, primary circuit pipelines and internal vessel structures. They require remote handling and special conditioning technologies.
- ❖ **Low-level waste** includes protective equipment, elements of building structures that have come into contact with radioactive substances. They can be processed using contact methods, provided that radiation protection measures are observed.
- ❖ **Conditionally clean materials** make up a significant part of building structures and can be exempted from regulatory control after detailed radiation monitoring.

Waste conditioning technologies

- **Segmentation of large-sized components** is carried out using various cutting technologies: plasma, laser, mechanical, water-jet. The choice of technology is determined by the characteristics of the material, the activity level and the geometry of the component.
- **Compaction of low-level waste** allows to significantly reduce waste volumes and optimize disposal costs. Hydraulic presses, supercompactors and metal waste melting technologies are used.
- **Vitrification of liquid high-level waste** ensures long-term matrix stability and minimizes radionuclide leaching. The technology involves evaporation, calcination, and vitrification in special furnaces.
- **Cementation of intermediate-level waste** is a cost-effective immobilization technology that provides the necessary physical and chemical properties of the waste form.

Ensuring radiation safety during decommissioning

Features of the radiation situation

The compact design of SMRs results in higher specific activation levels of materials compared to large power reactors. The integral layout creates difficulties with remote radiation monitoring in a limited space and requires the use of special means of personnel protection.

Strategies for Ensuring Radiation Safety

- ✓ **The optimization principle (ALARA)** is implemented through the maximum use of robotic systems, temporary shielding of work areas, optimization of the sequence of operations and preliminary decontamination of accessible surfaces.
- ✓ **Dosimetric planning** includes detailed calculation of dose fields, planning of personnel movement routes, determination of the time of operations and optimization of protective measures.
- ✓ **The collective dose is minimized** through the application of the substitution principle (use of robotics instead of manual labor), time protection (reducing the time spent in radiation fields) and distance protection (maximum distance from radiation sources).

Modern dismantling technologies

Modern technologies for dismantling radioactive objects widely use the latest technical, system and digital developments.

1. Robotic systems. The use of robotics is a key factor in ensuring the safety and efficiency of the SMR dismantling process:

- **Specialized robots** include compact robots for working in the confined spaces of integral structures, robotic manipulators for performing precise cutting and assembly operations, and mobile platforms for transporting materials and equipment.
- **Remote control systems** provide remote control of cutting systems, remote monitoring of radiation conditions and automation of waste handling processes.

2. Advanced decontamination methods

- **Laser decontamination** provides precise removal of contaminants from surfaces while minimizing secondary waste and the ability to work in hard-to-reach areas of integral structures.
- **Electrochemical decontamination** allows for controlled removal of activated metal layers, dissolution of surface contaminants and regeneration of decontamination solutions.

3. Digital technologies

- **3D modeling** is used for detailed planning of the sequence of dismantling operations, optimization of equipment and personnel movement trajectories, and modeling of radiation fields.
- **Augmented reality** is used to train personnel, visualize hidden design elements and support decision-making in real time.
- **Digital twins** provide virtual modeling of the dismantling process, optimization of process parameters and personnel training on virtual models.

Economic aspects of dismantling SMR

Cost structure

- **Planning and licensing (15-20%)** includes developing a detailed dismantling plan, conducting radiation surveys, obtaining licenses and regulatory approvals.
- **Special equipment (20-25%)** includes remote control systems, robotic complexes, specialized tools for cutting and handling activated materials.
- **Dismantling and decontamination (40-50%)** constitute the main cost item and include payment for specialized personnel, energy costs, and transportation costs.
- **Waste management (25-30%)** includes waste conditioning, transportation to disposal sites, and disposal fees.
- **Restoration of the site after dismantling (10-15%)** includes demolition of auxiliary structures, reclamation of the territory, and long-term monitoring of residual pollution.

Economic advantages of SMR dismantling

Smaller volumes of activated materials compared to large power reactors result in potentially lower dismantling costs. The modular design allows for standardization of processes and equipment, which helps reduce unit costs.

The expected cost of decommissioning SMRs is 10-20% of the capital costs of construction, which may be more profitable compared to large nuclear power plants, where this figure reaches 15-30%.

Regulatory aspects and international cooperation

➢ **Current regulatory status**

Since most SMRs are in the development or early operation phase, many countries do not yet have a comprehensive regulatory framework to address the specific decommissioning requirements of these facilities.

- Licensing of dismantling is characterized by the absence of standardized procedures, uncertainty of documentation requirements, and the need to adapt existing regulations to new technologies.
- The criteria for material clearance require clarification in terms of clearance from regulatory control, classification of new materials and accumulation of experience with activated SMR materials.

➢ **Regulatory development prospects**

Developing a standardized international regulatory framework for SMR decommissioning could significantly simplify the process and facilitate the dissemination of best practices across the industry. This includes harmonizing approaches to waste classification, unifying safety criteria, and standardizing licensing procedures.

Prospects for the development of dismantling technologies

✓ **Design for dismantling**. Current trends in the design of SMRs include the inclusion of dismantling requirements at the design stage. This includes the use of materials with short half-lives, modular design to simplify dismantling, and the use of removable joints instead of welded ones.

✓ **Development of processing technologies**. Promising areas include processing of activated metals with extraction of valuable elements, technologies for volumetric waste reduction, extraction of valuable isotopes from radioactive waste for medical and industrial applications.

International cooperation in the field of dismantling SMRs

Development of international cooperation in the field of dismantling SMRs includes the exchange of experience and technologies, the creation of international standards and recommendations, and the joint development of advanced dismantling technologies.

As experience in operating SMRs increases and dismantling technologies develop, it is expected that processes will be optimized, costs will be reduced, and the safety of decommissioning operations for these advanced power plants will be improved.

Chapter 9. Research and Development in SMR Technology

9.1 Current R&D trends in SMR development

Current research and development (R&D) trends in small modular reactor (SMR) development reflect the global effort to enhance nuclear energy's safety, flexibility, and competitiveness in the evolving energy landscape. Unlike traditional large-scale reactors, SMRs are being designed to meet a variety of modern energy challenges such as integration with renewables, provision of non-electric applications, and deployment in regions with limited infrastructure.

One major trend is advanced reactor designs. Several SMR concepts go beyond light-water reactor (LWR) technology and explore innovative coolants and configurations. For example, molten salt reactors (MSRs) and sodium-cooled fast reactors (SFRs) are receiving significant attention due to their potential for higher efficiency, improved safety margins, and the ability to burn long-lived actinides, thereby reducing nuclear waste. High-temperature gas-cooled reactors (HTGRs) are being developed for their capacity to deliver both electricity and process heat at temperatures exceeding 700°C, making them attractive for hydrogen production and industrial heat applications. Meanwhile, water-cooled SMRs—such as NuScale in the U.S., and SMART in South Korea—are progressing toward licensing and commercialization, serving as the first wave of deployable SMRs.

