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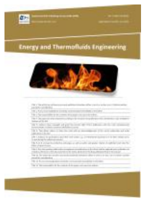

A Review on the Future of SMR Reactors in Nuclear Energy

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Abstract: The development of small modular reactors (SMRs) has emerged as a promising solution to provide clean, affordable, and reliable energy as global energy demand continues to rise. With a focus on different reactor types, their designs, and implementation strategies, this study offers a thorough overview of the state of SMR technology. This article evaluates the potential and challenges of small modular reactors concerning nuclear energy. It also thoroughly reviews the advantages and disadvantages of SMR technology, identifies regulatory barriers, public opinion, and infrastructure deficiencies, and investigates how SMRs might work with renewable energy sources to reduce greenhouse gas emissions. The SMR industry also emphasizes the significance of ongoing research and development. Adopting SMR reactors can be made easier with the support of advancements in design, technology, and regulatory frameworks. The integration of SMRs with renewable energy sources has the potential to provide a dependable, low-carbon, and sustainable energy solution. Advances in design, technology, and regulatory frameworks can facilitate the adoption of SMR. Annual operating and maintenance cost estimates can be affected by a wide range of additional factors, including the location of a plant, its capacity factor, regulatory considerations, plant obsolescence, and the number of reactors on the site. The difference in average cost ($/KWh) between SMR and Large-size reactors is about 20% less than anticipated. Furthermore, viable solutions for efficiently and securely handling SMR waste are deep geological repositories and dry cask storage. The SMR industry also emphasizes the significance of ongoing research and development.

1. Introduction

Comparing traditional large-scale nuclear power plants to small modular reactors (SMRs), SMRs are nuclear reactors with smaller dimensions and output (Locatelli et al., 2014). The potential of these reactors to provide cheap, safe, and clean energy to meet the world's increasing demand for electricity has made them more and more popular (Shobeiri et al., 2023). SMRs are constructed using prefabricated parts that can be transported to the installation site, and they are usually intended to produce between one and three hundred megawatts (MW) of electricity (Zohuri and McDaniel, 2019). In recent era, SMR have seen a significant interest in development, with several nations funding their research and development (Zohuri and Zohuri, 2020). In different stages of development across the globe, the International Atomic Energy Agency (IAEA) has identified over 70 SMR designs (Grossi, 2022). SMR proponents contend that offering energy security and a dependable, low-carbon energy source can help slow global warming (Peel et al., 2022). Small modular reactors are a promising solution developed in response to the growing demand for clean, affordable, and reliable (Blacketta et al., 2022). Due to their small size,

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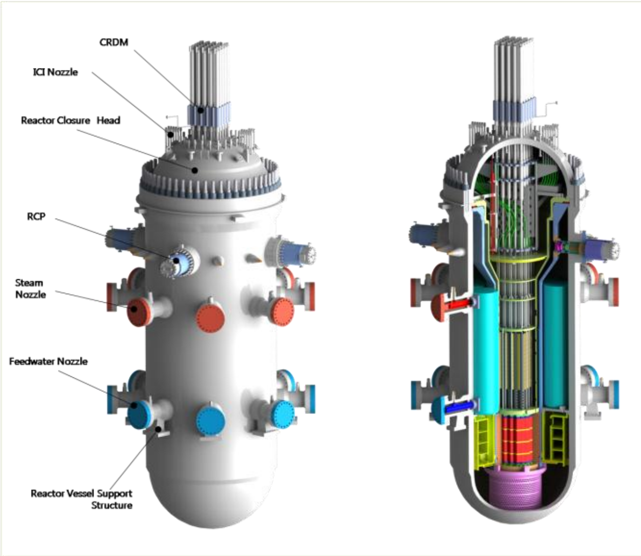

Fig. 1 Small modular reactors (Davis, 2013).

easy deployment, and scalability, SMRs are ideal for a variety of applications, ranging from remote communities to large-scale power grids (Hidayatullah et al., 2015). Despite their potential advantages, regulatory obstacles, public opinion, and economic viability, the SMRs have some challenges (Pearson et al., 2017). The present study investigates information regarding SMRs from a number of sources, such as government publications, technical reports, and peer-reviewed journals. It critically analyses the prospects and challenges facing SMR reactors, highlighting the importance of continued research and development in the SMR industry to address the challenges and maximize the benefits of this promising technology, which are missing in the open literature. Figure 1 shows the pictorial view of Small modular reactors (Davis, 2013).

