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Review

The Future of Microreactors: Technological Advantages, Economic Challenges, and Innovative Licensing Solutions with Blockchain

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Abstract: This study details the unique advantages and challenges associated with microreactors. Microreactors offer rapid installation and flexible application capabilities, meeting energy needs in remote and inaccessible areas. Unlike large nuclear power plants, they can be set up and start generating energy within a few days, resulting in significant time and cost savings. Their small size and modular design reduce capital and operational costs while enhancing economic competitiveness. However, some technical and regulatory challenges persist for the widespread adoption of microreactors. Licensing processes designed for large nuclear power plants may delay the widespread adoption of microreactors. Blockchain technology can play a crucial role in overcoming these challenges by providing transparency and reliability in the licensing processes. The operational settings of microreactors should be carefully considered, and regulatory authorities must be effectively designated. Collaboration and coordination are vital in this process. Consequently, the flexibility and innovative solutions offered by microreactors highlight the importance of future research to examine the optimal conditions for their use.

Keywords: microreactors; HALEU fuel; blockchain technology; energy production; licensing processes

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1. Introduction

Enhancing the share of low-carbon energy in global energy strategies is crucial for meeting climate change targets [1–3]. In addition to increasing renewable energy production, technologies capable of providing low-carbon baseload energy and load-following capacity are essential for achieving net-zero carbon emissions. Nuclear energy, which contributes 10% of the world's total electricity production, presents opportunities for new nuclear technologies to play a significant role [4–7].

The world is seeking sustainable energy sources to meet the current energy market's demands. Sustainable energy sources fulfill current needs without compromising future generations' requirements. Renewable energy sources (RES) like wind, solar, hydroelectric, geothermal, and ocean energy are considered sustainable energy production methods [8]. However, their intermittent nature makes it difficult to provide a consistent electricity supply, leading to the need for alternative sources that can act as critical load or baseload providers. Given their zero-carbon emissions, there is an increasing shift towards nuclear energy. Combining RES with nuclear reactors can result in a carbon-free, reliable, and innovative energy system [9–11].

Micro energy grids (MEGs) present a viable solution by delivering affordable energy and cutting greenhouse gas emissions through combined electricity and heat generation [12,13]. MEGs operate on a distributed generation concept and ensure stability and reliability with energy storage systems [12–14]. Various studies have focused on determining the optimal configurations of hybrid energy systems (HES) [15–18]. Integrating microreactors and large/medium-scale nuclear reactors holds the potential to create a zero-carbon and reliable energy network. Research indicates that integrating microreactors with RES can significantly reduce greenhouse gas emissions by replacing traditional diesel generators [17–19]. Nuclear-renewable hybrid energy systems (N-R HES) are evaluated for their environmental benefits, energy security, and cost-effectiveness, with a particular emphasis on enhancing energy supply security in remote and isolated areas [17–20].

Microreactors are emerging as new nuclear energy technologies with the potential to provide low-carbon energy [21–23]. Their growth potential increases considering their ability to enter new markets where large-scale energy technologies are unsuitable [24–27]. These very small reactors, typically producing less than 1 MWe to 20 MWe, can generate energy using advanced light water reactor (LWR) and non-LWR designs [28–31]. Maximum power levels can reach up to 50 MWe. They can provide electricity, process heat for direct use, or both [32–35]. If the challenges related to production and operating costs, as well as regulatory and institutional barriers, can be overcome, microreactors have the potential to fill unmet needs in energy portfolios where fossil fuel limitations are evident [33–36]. Microreactors can also become competitive in areas without large electrical grids, where fuel delivery is cumbersome or expensive, where economies of scale do not apply, or where space constraints or specific weather conditions make renewables unfeasible [32–40].

The ongoing technological advancements in microreactor designs offer both potential and hurdles for their integration into energy portfolios [41–43]. Innovations in microreactors can aid national low-carbon strategies and bolster resilience objectives in areas where severe weather and other unexpected events threaten security, safety, and economic stability [44,45]. The significance of microreactors grows with global concerns about energy supply security and resilience. The increase in remote work activities highlights the necessity of reliable power and energy security, areas where microreactors can contribute significantly [46–48]. Employing microreactors to enhance resilience can improve readiness and recovery from disruptions, ensuring the continuity of operations in critical sectors such as essential government functions, energy-intensive industries, emergency healthcare facilities, and high-speed networks for remote workers [42–47]. Although economic challenges remain for microreactors to be competitive with other low-carbon energy sources, certain cost projections suggest that microreactors could perform well in markets where large nuclear technologies are not feasible [49–54]. For example, microreactor designs support completely different operational strategies, such as mobile power generation for disaster recovery or potential semi-remote operations [55–59]. In terms of low-carbon energy production, large nuclear power plants are not suitable for smaller-scale applications, integration with microgrids, or small cogeneration uses, and they necessitate extensive emergency planning zones [60–66].

This study examines the status and adoption potential of microreactors by first discussing the profile of microreactor technology, highlighting differences from large nuclear power plants (NPPs) and small modular reactors (SMRs), and examining technological developments and commercialization aspects of microreactors. The core research into the costs and economic feasibility of microreactors thoroughly outlines the challenges of commercialization. Subsequently, the examination shifts to potential markets by considering the distinctive attributes of microreactors and their complementary application technologies, pinpointing niche markets ideal for their deployment. This paper provides an overview of recent studies on assessing the global market potential of smaller nuclear technologies and adapts these methodologies to microreactors. It encompasses the latest updates on microreactor technology, the economics of small reactors, and market dynamics. The analysis addresses deployment potential, regulatory hurdles, and institutional requirements in a balanced manner. The paper concludes with essential discussion points and final reflections.

2. Overview of Microreactors

Microreactors are in the initial stages of their development. The commissioning of a nuclear reactor requires several years of meticulous planning and collaboration between reactor designers and regulatory bodies. For instance, the U.S. Department of Defense aims to have the first microreactor operational by the end of 2027 (Nuclear Energy Institute, 2018). The typical timeline from the submission of a license application to the start of commercial operations and energy production is projected to be around 7 years. Nevertheless, the unique nature of this technology could introduce challenges and risks that might extend the overall timeline to anywhere between 5 and 10 years [67–70].

Designs that utilize light water cooling are relatively mature as they rely heavily on established technologies from conventional reactors [71–80]. On the other hand, advanced designs, including those using liquid metal, molten salt, or high-temperature gas, will necessitate more extensive design and certification efforts, likely resulting in a longer development timeline [81–93].

Microreactors are emerging as innovative technologies with the potential to revolutionize energy production. These small and modular reactors can be used for a wide range of applications, from providing energy supply in remote areas to industrial applications. The advantages of microreactors include rapid deployment, portability, flexibility, and low operational costs. However, the widespread adoption and effective use of this technology require overcoming various technical, economic, and regulatory challenges. Research questions are critical to understanding these challenges and fully realizing the potential of microreactors.

In this study, various research questions have been developed to examine different aspects of microreactors. These questions cover topics such as technical performance, economic feasibility, safety and licensing processes, fuel utilization, environmental impacts, and the role of blockchain technology in these processes. The research questions aim to determine the position of microreactors in the energy sector, understand the obstacles and opportunities, and guide the future development of this technology. This comprehensive set of questions will provide an in-depth understanding of the various dimensions of microreactors. The research questions (RQ) are as follows:

RQ1: *What is the energy production capacity of microreactors and how can this capacity be optimized?*

RQ2: *What are the main technical challenges encountered during the installation and operation of microreactors?*

RQ3: *How do fuel limitations affect the widespread adoption of microreactors?*

RQ4: *How does the economic feasibility of microreactors compare to large-scale nuclear power plants?*

RQ5: *What are the environmental impacts of microreactors and how can these impacts be minimized?*

RQ6: *What are the safety standards for microreactors and what challenges are encountered in the implementation of these standards?*

RQ7: *How do licensing processes affect the widespread adoption of microreactors and how can these processes be improved?*

RQ8: *What role can blockchain technology play in the licensing and regulatory processes of microreactors?*

RQ9: *How does the modular structure of microreactors affect maintenance and repair processes?*

RQ10: *What are the industrial applications of microreactors and how can these applications be developed?*

RQ11: *What advantages and challenges do microreactors bring in remote and hard-to-reach areas?*

RQ12: *How do the portability and deployment time of microreactors impact energy supply during emergencies?*

RQ13: *How can the capital and operational costs of microreactors be optimized?*

RQ14: *What are the refuelling processes of microreactors and how can these processes be improved?*

RQ15: *How can the energy efficiency of microreactors be increased?*

RQ16: *What are the safety protocols and emergency response plans for microreactors?*

RQ17: *How can the integration of microreactors into the electrical grid be ensured?*

RQ18: *How can the availability and reliability of microreactors in energy production be increased?*

RQ19: *What are the proliferation risks of microreactors and how can these risks be managed?*

RQ20: *What are the future research and development areas for microreactors and what innovations are expected in these areas?*

These research questions aim to explore the potential and challenges of microreactors in depth. Each question provides essential insights to better understand the role of microreactors in the energy sector and ensure the effective use of this technology.