Another area of focus is safety and passive systems. R&D is directed toward designs that maximize inherent safety through natural circulation, gravity-fed cooling, and other passive mechanisms that eliminate or minimize the need for active operator intervention in emergencies. These features are meant to substantially reduce the probability of core damage and enhance public trust in nuclear technology.

The modular manufacturing approach is also a defining trend. Researchers and industry are working on fabrication techniques that allow SMR components to be mass-produced in factories and shipped to sites for assembly. This approach not only reduces construction times and costs but also improves quality control and standardization. Coupled with digital engineering, advanced materials, and 3D printing technologies, modularity is expected to lower financial risks and attract broader investment.

There is also increasing emphasis on hybrid energy systems and grid integration. SMRs are being studied as flexible complements to renewable sources like solar and wind, providing backup generation during periods of intermittency and enhancing overall grid reliability. Pilot projects are exploring how SMRs can be operated in load-following modes, dynamically adjusting power output in response to fluctuating demand.

In addition, non-electric applications are emerging as a central driver of SMR innovation. These include water desalination, district heating, hydrogen production, and supplying high-quality process heat for industries such as steelmaking, chemical synthesis, and petrochemicals. Such applications can significantly expand the role of nuclear energy beyond electricity generation and strengthen its value proposition in decarbonization strategies.

International collaboration is another strong R&D trend. Organizations such as the International Atomic Energy Agency (IAEA), Generation IV International Forum (GIF), and World Nuclear Association (WNA) are coordinating efforts to establish safety standards, harmonize licensing processes, and encourage knowledge sharing. Several multinational projects, such as the European Union's work on advanced modular reactors, highlight how cooperative frameworks are accelerating innovation and deployment.

Finally, significant research is underway on fuel cycles and sustainability. Efforts include the development of accident-tolerant fuels (ATFs) that can withstand higher temperatures and prolonged transients, as well as the exploration of closed fuel cycles where SMRs use recycled nuclear material to minimize waste.

In summary, R&D trends in SMR development converge on four broad goals: making nuclear safer through passive and innovative designs, making it more economical through modular construction and factory production, expanding its role through hybrid and non-electric applications, and ensuring sustainability through advanced fuels and waste minimization. Together, these trends are shaping SMRs into a versatile, scalable, and globally relevant energy solution.

9.2 Materials science and advanced fuels for SMRs

Materials science and the development of advanced fuels are central to the ongoing progress and optimization of small modular reactors (SMRs). Since SMRs are designed to operate under unique conditions—often at higher levels of efficiency, with longer fuel cycles, and in remote or unconventional deployment scenarios—significant emphasis is placed on the selection and advancement of materials that can withstand harsh environments and provide enhanced safety margins.

One of the foremost considerations in SMR materials science is structural integrity under prolonged exposure to neutron irradiation, high temperatures, and corrosive coolants. Reactor pressure vessels, core internals, and piping must maintain strength and resist embrittlement despite years of exposure to radiation and thermal cycling. Advanced alloys, such as high-chromium ferritic-martensitic steels, oxide dispersion-strengthened steels, and nickel-based superalloys, are under extensive research for their superior creep resistance, thermal stability, and reduced swelling under irradiation. For SMRs using coolants beyond traditional light water—such as liquid metals (sodium, lead, or lead-bismuth eutectic), supercritical CO_2, or molten salts—the materials challenge becomes even greater. Corrosion resistance in these environments requires protective coatings, self-healing surface treatments, or the development of entirely new classes of high-performance alloys.

The fuel cycle is another domain of intense innovation in SMR technology. Traditional uranium dioxide (UO_2) fuel remains the baseline, but it has limitations in terms of thermal conductivity and burnup potential. To address this, accident-tolerant fuels (ATFs) are being investigated. These include uranium silicide (U_3Si_2), which has a higher uranium density and thermal conductivity, and silicon carbide or advanced metallic claddings, which are more resistant to oxidation and hydrogen production under accident conditions compared to conventional zirconium alloys. These ATFs not only improve safety margins but also extend fuel lifetimes, reducing the need for frequent refueling—an important feature for SMRs intended for deployment in remote regions or for maritime and space applications.

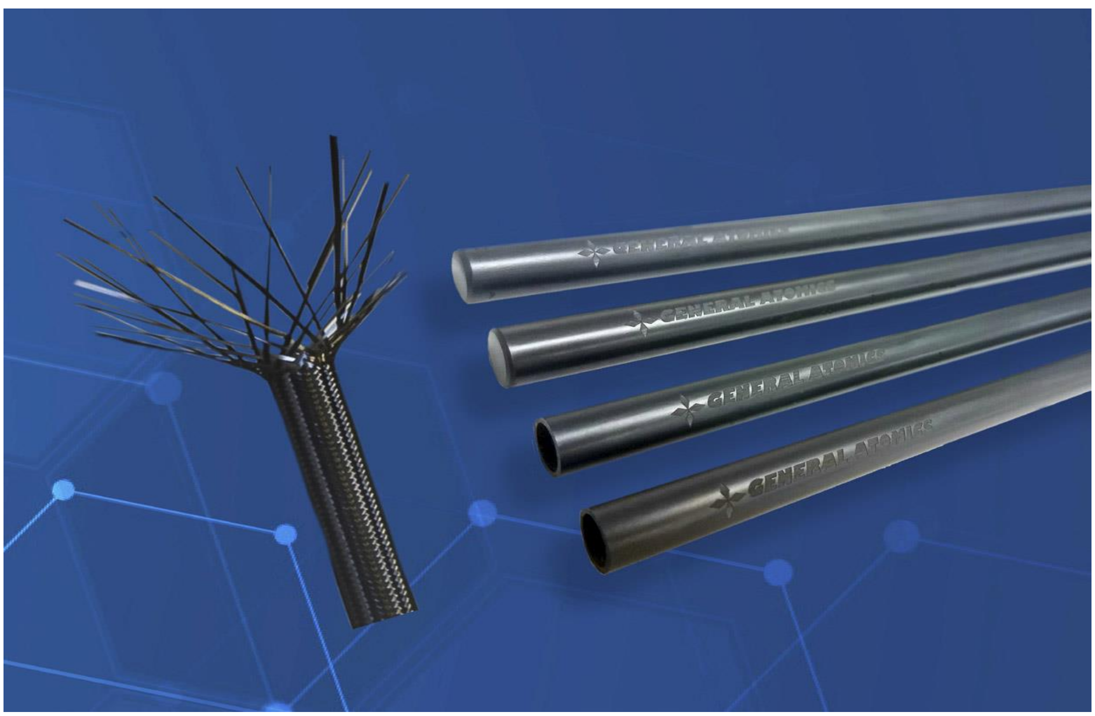
High-assay low-enriched uranium (HALEU), enriched between 5% and 19.75% U-235, is a particularly important fuel innovation for many advanced SMR designs. HALEU allows for more compact core configurations, longer fuel cycles (sometimes exceeding ten years), and supports advanced reactor types such as molten salt reactors and fast-spectrum SMRs. The use of HALEU, however, raises new challenges related to enrichment, fabrication, transportation, and proliferation safeguards, necessitating close cooperation between governments, industry, and international regulators.