2. SMR reactor types, advantages, and challenges

There are several types of SMRs, including pressurized water reactors (PWRs), boiling water reactors (BWRs), and high-temperature gas-cooled reactors (HTGRs). Some SMRs use passive safety features that rely on natural phenomena like gravity and convection to maintain safe operating conditions, while others use active safety systems. Table 1 shows the SMR reactor types, their advantages, and challenges. The advantages and challenges listed below are not exhaustive and may vary depending on the specific design and application of the SMR reactor.

3. Prospects and challenges of SMR reactors

SMR reactors can potentially revolutionize the nuclear energy industry but face several challenges. One of the significant challenges for SMR reactors is the regulatory environment. SMRs are subject to the exact regulatory requirements as larger nuclear reactors but with fewer resources available to navigate the regulatory process (Kessides, 2012). The regulatory process can be time-consuming, expensive, and complex, discouraging investment in SMR technology (Agency, 2018). Another challenge is the public perception of nuclear energy. Despite advancements in safety and technology, public perception of nuclear power remains negative due to incidents such as Chornobyl and Fukushima. This negative perception can make it difficult to gain public acceptance

Table 1 SMR reactor types, advantages, and challenges.

Type of SMR Reactor	Description	Advantages	Challenges
Pressurized Water Reactors (PWRs)	Water is used as a coolant and moderator, and the reactor core is housed in a pressure vessel.	The most common type of reactor proven technology, higher fuel efficiency and lower capital cost per kW than large reactors (Daniel and Kim, 2022)	With large size and limited flexibility, the potential for accidents (Temiz and Dincer, 2021)
Boiling Water Reactors (BWRs)	Water is used as a coolant and moderator, allowing it to boil and create steam to generate electricity.	Simple design, high thermal efficiency, compatibility with existing infrastructure (Ozawa and Saito, 2021)	Potential for radiation leaks and steam explosions (Commission, 2017)
High temperature Gas-Cooled Reactors (HTGRs)	Helium gas is used as a coolant, and the reactor can operate at high temperatures.	Potential for high efficiency and high-temperature process heat for industrial applications. It can be used in cogeneration systems (Bae et al., 2015).	Limited operational experience, potential for fuel contamination(Shin et al., 2015)
Liquid-Metal Cooled Reactors (LMRs)	Liquid metal, such as sodium or lead, is a coolant.	It can operate at higher temperatures, has the potential for a longer fuel cycle, and improves safety due to passive cooling (Davis, 2013).	Complex operation and maintenance, the potential for coolant leaks, and fire hazards (Energy, 2020)
Molten Salt Reactors (MSRs)	Liquid fluoride salts are used as both a coolant and fuel.	High operating temperatures, potential for improved fuel utilization and reduced waste, inherent safety features(LeBlanc, 2010)	Experimental technology, the potential for fuel contamination, and coolant leaks(Mignacca and Locatelli, 2020)

Table 2 Prospects and Challenges of SMR Reactors.

Prospects	Challenges	References
Greater flexibility and scalability	Regulatory hurdles	(Markard et al., 2020)
Complementary to renewable energy sources	Negative public perception	(Bragg-Sitton et al., 2020)
Lower capital costs and faster construction	Economic viability	(Black et al., 2019)
Potential for enhanced safety	Lack of infrastructure and specialized components	(Nian and Zhong, 2020)
Potential to meet changing energy demands	Nuclear waste management	(Kessides, 2012)
Reduced environmental impact	Limited operational experience	(Cao et al., 2022)

and support for SMR reactors (Lokhov et al., 2016). Economic viability is another challenge facing SMR reactors. Although they have lower capital costs and faster construction times than traditional large-scale nuclear reactors, SMRs may face challenges regarding economies of scale and site preparation costs (Black et al., 2019). The lack of infrastructure and the need for specialized components could increase the costs of SMR reactors. Despite these challenges, there are several prospects for SMR reactors. They can be deployed in various settings, from remote communities to large-scale power grids. Their modular design allows for greater flexibility and scalability, enabling them to meet changing energy demands. SMRs also have the potential to complement renewable energy sources, such as solar and wind power, to provide a reliable and consistent electricity supply (Michaelson and Jiang, 2022). A plethora of research have been carried out to address the challenges facing SMR reactors. Improvements in design, technology, and regulatory frameworks can help overcome the obstacles to deploying SMR reactors. Public education and outreach efforts can help increase public acceptance and support for nuclear energy and SMR technology. Table -2 Shows the Prospects and Challenges of SMR Reactors.