The search strategies employed are detailed in Table 1. Keywords and phrases such as "all: Microreactor", "Nuclear fuel", "HALEU", "Nuclear energy", "Small Modular Reactor (SMR)", and "blockchain" were utilized to encompass similar studies. As the initial search approach did not yield the desired outcomes, the method was broadened to cover all years, starting with the most recent publications.

Table 1. Search strategies in databases.

Database	Search Strategy
Google Scholar	("Microreactor" OR "Nuclear fuel" OR "HALEU" OR "Nuclear energy" OR "Small Modular Reactor (SMR)" OR "blockchain" AND PUBYEAR > 1980 AND PUBYEAR < 2025)
Web of Science	("Microreactor" OR "Nuclear fuel" OR "HALEU" OR "Nuclear energy" OR "Small Modular Reactor (SMR)" OR "blockchain" AND PUBYEAR > 1980 AND PUBYEAR < 2025)
Scopus	("Microreactor" OR "Nuclear fuel" OR "HALEU" OR "Nuclear energy" OR "Small Modular Reactor (SMR)" OR "blockchain" AND PUBYEAR > 1980 AND PUBYEAR < 2025)
ScienceDirect	("Microreactor" OR "Nuclear fuel" OR "HALEU" OR "Nuclear energy" OR "Small Modular Reactor (SMR)" OR "blockchain" AND PUBYEAR > 1980 AND PUBYEAR < 2025)
ProQuest	("Microreactor" OR "Nuclear fuel" OR "HALEU" OR "Nuclear energy" OR "Small Modular Reactor (SMR)" OR "blockchain" AND PUBYEAR > 1980 AND PUBYEAR < 2025)
Engineering Village	("Microreactor" OR "Nuclear fuel" OR "HALEU" OR "Nuclear energy" OR "Small Modular Reactor (SMR)" OR "blockchain" AND PUBYEAR > 1980 AND PUBYEAR < 2025)

2.1. Microreactor Designs

There are various microreactor designs listed by the World Nuclear Association (WNA) and currently under development by different developers, with more designs being explored. An example of this is the eVinci™ microreactor by Westinghouse Electric Company (Cranberry Township, PA, USA) (Figure 1), merging space reactor technology with commercial nuclear system design [94–97]. This high-temperature heat pipe reactor can produce 200 kW to 5 MW of electrical power for more than three years without the need for refueling. Utilizing High-Assay Low-Enriched Uranium (HALEU) TRISO fuel, it features a straightforward and safe design. The use of heat pipes eliminates the need for reactor coolant pumps and auxiliary systems, resulting in a compact and dependable reactor [94–100]. The eVinci™ microreactor benefits from its high-temperature heat pipe technology, which removes the need for reactor coolant pumps and related systems, offering a compact and reliable design. It can function for over three years without refueling and is inherently safe due to its strong negative temperature coefficient. Additionally, it features flexible load following, capable of automatically adjusting the heat load. However, operational performance data are limited since it is still under development, and initial production and installation costs may be high.

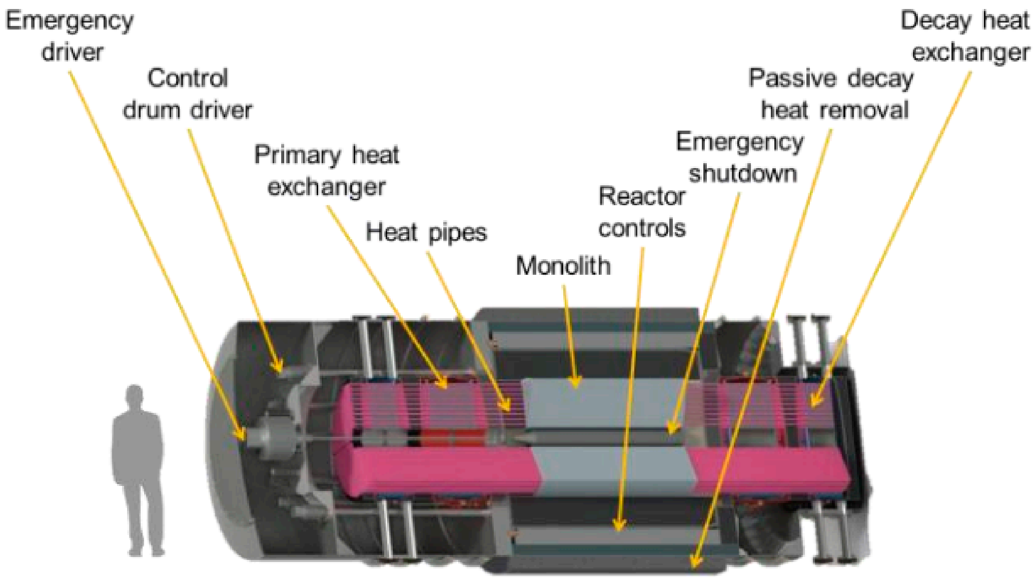

Figure 1. Overview of the eVinci™ microreactor developed by Westinghouse Electric Company [94].

The Aurora microreactor designed by Oklo Inc. (Santa Clara, CA, USA) (Figure 2) is intended to generate approximately 1.5 MWe of electricity and operate autonomously for 20 years [25,44,77,82]. This configuration, employing metallic fuel in heat pipes with liquid sodium, is designed to consume nuclear waste from light water reactors [94,101–105]. The US Idaho National Laboratory provides Oklo with access to reprocessed used nuclear fuel to test the Aurora concept [94,101–110]. The advantages of the Aurora microreactor include its ability to operate for 20 years without refueling and its capability to burn nuclear waste from light water reactors. The design features metallic fuel and a liquid sodium coolant in a compact configuration. However, due to the use of sodium, additional safety measures may be required, and sufficient technical and operational performance data are not yet available.

The Holos-Quad microreactor, developed by Holos Generators (Manassas Park, VA, USA) (Figure 3), combines commercial technologies with safer, melt-resistant fuels, functioning similarly to a turbo-jet engine [111–115]. This reactor employs TRISO fuel and features a straightforward design. The main thermodynamic process is configured as a gas Brayton cycle, utilizing helium or carbon dioxide as a coolant [113–117]. Incorporating a system for waste heat recovery and conversion, its thermodynamic efficiency can be boosted from 45% to 60% [111–122]. The advantages of the Holos Generators microreactor include its simple and highly efficient turbo-jet engine-like design. The ORC-Brayton combination allows for thermodynamic efficiency of up to 60%. The reactor offers scalable power options from 1 MWe to 100 MWe. However, this innovative design has not yet been widely applied commercially, and potential safety and operational challenges are not fully known.