In addition to uranium-based fuels, research is ongoing into thorium-based fuel cycles and mixed oxide (MOX) fuels. Thorium, with its abundance and potential for breeding fissile uranium-233 in situ, offers a pathway toward sustainable long-term nuclear fuel resources.

MOX fuels, combining plutonium with uranium, provide a mechanism for recycling fissile material from spent fuel, thereby contributing to waste reduction strategies.

Coatings and cladding innovations further strengthen SMR safety and performance. Silicon carbide composites, chromium-coated zirconium alloys, and advanced ceramic materials are being explored to enhance oxidation resistance, limit fission product release during accidents, and extend operational lifetimes. The miniaturized and modular nature of SMRs allows researchers to test these material combinations in pilot configurations more rapidly than in conventional large reactors, accelerating innovation cycles.

Ultimately, materials science and advanced fuel development are the foundation of SMRs' promise for safe, efficient, and flexible nuclear power. Breakthroughs in this field will dictate not only the technical feasibility of SMRs but also their economic competitiveness, their ability to integrate with renewable systems, and their role in long-term energy strategies worldwide. Research in this area remains highly interdisciplinary, combining nuclear physics, chemistry, metallurgy, and engineering, with a strong emphasis on international collaboration to standardize materials testing, qualification, and deployment for global SMR adoption.



9.3 Simulation and modeling of SMRs

Simulation and modeling play a central role in the development, optimization, and safe deployment of small modular reactors (SMRs). Unlike traditional large-scale reactors, SMRs rely heavily on advanced computational tools to design compact cores, evaluate novel passive safety systems, predict operational performance, and meet stringent regulatory requirements before physical prototypes are built. Modern computational methods allow engineers to create virtual environments in which all aspects of reactor operation, from neutron transport to thermal hydraulics, can be studied with high fidelity and under a wide range of scenarios that would otherwise be impossible or costly to reproduce experimentally.

One of the most important areas of SMR simulation is neutronics, which involves solving the neutron transport equations to predict the spatial and temporal distribution of neutron flux within the reactor core. Accurate neutronic modeling ensures that power generation remains stable, fuel utilization is optimized, and safety margins are maintained. State-of-the-art Monte Carlo codes such as MCNP and SERPENT are commonly used, alongside deterministic methods that provide faster calculations suitable for design iterations. These tools enable engineers to test different core geometries, fuel enrichments, and reflector materials, all within the constraints of SMR compactness and modularity.

Thermal-hydraulic simulations are equally critical, as they allow researchers to analyze coolant flow, heat transfer, and temperature distribution in both steady-state and transient conditions. In SMRs, where passive safety relies heavily on natural circulation and simplified coolant pathways, it is crucial to understand how fluids behave under normal operation and during potential accident scenarios. Computational fluid dynamics (CFD) software such as ANSYS Fluent, OpenFOAM, and STAR-CCM+ is used to model complex flow regimes, boiling phenomena, and phase changes within the coolant system. Coupling these models with neutronic codes creates multiphysics simulations that more accurately represent real reactor behavior.

Beyond neutronics and thermal hydraulics, structural mechanics and materials performance are modeled to ensure that reactor components can withstand thermal stresses, irradiation damage, and corrosion over long operational lifetimes. Finite element analysis (FEA) software is applied to predict deformation, fatigue, and fracture in reactor pressure vessels, piping, and fuel cladding. Since SMRs may be located in remote or offshore environments, modeling also extends to seismic and environmental loading conditions, ensuring that designs remain robust under external stresses.

Another important domain of SMR modeling is system dynamics and safety analysis. Advanced codes such as RELAP5, TRACE, and SAS4A/SASSYS are employed to simulate accident scenarios, such as loss-of-coolant accidents (LOCA), station blackout, or reactivity insertion events. These simulations provide regulators with essential data on how SMRs respond to extreme conditions and demonstrate that passive safety systems—such as natural circulation cooling and gravity-driven shutdown mechanisms—can effectively prevent core damage. By conducting thousands of virtual accident simulations, designers can refine system layouts, eliminate vulnerabilities, and optimize emergency procedures before real-world implementation.

Digital twins and high-performance computing are increasingly being adopted in SMR development. A digital twin is a continuously updated virtual replica of a reactor that integrates real-time operational data from sensors with predictive models. This approach allows operators to monitor system health, predict failures, and optimize performance during the entire reactor lifecycle. In parallel, the use of exascale supercomputers allows simulations with unprecedented resolution, enabling direct modeling of phenomena such as turbulent flow, fuel microstructure evolution, and multiphase boiling at scales that were previously inaccessible.

Human factors and operator training are also supported by simulation technologies. Virtual reality (VR) and augmented reality (AR) platforms are used to create immersive reactor control room environments where operators can practice responding to normal operations and emergency conditions. These training simulators reduce the risk of human error and improve preparedness without requiring access to an actual SMR.

Overall, simulation and modeling are indispensable for the SMR industry because they allow comprehensive testing, validation, and optimization of designs at a fraction of the cost and time required for physical experiments. They bridge the gap between conceptual reactor designs and commercial deployment, ensuring that SMRs achieve their goals of safety, efficiency, and adaptability. As computational methods continue to advance, the ability to simulate entire SMR systems with high fidelity will accelerate licensing processes, reduce development risks, and enhance public and regulatory confidence in this new generation of nuclear technology.

Chapter 10. SMRs in the Energy Transition

10.1 Role of SMRs in achieving energy security

Small Modular Reactors (SMRs) have a critical role to play in strengthening energy security at both national and global levels. Unlike large conventional nuclear plants that require significant upfront investments, long construction timelines, and complex infrastructure, SMRs provide a flexible and scalable solution that can adapt to the diverse energy needs of different regions. Their smaller size allows them to be deployed in areas where large reactors would be impractical, including remote locations, islands, and regions with less robust grid systems. This adaptability ensures that reliable, low-carbon energy can reach places traditionally dependent on imported fossil fuels, thereby reducing exposure to supply chain vulnerabilities and volatile fuel prices.

SMRs also contribute to energy diversification, a key pillar of energy security. By integrating nuclear power into the energy mix alongside renewables, natural gas, and other sources, they reduce overreliance on any single resource. Their ability to operate continuously, regardless of weather conditions, provides a stable backbone for electricity generation, complementing the intermittent nature of renewable sources such as solar and wind. This firm, dispatchable power is vital for ensuring grid stability, especially as more renewable capacity is introduced.