4. Economic feasibility of SMR reactors

SMRs offer advantages over larger nuclear power plants, such as lower upfront costs, faster deployment, and greater flexibility. The economic feasibility of SMRs depends on several factors, including the cost of construction, the cost of fuel, the cost of operation and maintenance, and the revenue generated by the electricity produced. One advantage is that it can be built in a factory and transported to the site, reducing construction costs (Lloyd et al., 2021). The smaller size of SMRs means they require less fuel and produce less waste, which can reduce their cost. The cost of SMRs can still be higher than that of conventional power plants, mainly due to the higher capital costs associated with their design and construction. Compared to a conventional nuclear power plant, the construction cost can be up to three times greater per unit of power capacity. Their regulatory environment has an impact on the economic viability as well (Playbell, 2017). Table 3 illustrates that although the licensing process for small modular reactors can be simplified compared to larger reactors, a substantial amount of time and resources are still needed. Operating an SMR can become more expensive overall if regulations are followed. SMRs are more advantageous than larger nuclear power plants in several ways, but how these advantages are balanced will ultimately determine whether or not they are economically viable. Numerous other variables, such as a plant's location, capacity factor, regulatory concerns, plant obsolescence, and the number of reactors on the site, can affect an annual operating and maintenance cost estimation. The average cost ($/KWh) difference between

Table 3. Economic Feasibility of SMR Reactors.

Cost Drivers	Potential Benefits	Potential Challenges	References
Capital Costs	Lower costs compared to large-scale reactors	Lower economies of scale	(Cserháti, 2017)
Construction Time	Shorter construction time	Lack of experience and standardization	(Michaelson and Jiang, 2022)
Operating Costs	Reduced costs due to a more straightforward design	Higher maintenance costs	(Kessides and Kuznetsov, 2012)
Fuel Costs	Lower fuel costs due to smaller reactor size	The higher price of enriched uranium	(Ross and Bindra, 2021)
Site Preparation	Lower site preparation costs due to a smaller footprint	Higher costs in remote locations	(De Jong et al., 2013)
Decommissioning and Disposal	Lower costs due to smaller reactor size and more straightforward design	Uncertainty around long-term waste management strategies	(Lloyd et al., 2021)

Large Size and SMR is about 20% lower than expected when all the factors are taken into account (Carelli et al., 2008). Table 3 shows the economic feasibility of SMR reactors, which is important to know for those who are working in this field.

5. SMR reactors and renewable energy

In the global shift to low-carbon energy systems, small modular reactors have been suggested to supplement renewable energy sources (Shropshire et al., 2012). Because they are sporadic, renewable energy sources like solar and wind power are unable to supply the grid with a steady and dependable power source consistently. SMRs can balance the unpredictability of renewable energy sources by offering a steady supply of low-carbon energy (Agency, 2019). Utilizing renewable energy sources with this kind of nuclear reactor allows for the creation of novel nuclear and renewable technology(El-Emam and Subki, 2021). The intermittent nature of renewable energy sources is complemented by the reactor's steady, continuous baseload power. Through thermochemical water splitting, it can also produce hydrogen, a clean fuel with a variety of uses. It has also been used in isolated, off-grid places with little access to conventional power infrastructure, where it works well with renewable energy sources. There could be environmental advantages to integrating SMRs with renewable energy sources. Combining nuclear power with renewable energy can help reduce carbon dioxide emissions as nuclear power has lower greenhouse gas emissions. In developing nations with limited access to renewable energy sources, the International Atomic Energy Agency found that SMRs may be crucial for lowering greenhouse gas emissions and boosting access to electricity (Khatib and Difiglio, 2016). Issues with public acceptability, regulatory frameworks, and cost hamper SMR integration with renewable energy sources. Successful integration with renewables depends on guaranteeing the safe and secure operation of SMRs and addressing issues with nuclear waste management, proliferation, and safety (DeCotis and Cartwright, 2022). Although careful planning, regulatory oversight, and public participation are necessary to ensure successful deployment, the integration of SMRs with renewable energy sources has the potential to provide a dependable, low-carbon, and sustainable energy solution.