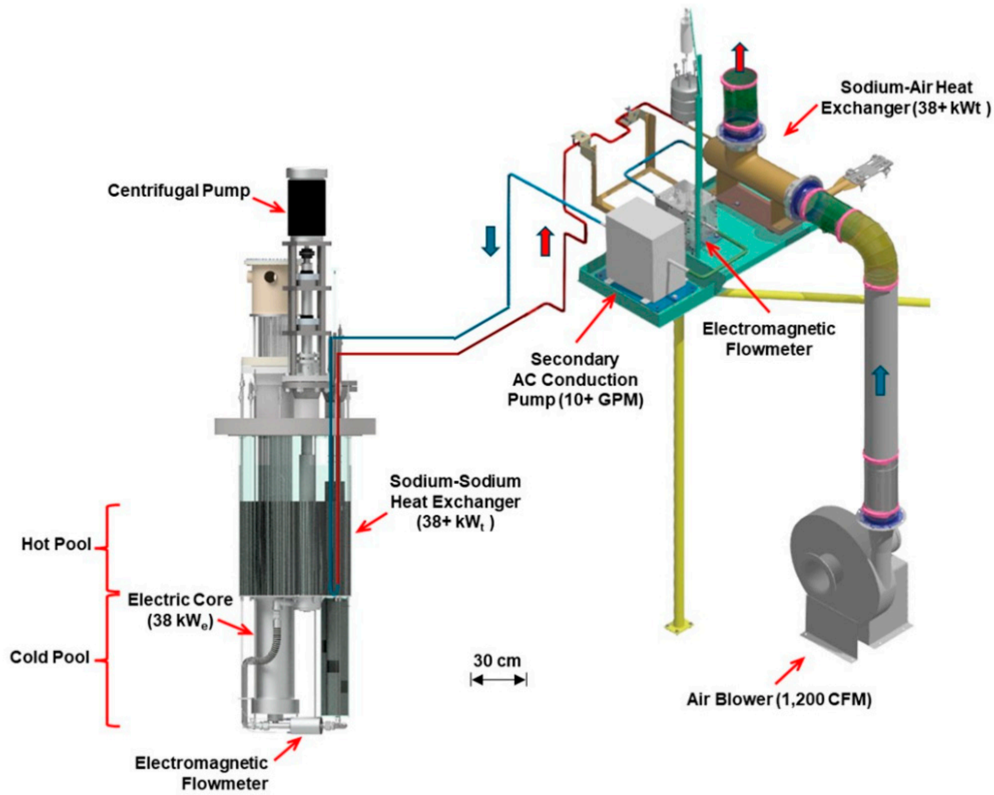

Figure 2. Overview of the Aurora microreactor designed by Oklo Inc. [110].

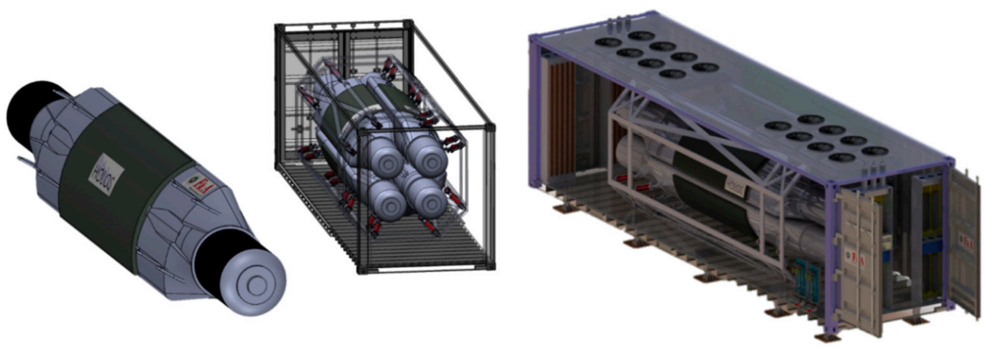

Figure 3. Overview of the Holos-Quad microreactor designed by Holos Generators [122].

The Xe-Mobile (Xe-100) reactor concept developed by X-energy (Rockville, MD, USA) (Figure 4) is suitable for small power generation applications on land, sea, and air [122–127]. It can fit into a standard container and operate for three years without refueling. It uses TRISO fuel and generates at least 1 MWe of electricity. It can operate autonomously without on-site operators [122–127]. The Xe-Mobile reactor stands out with its portability and autonomous operation capabilities. It can fit into a standard container and operate for three years without refueling. It uses TRISO fuel and generates at least 1 MWe of electricity. However, the portability and autonomous operation features require sophisticated control systems to ensure safe operation without on-site operators, potentially increasing costs [122–127].

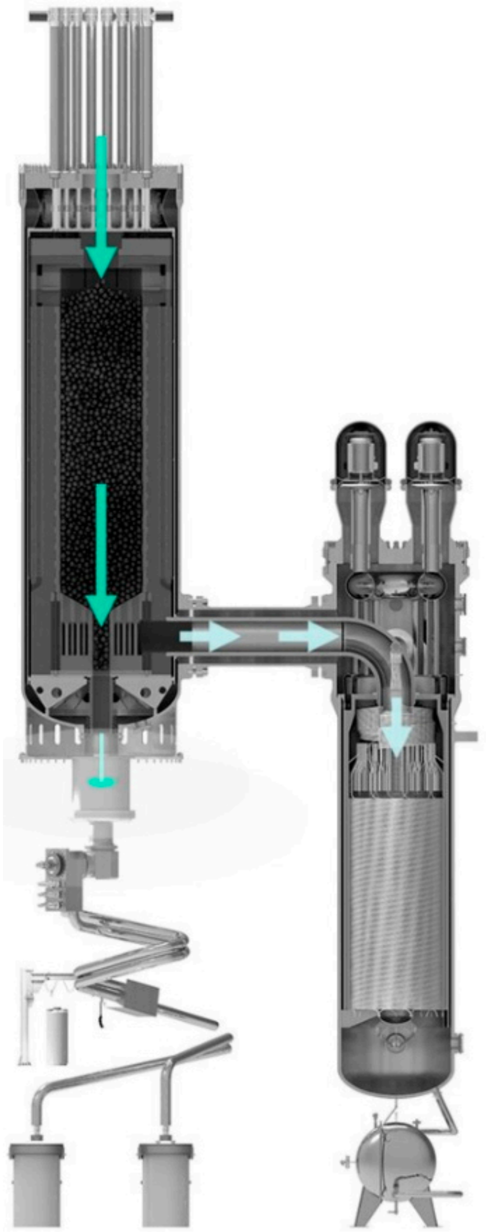

Figure 4. Overview of the Xe-Mobile (Xe-100) reactor concept developed by X-energy [128].

NuScale Power (Portland, OR, USA) is developing micro NuScale power modules with 10 to 50 MWe capacity and smaller 1 to 10 MWe heat pipe reactor designs (Figure 5) [25,83,129–133]. These technologies are suitable for various applications, including small power grids, remote villages, off-grid industrial facilities, and space travel [131–138]. Both concepts can operate for 10 years or more without refueling. The advantages of NuScale microreactors include their suitability for small power grids and remote facilities. These reactors can operate for 10 years or more without refueling. Using heat pipe technology, they provide high safety and efficiency. However, they have not yet been widely applied commercially, and initial investment costs may be high [129–142].