Furthermore, SMRs are designed with enhanced safety features, including passive safety systems and underground containment, which minimize the risk of accidents and reduce public and regulatory concerns. Their modular construction also shortens deployment times and lowers investment risks, enabling governments and private investors to gradually expand capacity as demand grows. This incremental approach makes nuclear energy more accessible to countries with limited capital or infrastructure.

In the broader geopolitical context, SMRs can reduce dependency on imported fossil fuels, which often come from politically unstable regions. By fostering domestic nuclear capacity, countries enhance their energy independence and resilience against global energy market disruptions. Additionally, SMRs hold the potential to support non-electric applications, such as district heating, hydrogen production, and desalination, further broadening their contribution to secure and sustainable energy systems.

Ultimately, the deployment of SMRs represents a strategic pathway to achieving long-term energy security. By ensuring reliable, clean, and adaptable power generation, they can help nations meet rising energy demands, stabilize their power grids, and reduce their vulnerability to external shocks, all while supporting the global transition toward a low-carbon future.

10.2 Contribution to Global Energy goals

Small Modular Reactors (SMRs) are increasingly recognized as an important component in advancing global energy goals, particularly in the context of decarbonization, energy security, and sustainable development. As the world works toward achieving the targets outlined in the Paris Agreement and the United Nations Sustainable Development Goals (SDGs), the need for clean, reliable, and scalable energy solutions has become more urgent. SMRs, with their unique design and operational advantages, provide a pathway to complement renewable energy sources while addressing the persistent challenges of carbon emissions, grid reliability, and equitable energy access.

One of the key contributions of SMRs lies in their potential to significantly reduce greenhouse gas emissions. Unlike fossil fuel–based energy sources, SMRs generate electricity with virtually no direct carbon emissions. Their deployment can therefore accelerate the transition away from coal, oil, and natural gas in both developed and developing regions. This makes SMRs an essential tool for countries striving to meet their Nationally Determined Contributions (NDCs) under the Paris Agreement. Furthermore, SMRs are well-suited to operate alongside renewable energy sources such as wind and solar. By providing reliable baseload power, they stabilize the grid, mitigate the intermittency challenges of renewables, and enable higher penetration of clean energy technologies. This synergy enhances the resilience and sustainability of global energy systems.

SMRs also contribute to energy security by diversifying the energy mix and reducing dependence on imported fossil fuels. Their smaller scale, modular construction, and flexibility in deployment make them accessible to a wide range of countries, including those with limited infrastructure to support traditional large-scale nuclear plants. For many nations, this means greater autonomy in meeting domestic energy needs and less vulnerability to fluctuations in international energy markets. In addition, SMRs can be deployed in remote or isolated regions, bringing reliable electricity to areas that otherwise rely on expensive and polluting diesel generators. This not only improves living standards but also fosters economic development by providing energy access for industries, healthcare, and education.

Beyond electricity generation, SMRs support broader global goals by enabling non-electric applications crucial for sustainable development. For example, they can supply process heat for industries, support hydrogen production through high-temperature electrolysis, and provide energy for desalination plants, thereby addressing water scarcity challenges. These applications demonstrate the versatility of SMRs in addressing interconnected global issues such as clean energy, climate adaptation, industrial modernization, and access to clean water.

On the international stage, SMRs also encourage cooperation in research, regulation, and technology transfer. The development of harmonized international safety standards, combined with collaborative R&D initiatives, can accelerate global adoption and ensure safe deployment across different regions. Such cooperation aligns with the broader goal of building global partnerships for sustainable development, as highlighted in SDG 17.

In sum, SMRs offer a multifaceted contribution to global energy goals by promoting decarbonization, enhancing energy security, supporting sustainable industrial applications, and fostering international cooperation. While challenges remain in terms of regulatory approval, financing, and public acceptance, the potential of SMRs to transform energy systems is undeniable. Their integration into national and international energy strategies represents a significant step toward achieving a cleaner, more resilient, and more equitable global energy future.

10.3 Policy and market dynamics shaping SMR deployment

The deployment of Small Modular Reactors (SMRs) is not solely a matter of technological innovation but is deeply influenced by policy frameworks and evolving market dynamics. Governments, international organizations, and private stakeholders all play critical roles in shaping the conditions under which SMRs can move from concept to commercial reality.

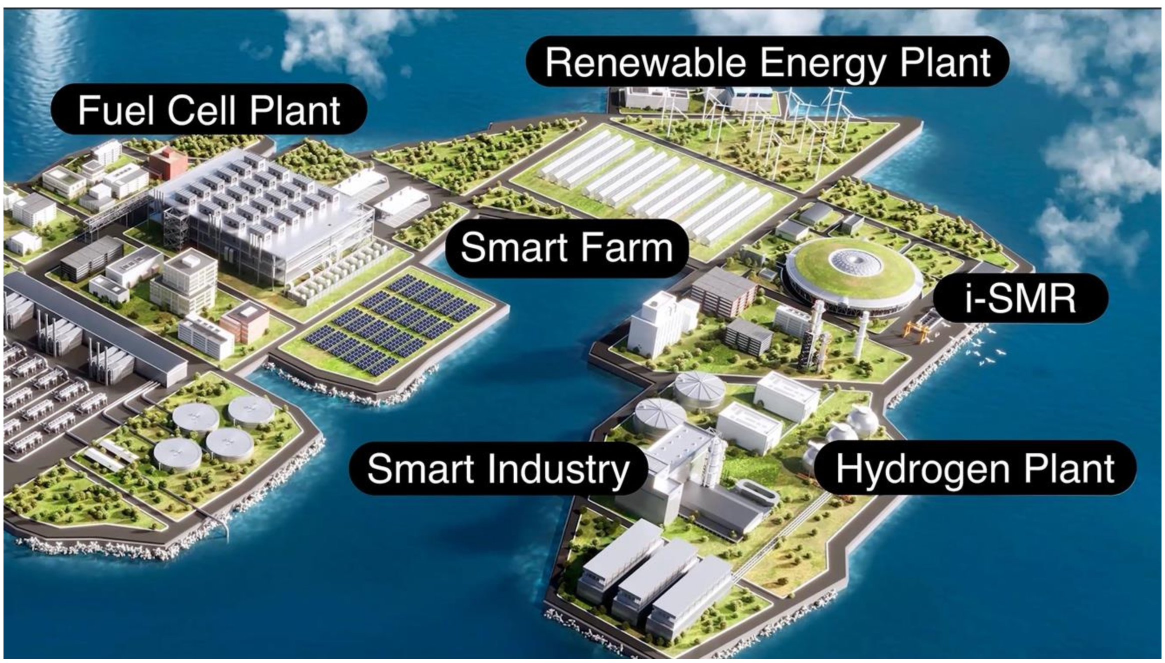
On the policy side, nuclear energy continues to be debated across the world, with some countries accelerating investment in advanced nuclear technologies while others remain cautious due to concerns over cost, waste management, and public acceptance. Policies that support decarbonization, energy security, and diversification of energy sources are particularly favorable to SMRs, since these reactors offer flexible deployment options, smaller capital investments compared to large nuclear plants, and the ability to integrate with renewable energy systems. In many regions, policies are being updated to account for SMRs' modularity and scalability, which differ from conventional nuclear regulatory assumptions. For example, regulatory bodies are beginning to explore risk-informed and performance-based licensing approaches tailored to SMRs rather than applying frameworks designed for gigawatt-scale reactors.