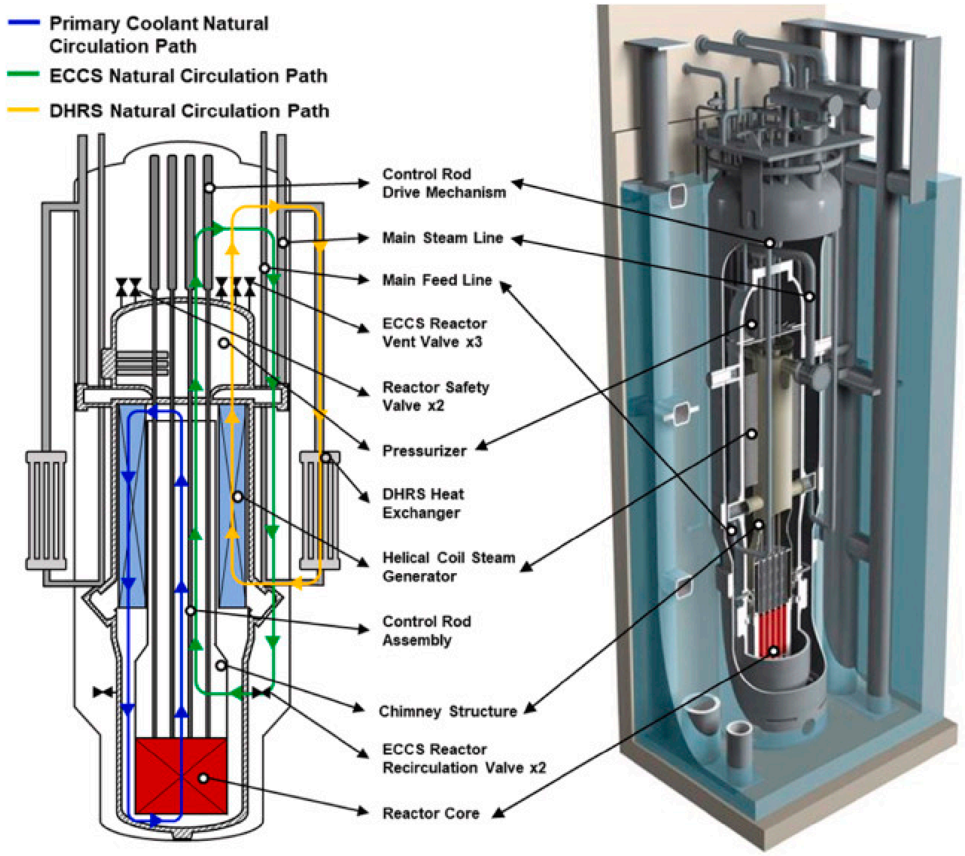

Figure 5. Overview of the micro NuScale power module developed by NuScale Power [143].

The SEALER microreactor developed by LeadCold (Stockholm, Sweden) (Figure 6) is a lead-cooled microreactor [25,144–147]. It generates 3 MWe of electricity and can operate for 30 years without refueling. The core can be enclosed to boost safety and mitigate proliferation concerns [25,144–148]. Passive removal of decay heat is achieved through natural convection and thermal radiation. The U-Battery microreactor, which uses helium as a coolant and graphite as a moderator, produces 4 MWe and has a core lifespan of 5 Effective Full Power Years (EFPY). Its design features a compact, underground reactor cavity. However, using an indirect Brayton cycle with helium coolant can introduce operational complexities due to the extensive development needs of the helium turbine [144–150]. The SEALER reactor's benefits include its lead-cooled design and the capability to operate for 30 years without refueling. Sealing the core enhances safety and decreases proliferation risks. Additionally, decay heat is removed passively. However, there may be technical challenges related to managing and operating the lead coolant.

The U-Battery developed by Urenco (Stoke Poges, UK) (Figure 7) is an advanced high-temperature gas reactor. This reactor is designed using modern nuclear technology for reliable and efficient energy production [151–156]. The U-Battery is cooled by helium gas and uses a graphite moderator to slow down neutrons and control nuclear reactions [154–158]. This design aims to increase energy efficiency by operating at high temperatures. The reactor is capable of producing 4 megawatts of electrical power (MWe) and uses an indirect Brayton cycle to convert energy into electrical energy [153–158]. The Brayton cycle uses nitrogen gas as the working fluid to convert energy into electrical energy. This method ensures high efficiency and safety in energy production [151–158]. The U-Battery's core lifetime is planned to be 5 Effective Full Power Years (EFPY), meaning the reactor can operate continuously at full electrical power [159–162]. The Kalinos microreactor is designed to be a fully portable unit housed within a shipping container, allowing for easy transportation by truck, ship, or aircraft. This portability feature is particularly advantageous for meeting energy needs in remote areas and providing emergency power supply [159–162]. The reactor is equipped with passive cooling systems that do not require water, simplifying the regulatory approval processes. The design aims to provide a robust power supply with minimal on-site infrastructure requirements. Once installed, the reactor can begin operating at full capacity immediately, offering long-term, reliable energy production. Additionally, the Kalinos design includes the capability to provide clean electricity and heat during energy production, making it suitable for various industrial and commercial applications [152–158,163–165].

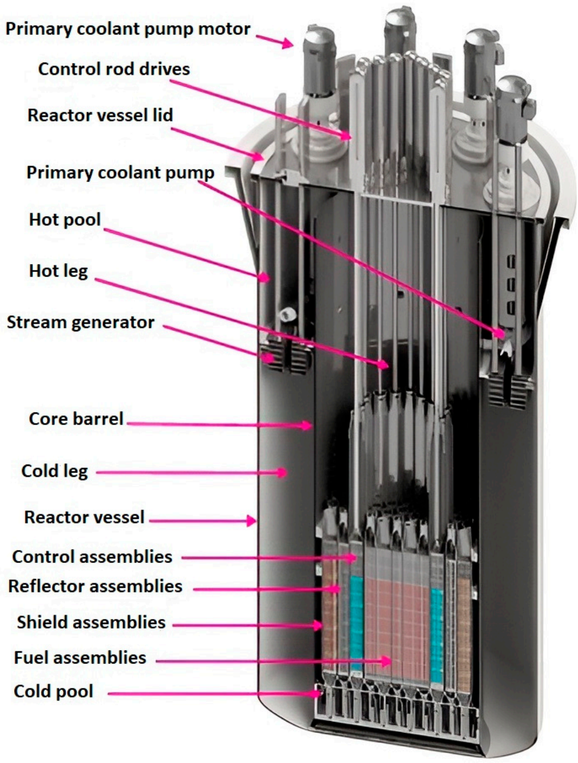

Figure 6. Overview of the SEALER microreactor developed by LeadCold [150].

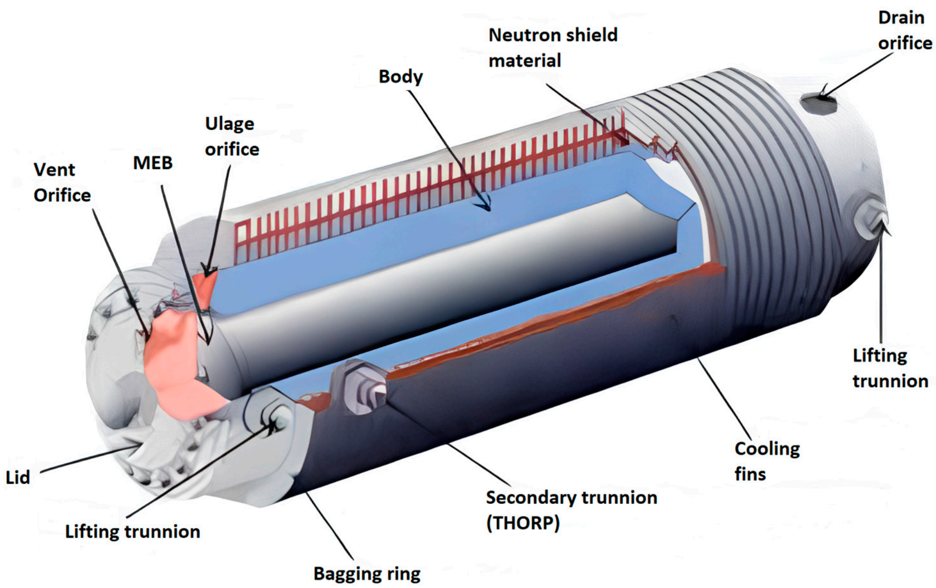

Figure 7. Overview of the U-Battery developed by Urenco [151].

The MMR™ (Micro Modular Reactor) developed by Ultra Safe Nuclear Corporation (Seattle, WA, USA) (Figure 8) is an advanced nuclear reactor designed for high efficiency and safety. This reactor is cooled by helium gas and uses graphite as a moderator to control the nuclear reactions. The MMR™ is capable of producing 5 megawatts of electrical power (MWe) and is designed to operate for 20 years without the need for refueling, making it highly reliable and low-maintenance [166–170]. The reactor utilizes TRISO (tristructural isotropic) and FCM™ (Fully Ceramic Microencapsulated) fuels, which are known for their robustness and high safety margins. These fuels allow the reactor to maintain stability at high temperatures and ensure safe operation under various conditions [168–172]. In addition to its efficient fuel use, the MMR™ incorporates a molten salt storage system and a steam turbine generator to convert thermal energy into electrical energy. This combination allows for flexible heat transfer and high-temperature stability, which are essential for efficient power generation and safe operation [166–170]. Despite its many advantages, the MMR™ also faces some challenges. It is still in the development stage, which means that further research and testing are required to fully commercialize the technology. Additionally, the operational costs of the MMR™ can be relatively high compared to more established energy sources. However, the potential benefits of this reactor, such as its long operational life without refueling and its high safety standards, make it a promising option for future energy needs [168–172]. The MMR™ is particularly suited for applications in remote areas or regions with limited access to conventional energy sources. Its compact size and modular design allow for easy transportation and installation, making it a versatile solution for various energy demands [166–172]. Overall, the MMR™ developed by the Ultra Safe Nuclear Corporation represents a significant advancement in nuclear technology, offering a reliable, safe, and efficient source of low-carbon energy [170–174].

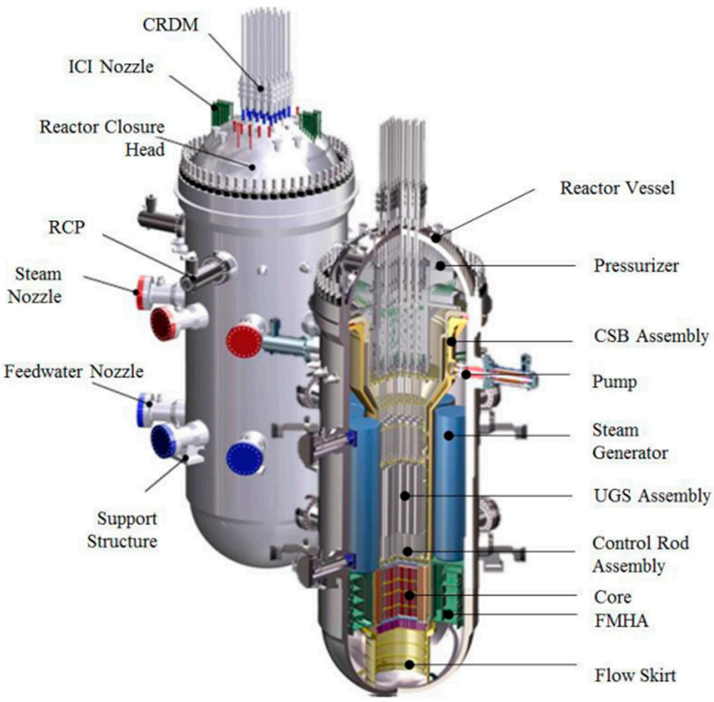

Figure 8. Overview of the MMR™ developed by the Ultra Safe Nuclear Corporation [175].

The Kaleidos microreactor developed by Radiant Nuclear (El Segundo, CA, USA) (Figure 9) is an innovative solution for portable nuclear power generation [159–161]. This reactor utilizes high-temperature gas-cooled reactor (HTGR) technology, using helium gas as the coolant and TRISO fuel [159–162]. TRISO fuel is superior in terms of safety features, being resistant to meltdown. Kaleidos is designed to produce 3 MWt of thermal power and approximately 1 MWe of electric power [159–162]. The Kaleidos microreactor is fully portable and housed in a transport container. This design allows the reactor to be easily transported by truck, ship, or aircraft. This portability feature is particularly advantageous for meeting energy needs in remote areas and providing emergency power supplies [159–162]. The reactor is equipped with passive cooling systems that do not require water, facilitating regulatory approval processes. Kaleidos aims to provide a resilient power supply with minimal on-site infrastructure requirements. Once installed, the reactor can immediately operate at full capacity and provide long-term, reliable energy production. Additionally, Kaleidos can provide clean electricity and heat during energy production, making it suitable for various industrial and commercial applications [159–162].

Figure 9. Overview of the Kaleidos microreactor developed by Radiant Nuclear [161].

Table 2 provides a detailed comparison of various features of microreactors. This table includes different microreactor designs and compares their power output, operational duration, fuel type, coolant type, and general characteristics. The reactors listed in the table include eVinci™, Aurora, Holos Generators, Xe-Mobile, NuScale, SEALER, U-Battery, MMR™, and Kaleidos. The power output (MWe) of these reactors ranges from 0.2 to 100, with operational durations extending from 3 to 30 years. Fuel types among these reactors include HALEU TRISO, metallic fuel, UO2 or UN, and TRISO/FCM™. The coolant types include liquid sodium, helium, carbon dioxide, and pressurized water. For instance, the eVinci™ microreactor offers a power output of 0.2–5 MWe and can operate for at least 3 years. It features high-temperature heat pipes and a compact design that ensures reliability. The Aurora microreactor can generate 1.5 MWe of power and operate autonomously for 20 years. It uses metallic fuel and liquid sodium as a coolant and has the capability to burn nuclear waste. The Holos Generators microreactor offers scalable power options ranging from 1 to 100 MWe and features a simple design similar to a turbojet engine, providing high efficiency [25]. Table 2 thus highlights the diverse capabilities and specifications of different microreactor designs, showcasing their potential applications and the advanced technologies they incorporate. This comprehensive comparison underscores the versatility and adaptability of microreactors in addressing various energy needs across different settings.

Table 3 highlights the distinct advantages and disadvantages associated with various microreactor designs. Each microreactor presents unique benefits tailored to specific needs and challenges. For instance, the eVinci™ microreactor, developed by Westinghouse Electric Company, boasts a high-temperature heat pipe and a compact design, making it reliable for long-term operation without refueling for over three years. However, the limited operational data and high initial costs present notable challenges. Similarly, the Aurora microreactor by Oklo Inc. offers long autonomous operation (up to 20 years) and the capability to burn nuclear waste, yet it remains in the developmental stage with insufficient technical data and requires additional safety measures for the sodium coolant. Other designs, like the Holos Generators and Xe-Mobile, emphasize high efficiency and portability, respectively, but face challenges related to their innovative designs and increased costs for sophisticated control systems [25].

Table 2. Features of micro reactors [25].

Reactor Name	Power Output (MWe)	Operating Time (years)	Fuel	Coolant	Features
eVinci™	0.2–5	≥3	HALEU TRISO	Liquid sodium	High-temperature heat pipe, compact design, reliability
Aurora	1.5	20	Metallic	Liquid sodium	Long autonomous operation, nuclear waste burning
Holos Generators	1–100	3–20	TRISO	Helium/CO_2	Turbojet engine-like, simple design, high efficiency
Xe-Mobile	≥1	3	TRISO	Helium	Portable, autonomous operation
NuScale	1–50	≥10	HALEU	Pressurized water	Suitable for small power grids and remote facilities
SEALER	3	30	UO_2 or UN	Lead	Sealed core, long operation without refuelling
U-Battery	4	30	TRISO	Helium	Annular prismatic core, indirect Brayton cycle
MMR™	5	20	TRISO/FCM™	Helium	Flexible heat transfer, high temperature stability
Kaleidos	0–1	20	UO_2	Helium	Portable, autonomous operation

Table 3. Advantages and disadvantages of micro reactors [25].

Reactor Name	Advantages	Disadvantages
eVinci™	High-temperature heat pipe, compact design, reliability, ≥3 years without refueling	Limited operational data, high initial costs
Aurora	Long autonomous operation (20 years), nuclear waste burning, compact design	Developmental stage, insufficient technical data, safety measures for sodium coolant
Holos Generators	Turbojet engine-like, simple design, high efficiency (up to 60%), scalable power options	Innovative design not widely commercially applied, potential safety and operational challenges
Xe-Mobile	Portable, autonomous operation, ≥3 years without refueling, TRISO fuel	Requires sophisticated control systems for autonomous operation, increased costs
NuScale	Suitable for small power grids and remote facilities, ≥10 years without refueling, high safety and efficiency	Not yet widely commercially applied, high initial investment costs
SEALER	Sealed core, long operation without refueling (30 years), passive decay heat removal	Technical challenges with lead coolant management and operation
U-Battery	Annular prismatic core, indirect Brayton cycle, 4 MWe power, 5 EFPY core life	Complexity due to helium turbine development requirements, developmental stage
MMR™	Flexible heat transfer, high temperature stability, 20 years without refueling, TRISO/FCM™ fuel	Developmental stage, high operational costs
Kaleidos	Portable and compact design, operates autonomously, ≥5 years without refueling, meltdown-proof TRISO fuel, air-cooled system, eliminates the need for on-site water use	Developmental stage, high initial investment costs, potential regulatory challenges due to new technology

2.2. Technological Features and Advantages

The advanced technological innovations in microreactor designs offer various advantages to users. Microreactors continue to attract attention due to the intensive technological infrastructure required in their production processes and the benefits provided during their use. One critical technological feature is reactivity control, essential for the efficient and safe operation of microreactors. Reactivity control can be achieved through three main options to ensure high energy production within a small core [20].