Market dynamics are equally important. Traditional large nuclear reactors often face financial barriers due to high upfront costs and long construction timelines. SMRs, by contrast, promise lower initial capital expenditure, shorter construction cycles, and the potential for mass production of standardized modules. This shift could make nuclear power more competitive in liberalized electricity markets and in emerging economies that cannot finance large-scale plants. Furthermore, SMRs are well-suited to serve niche markets such as remote areas, mining operations, or industrial facilities requiring combined heat and power. Their compatibility with renewable energy sources also positions them as a stabilizing component in future energy grids characterized by high variability from wind and solar generation.

International cooperation and market harmonization will also influence deployment. Shared safety standards, cross-border technology partnerships, and coordinated regulatory frameworks could help accelerate commercialization while reducing redundancy in licensing processes. Countries with strong nuclear industries, such as the United States, are actively positioning themselves to lead in the SMR market, both domestically and as exporters. This competition could spur innovation, but it also highlights the need for common international rules to avoid fragmentation.

At the same time, market acceptance depends on overcoming challenges related to financing, supply chain readiness, and public perception. Investors need confidence that SMR projects will be delivered on time and within budget, while communities and policymakers require assurance that these reactors will operate safely and manage waste responsibly. Clear policy signals—such as government-backed demonstration projects, financial incentives, and long-term energy strategies that include nuclear—are crucial to build confidence among stakeholders.

Ultimately, the interplay between policy frameworks and market dynamics will determine how quickly SMRs are deployed at scale. Favorable policies can reduce barriers and create incentives for adoption, while strong market signals can demonstrate the economic viability and versatility of SMRs in diverse applications. Together, these forces will shape the trajectory of SMR deployment, influencing whether they become a cornerstone of the global energy transition or remain a niche solution adopted only in specific contexts.



Chapter 11. Case Studies and Global Perspectives

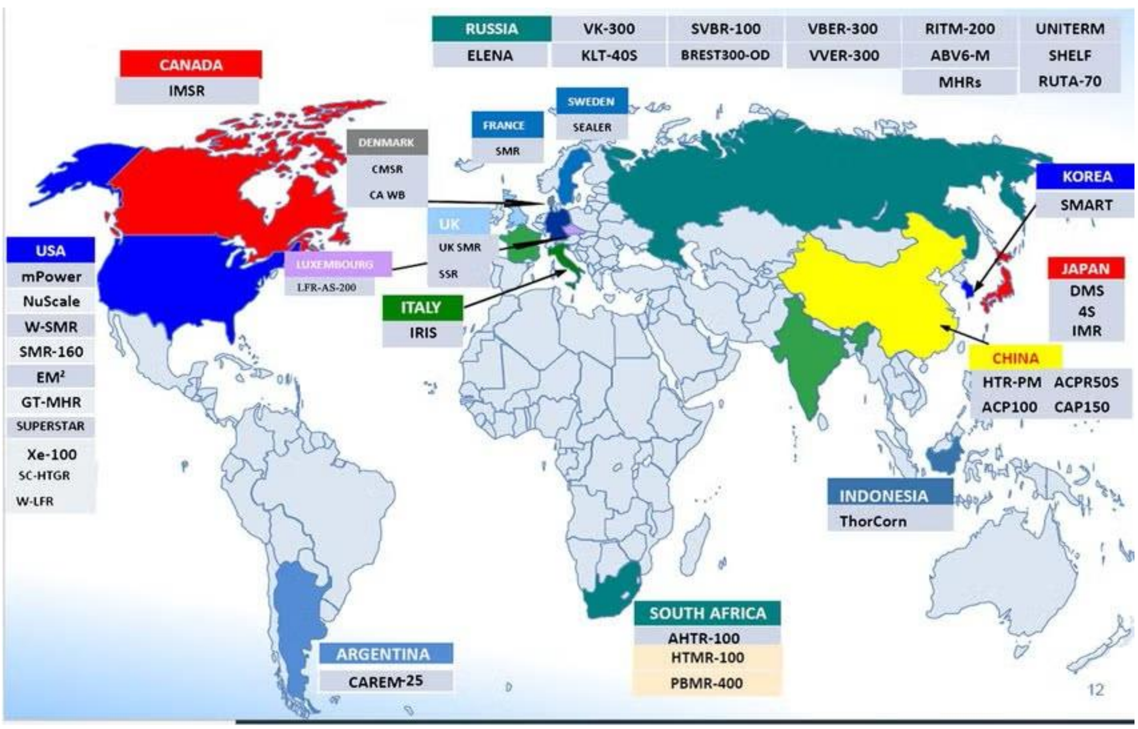
11.1 Analysis of existing and planned SMR projects in US, UK, South Korea.

In the United States, the SMR landscape is shifting from first movers that stumbled to projects now entering formal licensing and early construction. NuScale's Carbon Free Power Project with UAMPS in Idaho was terminated in late 2023 after escalating cost projections, even though NuScale's design remains certified by the NRC—an episode that reshaped investors' and utilities' expectations about commercial pathways and contracting models. world-nuclear-news.orgutilitydive.com A different arc is emerging around GE Hitachi's BWRX-300: the Tennessee Valley Authority submitted the nation's first construction-permit application for a BWRX-300 at Clinch River in Oak Ridge in spring 2025, with the NRC docketing the filing and TVA publishing a public project dashboard. world-nuclear-news.orgNRC Web Beyond light-water SMRs, the U.S. is seeing tangible progress on advanced designs. Kairos Power's Hermes low-power demonstration reactor—a fluoride-salt-cooled, high-temperature system—received an NRC construction permit in 2023 and began safety-related nuclear construction in 2025, marking the first non-LWR to reach this milestone in the U.S. in over half a century; DOE and industry updates point to rapid, iterative development toward a future commercial unit. ans.orgworld-nuclear-news.orgThe Department of Energy's Energy.govReuters On the industrial heat and cogeneration front, X-energy and Dow advanced their Xe-100 project at Dow's Seadrift, Texas complex: the NRC set an 18-month review schedule for the construction-permit application, with Dow indicating final investment timing later in the decade. X-energyutilitydive.comThe Department of Energy's Energy.gov Holtec is pursuing a parallel track: restarting the Palisades large reactor in Michigan while targeting deployment of two SMR-300 units at the same site by 2030 under "Mission 2030," with NRC pre-application engagement underway. Holtec International+1NRC Web