Firstly, higher neutron leakage occurs in small cores compared to larger plants, making it crucial to manage these leakages. The first method to achieve this is by increasing the neutron flux level. This can be achieved by choosing core and coolant materials that have low absorption cross-sections within the neutron spectrum and incorporating neutron multipliers, such as beryllium compounds, into the system [176,177]. However, increasing the flux level also increases irradiation damage within the core and incurs additional costs due to the use of neutron multipliers [178,179].

The second option is to increase the concentration of fissile material. This can be achieved by selecting fuel compounds with a higher proportion of uranium and high U-235 enrichment levels [35,76,180–183]. For instance, HALEU fuel can be used. However, higher enrichment levels lead to increased costs and the risk of forming a plutonium-rich core [76,180–183].

The third approach involves leveraging the thermal portion of the neutron energy spectrum to increase the likelihood of fission. This can be accomplished by employing efficient neutron moderators like water, heavy water, or graphite. Given the compact nature of the core, it is essential to optimize all three methods. Balancing these methods with considerations of reactor safety, proliferation resistance, and cost-effectiveness is crucial. Consequently, reactivity control plays a critical role in microreactor design [35,76,180–183].

Table 4 provides a comparative view of the spectrum and fuel enrichment levels across different microreactor designs. The table illustrates the diversity in spectrum types—thermal and fast—and the range of enrichment levels, predominantly between 5% and 19.75%. For example, the eVinci™ and Holos Generators microreactors utilize thermal spectrums with fuel enrichment levels of 5–19.75% and 8–15%, respectively. In contrast, the Aurora microreactor operates on a fast spectrum with fuel enrichment levels below 20%. This variation in spectrum and enrichment levels reflects the tailored approaches to achieving optimal reactivity and efficiency in different operating environments. The diversity in fuel types, such as HALEU and TRISO, further underscores the adaptability of microreactors to specific needs, enhancing their performance and safety profiles. By examining these tables, it becomes evident that microreactors offer versatile and innovative solutions for energy production. However, the successful deployment of these reactors hinges on overcoming challenges related to initial costs, operational data, and safety measures, emphasizing the need for continuous research and development [25].

Table 4. Spectrum and enrichment levels of microreactors [25].

Design	Spectrum	Fuel Enrichment
eVinci™	Thermal	5–19.75%
Aurora	Fast	<20%
Holos generators	Thermal	8–15%
Xe-Mobile	Thermal	<20%
NuScale	Thermal	<20%
SEALER	Fast	19.75%
U-Battery	Thermal	<20%
MMR	Thermal	19.75%
Kaleidos	Thermal	20%

Another crucial technological feature is the choice of coolant. This system is fundamental for heat control and removal. The ideal coolant for microreactors should possess characteristics such as high volumetric heat capacity, stability without phase change under normal and accident conditions, low neutron absorption, operation at low pressures, limited activation in neutron-rich environments, chemical compatibility with core and structural materials, and excellent thermal conductivity. Analyzing the coolant choices for microreactors, molten salts, sodium, and lead-based coolants emerge as the most effective due to their high power density, substantial heat capacity, phase stability, and capability for low-pressure passive heat removal [20]. Molten salts provide advantages like natural convection cooling, large temperature differentials within the core, and high volumetric heat capacities, though they also present issues such as corrosion and high melting points [184–193]. Sodium provides advantages such as a low melting point, established technical knowledge, the potential to achieve high-temperature differentials, and natural circulation cooling. However, sodium has drawbacks, including restricted natural circulation control and chemical reactivity with water and air. Lead-based coolants offer benefits such as natural convection cooling, significant thermal inertia, and high volumetric heat capacity, but also present challenges like high melting points, corrosiveness, and the production of volatile polonium compounds [20,184–193].

Most microreactor designs convert power using a Brayton cycle with an intermediate heat exchanger [20,194]. Notably, in some microreactor designs, heat transfer from the core to the intermediate heat exchanger is facilitated by heat pipes, which is a significant deviation from traditional and advanced large nuclear plants [195]. Microreactors and small modular reactors (SMRs) encompass a broad spectrum of technologies, such as light water reactors (LWRs); high-temperature gas reactors (HTGRs); and advanced reactor concepts like liquid metal fast reactors (FRs), molten salt reactors (MSRs), and heat pipe (HP) reactors [196–202]. These designs can differ greatly in fuels, materials, coolants, reflectors, manufacturing techniques (e.g., additive manufacturing), and heat exchangers [203].

In terms of radioactive material containment, microreactors require simpler and more economical barriers compared to larger reactors. This advantage stems from factors such as lower source terms, lower system pressures under normal conditions, and a reduced likelihood of chemical reactions. In configurations using molten salt as a coolant, the fuel can dissolve into the molten salt. This configuration offers various advantages [20]. For instance, it provides features such as a strong negative temperature coefficient, high burnup rates, continuous fuel cleanup, and the ability to facilitate backup shutdown mechanisms by transferring fuel to subcritical tanks. These attributes are essential for improving the safety and performance of microreactors [203–208]. However, this technology is still developing and encountering specific obstacles. For example, the depth of defense capacity is reduced, meaning coolant loss equates to active fuel loss. Moreover, the upfront investment and construction expenses for a system integrated with chemical salt purification are significantly high. Establishing such a system requires a significant amount of capital, which is a factor to consider in terms of cost-effectiveness [203–208].

The absence of containment structures typically mandated for large nuclear power plants (NPPs) can result in several issues. This gap means fewer barriers separating radioactive materials from the environment and a higher risk of incidents such as aircraft impacts, which are usually considered in the design of large NPPs. The initial generation of small modular reactors (SMRs) will likely utilize low enriched uranium (LEU) fuel with uranium-235 enrichment levels between 3% and 5% [209–211]. Conversely, microreactor designs typically employ highly enriched low enriched uranium (HALEU) fuels with enrichment levels above 5% but below 19.75% [212–218]. This higher enrichment level improves reactor performance and lengthens the refueling intervals from several years to the reactor's full operational life [198,216–219]. According to economic studies by the Massachusetts Institute of Technology (MIT), the fuel costs for microreactors can be substantial. Therefore, the advantages of these more costly fuels need to be assessed in light of performance requirements and current production constraints [26].

In the United States, commercial light water reactors (LWRs) produce electricity using low enriched uranium (LEU) fuel, which contains between 0.7% and 20% uranium-235.

The existing LWR fleet typically utilizes LEU with uranium-235 levels below 5%. However, some advanced reactors and LWR designs are planned to use LEU with uranium-235 concentrations ranging from 5% to 20%. These higher enrichment fuels, known as HALEU, can enhance fuel efficiency and positively impact the economic performance of the facility [20,220–223]. HALEU fuel intended for microreactor use is commonly available in metallic, ceramic, or TRISO forms [194,198]. While conventional light water reactors use fuel with less than 5% uranium-235, microreactors and some advanced reactor designs use HALEU fuels with uranium-235 enrichment levels between 5% and 19.75% [20,220–223]. The higher enrichment level of HALEU enhances reactor performance and extends refueling intervals, thus improving operational efficiency. The various forms of HALEU fuel provide flexibility for different reactor types and optimize fuel management [20,220–223]. Economic assessments and studies in the United States suggest that using HALEU fuel can increase cost efficiency in microreactors. However, the production and processing of these fuels involve complexities due to current technical and logistical limitations. Therefore, the advantages of HALEU fuel should be carefully evaluated in terms of performance requirements and cost-effectiveness [20,220–223]. As advanced reactor technology progresses, both new and existing power reactors will need HALEU fuel [29,79,217,224]. The US nuclear fuel cycle infrastructure is currently not equipped to provide new HALEU sources or the necessary qualified packaging for HALEU transportation [29,79,217,224]. It is likely that commercial supply will not be realized until the microreactor market becomes established.

Microreactors stand out with their technological innovations and the advantages they offer. These reactors, equipped with autonomous and remote operation systems, can operate safely without continuous human intervention, making them suitable for use in remote and inaccessible areas [25,205,225–227]. The installation of microreactors is relatively quick compared to large nuclear power plants; they can be set up and start generating power within a few days. These features provide a significant advantage by reducing installation time and costs [25,205,225–227]. Additionally, these reactors can be easily removed from one site and transported to another, enhancing flexibility and reducing costs. Microreactors are also an ideal solution for providing electricity during natural disasters or system outages. Numerous microreactors are engineered to fit within standard ISO containers, which simplifies their transportation [25,225–227]. However, the transportation of fueled microreactors can pose some regulatory challenges. All these advantages make microreactors flexible and economical while enhancing energy security and resilience [25,225–227].

2.3. Expectations and Challenges

Microreactors can address energy needs with the advantage of rapid deployment and portability in remote or hard-to-reach areas. Unlike large nuclear power plants, they can be set up and start generating power within a short time, offering significant time and cost savings [25,29,116,161,228,229]. Designed to fit standard containers, they can be easily transported using various means of transportation, although this process can present regulatory challenges [25,29].

Economic analyses evaluate the advantages and costs of microreactors. The Nuclear Energy Institute has conducted cost assessments for microreactor facilities that require long-term operation and periodic refueling [25,228,229]. These analyses indicate a wide range of costs, influenced by capital expenditures, credit guarantees, and ownership types [161,191,207,217]. Compared to diesel generators, microreactors stand out for their economic competitiveness. Diesel generators incur high capital costs and fuel requirements, making microreactors a more advantageous long-term option. In terms of electricity production costs, microreactors are generally more competitive [228,229].

The small size and factory production capabilities of microreactors help reduce costs. As production volumes increase, capital and fuel costs are expected to decrease [25,29,228,229]. Additionally, operational and maintenance costs may also decline. Costs vary depending on distribution conditions and microreactor designs. Ownership type and credit guarantees also impact capital costs. The compact size and portability of microreactors reduce setup time and costs, addressing some issues typical of mega projects [25,29,228,229].

Despite the numerous advantages provided by microreactors, several challenges exist. One major challenge is the limited availability of HALEU fuel, essential for the effective operation of microreactors, but currently not available on a large scale [25,29,228,229]. The safety and proliferation risks associated with microreactors can be higher compared to large nuclear power plants. These reactors require stringent implementation of safety standards. Proliferation risks involve concerns about the malicious use of nuclear materials. Therefore, to ensure the safety of microreactors, security measures and regulatory mechanisms that comply with international standards must be developed [25,29,228,229]. Blockchain technology can be utilized to address these issues to some extent [230].

The successful deployment of microreactors heavily depends on the current state and future of nuclear fuels. Most microreactors use HALEU fuel. However, the production of HALEU fuel is currently limited, and commercial supply is not fully established. In the United States, the existing nuclear fuel cycle infrastructure is not suitable for providing new HALEU sources or producing the necessary qualified packaging for HALEU transportation. Therefore, commercial supply is unlikely to be realized until the microreactor market matures. The production of HALEU fuel involves various technical and logistical challenges. Technical challenges include achieving high enrichment levels and safely processing the fuel, while logistical challenges involve the safe transportation and storage of the fuel. To overcome these challenges, it is necessary to increase existing production capacities and establish new production facilities [228,229].

Several strategies are being developed to increase HALEU production capacity in the future. These strategies include modernizing existing production facilities, establishing new facilities, and fostering international collaborations. The United States, in particular, is conducting various research and development projects aimed at increasing HALEU production capacity. These projects aim to develop new production techniques and improve existing ones. Supply chain management also plays a crucial role in the future production of HALEU fuel. To establish a secure and efficient supply chain, strict security protocols and logistical planning must be implemented at all stages from production to consumption. In this context, innovative solutions such as blockchain technology can be used to enhance the traceability and security of the supply chain. Blockchain can increase transparency and reliability by recording and tracking all movements of the fuel from production to final use [228–230].

The economic impacts of HALEU fuel must also be considered. According to economic studies conducted by the Massachusetts Institute of Technology (MIT), the costs of HALEU fuel can be high. However, these high costs can be balanced by the performance advantages and long service life of the fuel. Additionally, the use of HALEU fuel can increase the operational efficiency of microreactors, providing long-term economic benefits. From an environmental perspective, the use of HALEU fuel can contribute to environmental sustainability by reducing carbon emissions. Microreactors, when integrated with renewable energy sources, can minimize the carbon footprint and enable the development of environmentally friendly energy systems. This integration can reduce dependence on fossil fuels, contributing to a cleaner and more sustainable energy future. However, the use of HALEU fuel also brings security and proliferation risks. Highly enriched uranium increases the risk of malicious use, necessitating strict security measures. To ensure the safe operation of microreactors, security protocols and regulatory mechanisms in line with international standards must be developed. Additionally, innovative solutions such as blockchain technology can help manage these risks by enhancing the traceability and security of nuclear fuels [228,229].

Licensing requirements are another barrier to the widespread adoption of microreactors. Existing nuclear regulations and licensing procedures are designed for large nuclear power plants and are not suitable for the characteristics of microreactors. The licensing process for microreactors should be more flexible and expedited due to their smaller size and portability. The creation and implementation of these yet-to-be-established licensing requirements could delay the practical use of microreactors [25,29,228,229].

Blockchain technology is highly effective for monitoring and securing nuclear fuels. Initially, non-digital materials need to be incorporated into the blockchain. The lack of digital access can hinder the tracking and verification of materials. Blockchain technology can bridge the gap between the physical and digital worlds [41]. Attaching radio frequency identification tags or quick response codes with unique identifiers to radioactive materials allows each movement or transaction to be meticulously tracked and documented on the blockchain [41]. By incorporating Internet of Things (IoT) devices, it becomes possible to continuously monitor the location, condition, and environmental factors of nuclear fuels via IoT sensors. The data from these sensors are immediately uploaded to the blockchain. Non-digital information can be manually entered into the blockchain by authorized personnel. These procedures are reinforced by verification and audit protocols [41].

Blockchain technology provides multiple mechanisms to combat fraud and the counterfeiting of nuclear fuels. One of the critical aspects is that the data stored on the blockchain, consisting of immutable records, cannot be altered afterward. This ensures the reliability and integrity of the data. Moreover, every transaction is verified through cryptographic signing, ensuring that only authorized individuals can make modifications. Smart contracts carry out transactions autonomously once certain criteria are fulfilled, minimizing human error and the necessity for human involvement [41].

Blockchain technology can improve the physical protection of nuclear fuels by combining both physical and digital security methods. This process can be divided into multiple stages. At the outset, IoT sensors and global positioning system devices can enable real-time monitoring, with this information being directly logged into the blockchain for instant tracking. The second stage, access control, determines who is allowed to access specific data, preventing unauthorized access. This integration with physical security measures ensures strong protection [41]. The third stage involves systematic audits, with regular checks to detect any irregularities or security breaches in the data stored on the blockchain. By implementing these steps, blockchain technology has evolved into an effective means for securely and transparently monitoring and managing nuclear fuels. By connecting the physical and digital realms, it can deter fraud and integrate smoothly with current physical security measures. These suggestions will improve the seamless incorporation of blockchain technology within the nuclear industry [41].