In the United Kingdom, SMR policy has become a central pillar of new-build strategy, with the government running a technology selection process through Great British Nuclear (GBN). The competition drew bids from several vendors; in 2025 press reports indicated that Rolls-Royce SMR was selected as the preferred bidder for initial projects alongside broader funding for Sizewell C, while other contenders, including GE Hitachi and Holtec, submitted final tenders. The emphasis is on moving to site selection and delivery after design and tendering phases. In parallel, the UK has discussed regulatory streamlining to accelerate nuclear approvals, signaling a shift toward risk-informed, faster pathways. world-nuclear-news.orgThe GuardianThe Times+1

South Korea's program centers on the domestically developed SMART reactor from KAERI—a 100 MWe integral pressurized water SMR that achieved Korean design approval earlier and has been the focus of a longstanding cooperation framework with Saudi Arabia that envisions design refinement, licensing support, and potential first deployment in the Kingdom. While no unit is built in Korea yet, the SMART platform remains the country's export-oriented SMR flagship, complemented by other micro- and small-reactor concepts in development with Korean industry. world-nuclear-news.orgNucleus

Taken together, these programs illustrate the diversity of SMR pathways now unfolding across liberalized and state-directed markets. The U.S. is demonstrating regulatory traction through TVA's BWRX-300 application and the Hermes advanced reactor build, with industrial decarbonization pilots moving through the NRC queue. The UK is consolidating its vendor field and aligning policy levers for delivery. South Korea is maintaining an export-first SMR strategy with SMART.



11.2 Success stories and challenges from different countries

Several countries pursuing Small Modular Reactors (SMRs) have reported early successes while also facing significant challenges, highlighting both the promise and complexity of deploying this new nuclear technology.

In the United States, NuScale's SMR design achieved the first-ever U.S. Nuclear Regulatory Commission (NRC) design certification in 2020, marking a milestone in regulatory approval for SMRs. The project demonstrated that safety arguments for smaller, modular designs could meet stringent U.S. standards. However, challenges arose when the planned Utah Associated Municipal Power Systems (UAMPS) project faced escalating costs and shifting market conditions, ultimately leading to its cancellation in 2023. Despite this setback, NuScale and other developers like TerraPower continue to advance, with strong support from the Department of Energy (DOE) through cost-sharing agreements and R&D initiatives.

The United Kingdom has positioned SMRs as a cornerstone of its future nuclear program. Rolls-Royce SMR Ltd. has secured significant government funding and private investment, with a focus on standardized factory-built modules. The UK government's streamlined regulatory approach and its ambition to expand nuclear capacity by 2050 have supported momentum. Still, challenges remain in securing long-term financing and scaling up manufacturing capacity. The UK model is often cited as a promising case of aligning industrial policy with nuclear innovation.

In South Korea, the SMART (System-integrated Modular Advanced Reactor) design represents one of the earliest full SMR concepts to complete licensing within the country. While no commercial units have been built domestically, South Korea has aggressively pursued international partnerships, particularly with the Middle East, to export SMR technology. The challenge has been moving from paper designs and licensing to large-scale deployment, especially given South Korea's evolving domestic nuclear policies and public sentiment.

Taken together, these country experiences highlight a pattern: successes have been achieved in design certification, early project launches, and political endorsement, while challenges are concentrated around cost escalation, regulatory alignment, financing, and public acceptance. The diverse strategies - the UK's private-public partnership model, demonstrate that there is no single path to SMR deployment, but rather a spectrum of approaches shaped by national priorities and institutional capacities.

11.3 Collaborative initiatives and international programs

Several collaborative initiatives and international programs have been launched to accelerate the development, deployment, and safe operation of Small Modular Reactors (SMRs). These frameworks serve as platforms for knowledge exchange, regulatory harmonization, and joint research, enabling countries to address common technical, economic, and policy challenges.

One of the most prominent initiatives is the International Atomic Energy Agency (IAEA) SMR Platform, launched in 2020. This platform brings together governments, industry players, and regulators to share experience, identify gaps in licensing and supply chains, and coordinate efforts to support global SMR deployment. The IAEA also organizes technical working groups, publishes safety standards, and provides training for member states preparing to adopt SMR technologies.

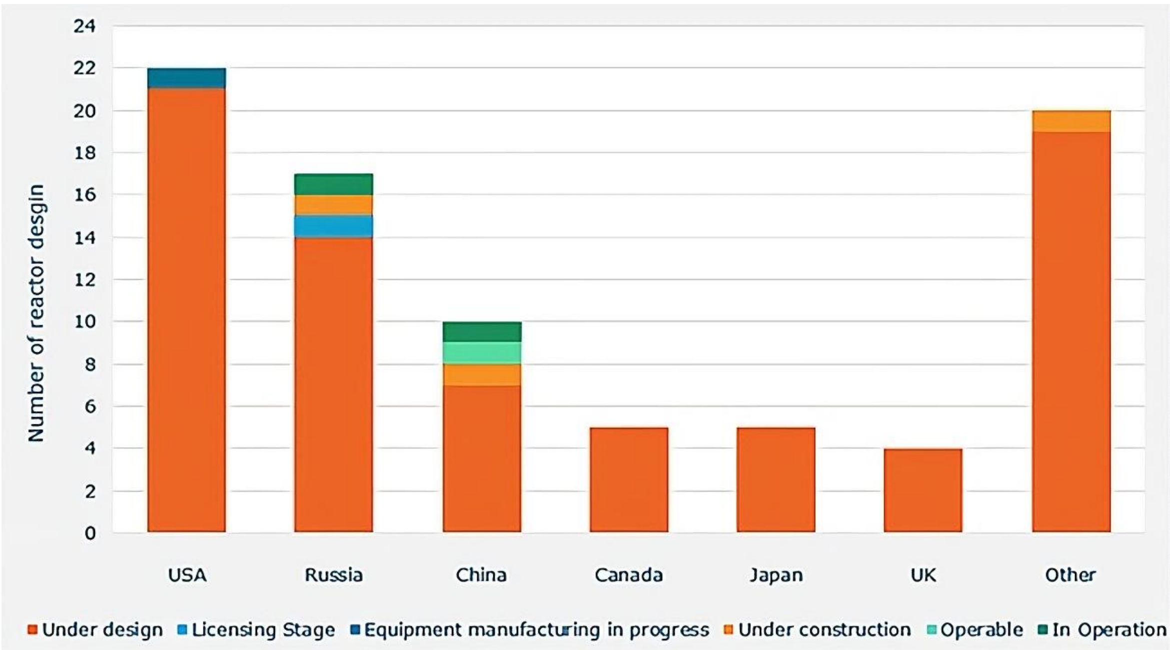
In the United States, the U.S. Department of Energy (DOE) has been instrumental in supporting collaborative programs through initiatives such as the Advanced Reactor Demonstration Program (ARDP), which funds partnerships between government, industry, and research laboratories to develop demonstration SMRs. This program has direct collaborations with international partners, helping to align research priorities and facilitate knowledge transfer.

Europe has also been proactive, with the European SMR Pre-Partnership led by FORATOM and the European Commission, aimed at building a roadmap for SMR deployment across the EU. This initiative emphasizes cooperation between utilities, technology vendors, and regulators to overcome barriers such as licensing complexity and financing models. Similarly, the EURATOM research framework programs provide funding for SMR-related R&D, especially in areas like safety, waste management, and materials science.

Other notable programs include the OECD Nuclear Energy Agency (NEA) Working Group on SMRs, which facilitates collaboration among OECD countries by analyzing technical, economic, and regulatory challenges. This group also works on harmonizing safety approaches to support international licensing cooperation.

Bilateral and regional collaborations are also shaping SMR development. For example, Canada and the United States are working together under a memorandum of understanding to advance regulatory alignment for SMRs, while the UK is cooperating on deployment strategies as Poland seeks to decarbonize its coal-heavy energy system.

These collaborative efforts underscore the recognition that SMR development is not only a technological challenge but also an international endeavor requiring harmonized standards, cooperative financing, and shared safety practices. By pooling expertise and resources, these programs accelerate innovation, reduce duplication of effort, and pave the way for SMRs to contribute meaningfully to global clean energy goals.



Chapter 12. Future Trends and Innovations

12.1 Emerging technologies in SMR designs

Emerging technologies in Small Modular Reactor (SMR) designs represent one of the most dynamic and forward-looking areas of nuclear innovation. While traditional SMR concepts rely on scaled-down versions of established pressurized or boiling water reactors, the current wave of development is centered around advanced technologies that aim to make SMRs safer, more efficient, and more versatile for diverse energy applications.

One key area of innovation is the use of advanced coolants and reactor types. Beyond light-water reactors, developers are investing in designs that employ molten salt, liquid metal (sodium, lead, or lead-bismuth eutectic), and high-temperature gas as coolants. These alternatives provide significant safety advantages due to their passive cooling characteristics and can operate at higher temperatures, thereby improving efficiency and enabling industrial applications such as hydrogen production and process heat. For instance, high-temperature gas-cooled SMRs are being tailored for combined heat and power, offering a pathway for decarbonizing heavy industries.

Another emerging technology is the integration of advanced fuels. Unlike conventional uranium dioxide, SMRs are exploring accident-tolerant fuels, TRISO (tristructural-isotropic) particle fuels, and metallic fuels. These materials are more resistant to high temperatures and irradiation, enhancing both reactor performance and safety margins. TRISO fuel, in particular, has become a central focus in several SMR programs because of its ability to contain radioactive fission products even under extreme accident conditions.

Modular construction and factory fabrication also represent a breakthrough technological shift. SMRs are designed to be built in factories and transported to sites, which reduces costs, shortens construction timelines, and enhances quality control compared to traditional gigawatt-scale reactors. This manufacturing approach makes nuclear power more adaptable to different locations, including remote areas and industrial clusters. Advances in digital engineering, including modular digital twins and additive manufacturing, further support this concept.

The adoption of smart control systems and digitalization is another defining feature of emerging SMRs. Developers are implementing artificial intelligence (AI)-based monitoring, predictive maintenance systems, and highly automated operations to reduce human error, cut operational costs, and improve reliability. These digital tools also allow SMRs to integrate more seamlessly into smart grids, where their flexible load-following capabilities complement intermittent renewable sources like wind and solar.

A particularly exciting trend is the development of microreactors, which are ultra-compact SMRs designed to produce just a few megawatts of electricity or heat. These units can be deployed in isolated communities, military bases, or disaster relief scenarios, where traditional grid power is unavailable. Microreactors, often based on gas-cooled or heat-pipe-cooled designs, emphasize mobility, resilience, and minimal staffing needs.

Finally, SMR developers are increasingly considering hybrid energy systems, in which SMRs are integrated with renewables, storage, and emerging technologies like hydrogen electrolysis. This versatility positions SMRs as multipurpose energy hubs, not only providing electricity but also contributing to synthetic fuel production, desalination, and district heating.

Overall, emerging SMR technologies reflect a paradigm shift in nuclear energy—from large, centralized, capital-intensive plants to flexible, safer, and more sustainable systems tailored for the future low-carbon economy. The innovations being developed today will determine how effectively SMRs can contribute to global decarbonization and energy security in the decades ahead.

12.2 Potential for hybrid systems combining SMRs with renewables

The integration of Small Modular Reactors (SMRs) with renewable energy sources represents one of the most promising directions for future energy systems, offering the potential to create flexible, resilient, and low-carbon hybrid grids. Unlike large nuclear plants, SMRs are designed for modularity, scalability, and adaptability, making them particularly well-suited for coupling with variable renewable sources such as solar and wind power. This hybridization seeks to overcome the intermittency challenges of renewables while leveraging the reliability of nuclear energy.

One of the key advantages of SMR-renewable hybrid systems lies in their ability to provide grid stability. Solar and wind are inherently variable, depending on weather and seasonal conditions. SMRs, by contrast, can operate continuously as baseload power sources but can also be configured for flexible operation, ramping up or down to complement fluctuations in renewable generation. This synergy reduces reliance on fossil-fuel-based backup systems, thus cutting greenhouse gas emissions further.

Another important role for hybrid systems is in energy storage and sector coupling. SMRs can be used to generate heat as well as electricity, allowing surplus energy from renewables to be stored in thermal reservoirs or hydrogen production facilities. For instance, when renewable output is high and demand is low, SMRs can divert their heat or electricity to produce hydrogen through electrolysis, creating a clean fuel that supports the transportation and industrial sectors. This approach enhances the overall efficiency of the system while supporting broader decarbonization beyond the power grid.

Geographically, such systems can be particularly transformative in remote or off-grid regions, where neither large nuclear plants nor large renewable installations are practical. SMRs can be deployed in compact configurations and paired with local renewable resources to provide resilient and independent power systems, reducing reliance on costly diesel or imported fuels. This is especially attractive for island nations, Arctic regions, and developing economies seeking energy independence.

Economically, hybrid systems offer a pathway to maximize asset utilization. Renewables alone often suffer from curtailment during periods of oversupply, while nuclear plants are most efficient when operated continuously. SMRs, with their modular design and smaller capacity, can be tailored to balance renewable penetration without the overproduction inefficiencies seen in larger systems. The combined operation ensures a more balanced load curve, reducing costs for utilities and consumers.

From a policy perspective, SMR-renewable hybrid systems also align well with global energy transition strategies. International frameworks such as the Paris Agreement emphasize both clean baseload capacity and the rapid deployment of renewables. By combining these two pillars, hybrid systems offer a pathway to accelerate decarbonization while ensuring reliable energy access.