Microreactors are intended to be created, built, owned, and managed using machinery and services tailored to generate energy and power for particular uses. The operational parameters of microreactors require focused consideration, and the regulatory authority needs to be explicitly established [30–59]. The licensing process for such reactors may require new regulations or amendments to existing ones, potentially causing delays. For instance, regulations applicable to large nuclear power plants mandate the presence of personnel in the control room [1–15]. However, since microreactors are typically designed for remote control, these regulations may need to be modified. Additionally, further regulations will be necessary for the transportation of fuel-loaded reactor modules to distributed usage areas [69–91]. Current safety assessment methodologies may be inadequate to ensure safety during the transportation and mobilization of fuel-loaded microreactor modules in remote sites. Hence, it is essential to develop new safety guidelines and regulatory structures to guarantee the safe and effective operation of microreactors [148–186,231,232]. Regulatory authorities should update existing regulations or develop new ones, considering the remote-control capabilities and mobilization requirements of microreactors [196–225]. This process will accelerate the widespread adoption of microreactors and their broader acceptance in the energy sector.

To better understand the global development of microreactors, it is beneficial to conduct a comparative analysis of small modular reactor (SMR) projects in different countries. This analysis includes key factors such as technological advancements, regulatory frameworks, market acceptance, and types of fuel used. Comparing SMR projects in various countries reveals the global status and potential advantages of this technology, providing valuable insights into the future development of microreactors. The following table summarizes the main features of SMR projects in several countries:

Table 5 compares the development of SMR projects in different countries, highlighting the global status and potential advantages of microreactors. By including this comparative analysis in our paper, we aim to provide readers with a broader perspective on the global development of microreactors [30,233–236].

Table 5. Comparative analysis of small modular reactor (SMR) development in different countries [30,233–236].

Country	Developed SMR Projects	Technological Advancements	Regulatory Framework	Market Acceptance and Applications	Start Date	Type of Fuel Used
United States	NuScale Power	Advanced safety systems, modular design	Ongoing approval processes by NRC	Commercial applications and public–private partnerships	2007	Low enriched uranium (LEU)
Canada	Ontario Power Generation SMR Projects	Innovative fuel use, environmental sustainability	Supported regulatory processes by CNSC	Provincial government and private sector support	2011	Low enriched uranium (LEU)
Russia	Floating Nuclear Power Plants	Mobile and flexible energy production, supplying remote areas	Supported regulatory framework by Rosatom	Successful applications in remote and hard-to-reach areas	2010	Low enriched uranium (LEU)
United Kingdom	Rolls-Royce SMR Project	Compact and economic design, rapid construction times	Ongoing approval processes by ONR	Government support and international collaborations	2015	Low enriched uranium (LEU)
China	ACP100	Small scale, multipurpose use	Approved by NNSA	Increasing interest in local and international markets	2010	Low enriched uranium (LEU)

In conclusion, the successful integration of microreactors requires careful consideration of their operational settings and effective determination of regulatory authorities [25,29]. Overcoming delays and changes in regulations necessitates collaboration and coordination. As these challenges are addressed, the flexibility and innovative solutions offered by microreactors will enable them to play a significant role in energy production.

3. Conclusions

This study highlights the unique advantages and challenges associated with microreactors. The compact and portable design of microreactors offers significant advantages in terms of rapid deployment and flexible application, particularly in remote or hard-to-reach areas. Unlike large nuclear power plants, microreactors can be installed and start generating energy within a few days, providing significant time and cost savings. Although their compatibility with standard ISO containers facilitates transportation by various means, it also presents certain regulatory challenges. Economic analyses show that despite their high initial costs, the long-term operational benefits of microreactors can make them competitive, especially compared to diesel generators. The learning curve in the production and operation of microreactors can lead to cost reductions. Additionally, the small size and factory production capabilities of microreactors are expected to reduce capital and fuel costs. Operating and maintenance costs may also decrease.

However, there are several challenges to the widespread adoption of microreactors. The limited availability of HALEU fuel is a significant barrier to the effective operation of microreactors. Potential hazards and proliferation threats can be more significant than those in large nuclear power plants, requiring the establishment of security protocols and regulatory frameworks that adhere to international standards. Licensing processes, designed for large nuclear power plants, need to be more flexible and expedited to suit the characteristics of microreactors. The creation and implementation of these yet-to-be-established licensing requirements could delay the practical use of microreactors. Blockchain technology can help overcome these challenges by providing transparency, traceability, and reliability in the licensing process. For example, securely recording and verifying data at every stage of the licensing and regulatory processes can enhance trust among regulatory authorities and stakeholders, accelerate processes, and reduce costs.

The successful deployment of microreactors heavily depends on the current state and future of nuclear fuels. In this context, various strategies must be developed for the production and supply chain management of HALEU fuel.

Firstly, it is essential to increase the existing HALEU production capacity. Modernizing current production facilities plays a critical role in this process. Updating these facilities with new technologies will enhance production efficiency and allow for higher quantities of HALEU production. Additionally, establishing new facilities for the production of highly enriched uranium is crucial. These new facilities should be planned to meet increasing demand and operated in compliance with international standards.

Various research and development projects should be conducted to develop HALEU production techniques and improve existing methods. The United States, in particular, is undertaking several R&D projects aimed at increasing HALEU production capacity. These projects should focus on developing new production techniques and improving current ones. Moreover, these projects should be supported through international collaborations and increased knowledge sharing.

Effective supply chain management must be established to ensure the secure and efficient supply of HALEU fuel. Strict security protocols and logistical planning should be implemented at all stages from production to consumption. Innovative solutions like blockchain technology should be utilized in this context. Blockchain can enhance the transparency and reliability of the supply chain by recording and tracking all movements of the fuel from production to final use.

To balance the high costs of HALEU fuel and make microreactors economically attractive, economic incentives and support programs should be developed. Such incentives will facilitate the long-term economic benefits of microreactors.

Finally, the use of HALEU fuel can contribute to environmental sustainability by reducing carbon emissions. Microreactors should be integrated with renewable energy sources to minimize dependence on fossil fuels. However, the use of highly enriched uranium also brings security and proliferation risks. Therefore, to ensure the safe operation of microreactors, security protocols and regulatory mechanisms in line with international standards must be developed. Innovative solutions like blockchain technology can help manage these risks by enhancing the traceability and security of nuclear fuels.

This review paper comprehensively addresses the technological advantages, economic challenges, and blockchain-technology-related solutions for microreactors. The main points of the paper and future perspectives are summarized below.

Firstly, microreactors offer numerous technological advantages such as high safety standards, flexibility, and modularity. These reactors can be installed more quickly and operated at lower costs compared to traditional large-scale nuclear reactors. However, the limited production capacity of HALEU fuel and supply chain issues hinder the widespread economic adoption of microreactors. To overcome these challenges, it is essential to increase production capacities and develop new supply chain solutions. Blockchain technology can play a significant role in overcoming economic challenges by enhancing the traceability and security of the nuclear fuel supply chain. The implementation of this technology will increase transparency and reliability in the supply chain. Additionally, the comparative analysis of small modular reactor projects in different countries reveals the global status and potential advantages of microreactors. Projects in countries like the United States, Canada, and Russia demonstrate various applications and regulatory approaches of microreactors.

In the future, it will be crucial to modernize existing facilities and establish new ones to boost HALEU fuel production capacity. International collaborations and joint projects can help accelerate this process. Innovative solutions, especially blockchain technology, should be further researched and applied to create a secure and efficient supply chain. This will enhance the traceability and security of the supply chain. Economic incentives and support programs should be developed to make microreactors economically attractive. This will facilitate the widespread adoption of microreactors in the long term. Additionally, to ensure the safe operation of microreactors, security protocols and regulatory mechanisms aligned with international standards must be developed to mitigate security and proliferation risks. Finally, increasing global collaborations in the development and application of microreactors will support technological knowledge sharing and the advancement of joint projects.

Successful integration of microreactors into energy production requires careful consideration of their operational settings and the establishment of effective regulatory frameworks. Collaboration and coordination are crucial to overcoming delays and adapting to regulatory changes. The flexibility and innovative solutions offered by microreactors will enable them to play a significant role in energy production as these challenges are addressed. In conclusion, given the advantages and challenges associated with microreactors, future research should focus on exploring optimal conditions for their deployment, as well as examining their regulatory, institutional, and societal impacts.

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