In conclusion, the integration of SMRs with renewable energy technologies represents a forward-looking solution to many of the challenges of the modern energy transition. By combining the strengths of continuous, low-carbon nuclear energy with the growing share of renewables, these hybrid systems can ensure reliability, enable decarbonization of multiple sectors, and open new opportunities for resilient, localized energy solutions. As research, demonstration projects, and supportive policies expand, SMR-renewable hybrids are likely to become a central feature of sustainable energy infrastructures worldwide.

12.3 Vision for SMRs in the energy mix of the future

The vision for Small Modular Reactors (SMRs) in the energy mix of the future is centered on their ability to complement and enhance the transition toward a more sustainable, resilient, and diversified energy system. Unlike conventional large nuclear reactors, SMRs are designed to be scalable, flexible, and deployable in a variety of contexts—ranging from urban power grids to isolated or resource-constrained regions. Their modular nature allows for incremental capacity additions, reducing the financial and logistical risks typically associated with large-scale nuclear projects while accelerating the pace of deployment.

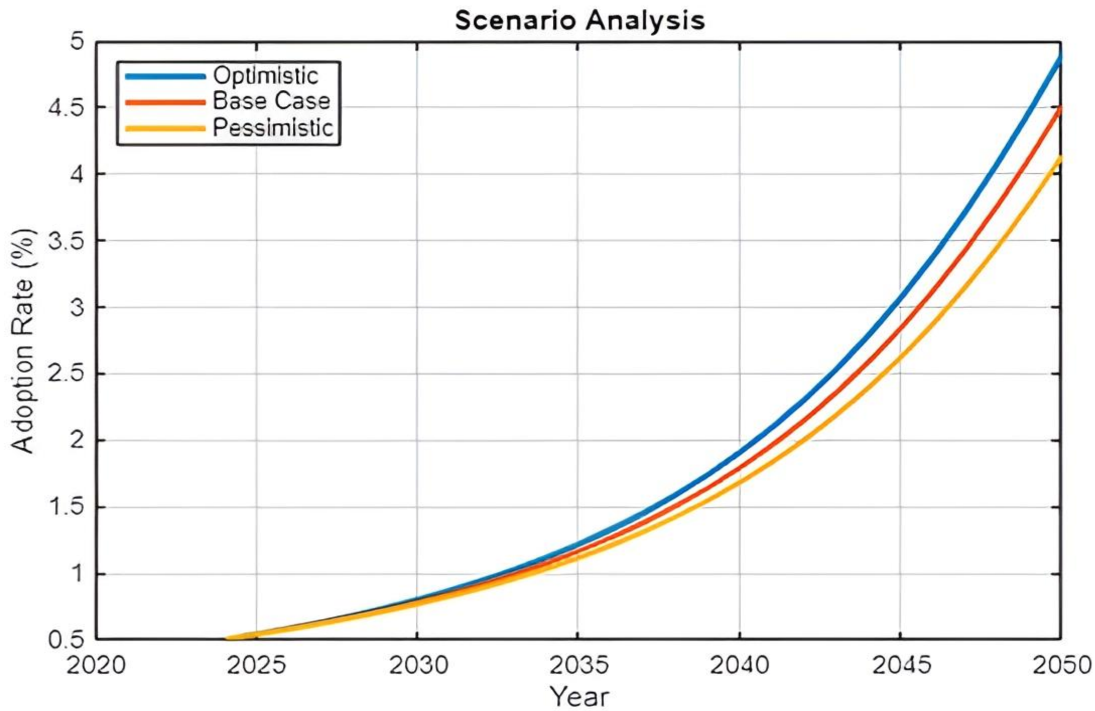
One of the most promising aspects of SMRs is their potential to serve as a stabilizing backbone for grids increasingly reliant on variable renewable energy sources such as solar and wind. As renewables expand, the need for reliable, carbon-free baseload and dispatchable generation becomes critical. SMRs, with their ability to operate at flexible power outputs, can help balance supply and demand while reducing the reliance on fossil-fueled backup systems. This grid-support role positions SMRs as a key enabler of deep decarbonization strategies across both developed and developing economies.

Looking ahead, SMRs are also envisioned to play a role beyond electricity generation. Their high-grade thermal output makes them attractive for applications such as district heating, industrial process heat, hydrogen production, and even water desalination—sectors that are traditionally difficult to decarbonize. In particular, coupling SMRs with emerging hydrogen economies could help scale low-carbon hydrogen production, providing clean fuel for transportation, heavy industry, and energy storage.

From a global energy strategy perspective, SMRs are expected to contribute to national energy security by diversifying supply options, reducing reliance on imported fossil fuels, and ensuring a more resilient energy infrastructure. Their deployment in regions with weaker grids or remote locations could help extend reliable electricity access, supporting development goals while aligning with global climate commitments.

The long-term vision also involves greater integration of SMRs into hybrid energy systems, smart grids, and next-generation infrastructure. As technological maturity increases, SMRs are expected to become cost-competitive, benefiting from standardization, factory fabrication, and economies of scale. This trajectory points to a future where SMRs not only supplement large reactors but also emerge as a mainstream, widely accepted technology in the diversified clean energy portfolio of the mid-21st century.

In sum, the future of SMRs lies in their ability to provide clean, reliable, and versatile energy solutions tailored to the diverse needs of societies. By bridging the gap between renewables, industry, and secure energy supply, they are poised to become a cornerstone of global efforts to achieve sustainable, carbon-neutral energy systems.



Concluding remarks

Small Modular Reactors (SMRs) represent a transformative step in the evolution of nuclear power, offering a flexible, scalable, and safer approach to meeting the world's growing energy demands. As this handbook has outlined, SMRs combine advances in reactor design, materials science, fuels, and simulation tools with strong international collaboration and innovative deployment strategies. They are uniquely positioned to address some of the most pressing global challenges: achieving energy security, reducing carbon emissions, and enabling a sustainable transition to a cleaner energy future.

While challenges remain—ranging from regulatory harmonization and public acceptance to financing and supply chain readiness—the momentum surrounding SMR development is unmistakable. Countries across the globe are actively pursuing projects, building strategic partnerships, and aligning policy frameworks to bring SMRs from concept to reality. Their potential integration with renewable energy sources further underscores their importance in enabling resilient hybrid energy systems and ensuring reliable baseload capacity in the decades ahead.

The future of SMRs lies not only in technological innovation but also in the collective vision and determination of governments, research institutions, industry leaders, and the next generation of scientists and engineers. By fostering international collaboration and investing in education and training, the global community can ensure that SMRs become a cornerstone of a secure, sustainable, and equitable energy system.

This handbook is a step toward that vision—providing a comprehensive overview of SMR development and highlighting the opportunities they present. The path ahead is ambitious, but with continued effort, SMRs can and will play a pivotal role in shaping the future of energy for generations to come.

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