6. Nuclear waste management of SMRs

Nuclear waste management, including small modular reactors, is critical to nuclear energy production (Kessides and Kuznetsov, 2012). Although SMRs produce much more nuclear waste than conventional large-scale reactors, it is still necessary to manage this waste (Krall et al., 2022). With a higher burnup rate of fuel in SMRs the nuclear waste can be reduced, and the fuel is used more efficiently. Nuclear waste generation can be further reduced by incorporating advanced fuel cycles, such as recycled fuel, into SMR designs. SMR nuclear waste needs to be handled and stored safely (Keto et al., 2022). Dry cask storage represents a viable option for managing radioactive waste in SMRs. Storing spent fuel in steel and concrete casks on-site at the nuclear plant is known as dry cask storage. Spent nuclear fuel can be safely and effectively stored for a long time using this method. Utilizing deep geological repositories, which entail burying radioactive waste beneath stable geological formations, is an additional viable choice. This technique could be used for SMR waste and the long-term storage of nuclear waste, which is currently employed in many nations (Fuks et al., 2022). It is significant to remember that handling radioactive waste is highly regulated and subject to tight safety requirements. To manage nuclear waste, the International Atomic Energy Agency has established guidelines and recommendations. These include creating comprehensive waste management plans and implementing safety precautions to safeguard the environment and public health (Moniz, 2011). The

Table 4. Waste Management Challenge of SMRs.

Challenge	Description	Reference
Regulatory compliance	Compliance with strict safety standards and regulations for nuclear waste management is necessary to ensure public health and environmental protection.	(Hietava et al., 2023)
Limited storage capacity	SMRs have limited on-site storage capacity for nuclear waste, requiring a long-term storage and disposal solution.	(Carvajal Nunez, 2022)
Public acceptance	There may be public concern and opposition to the transportation and storage of nuclear waste, which can create challenges for implementation.	(Fuks et al., 2022)
Radioactive waste production	SMRs produce nuclear waste that must be managed and stored safely.	(Moniz, 2011)
Cost	The cost of nuclear waste management for SMRs must be considered and accounted for in the overall economic feasibility of SMRs.	(Röhlig, 2022)

challenges in managing SMR waste are listed in Table 4. Dry cask storage and deep geological repository storage systems can overcome all challenges (Röhlig, 2022, Freeze et al., 2021).

7. **Advantages and Consequences**

Compared to the vast power output of large-scale nuclear reactors, one of the primary drawbacks of small modular reactors is their limited power output. This limit raises concerns about the capacity to expand and fulfil the world's growing energy needs, in addition to raising operating costs per kilowatt-hour (kWh) of electricity generated (Hietava et al., 2023). Another primary safety concern in SMRs is fast neutron usage, primarily motivated by waste reduction rather than safety improvement. Some who oppose this approach claim that it carries risks that could compromise safety procedures (Mijolović, 2023). There are also operational disadvantages. SMRs can produce up to 40% more nuclear waste than other reactors (Keto et al., 2022). Significant issues like increased waste production and nuclear fuel transportation emerge as SMRs rise. Small modular reactor (SMR) detractors highlight the higher risk profile of integrating multiple small reactors, even though SMR proponents favour integrating nuclear power as a supplemental source alongside variable electricity sources like solar or wind power (Zohuri, 2019.). The increased need for fuel transportation and waste production are blamed for the risk because they worsen the issues related to waste management and environmental impact. However, the advantages of SMRs should not be discounted. These reactor's off-site production could reduce building costs and increase economic viability. SMR designs also include passive safety features that lessen the requirement for active systems and the possibility of system failures (Playbell, 2017). SMRs are less expensive because of their smaller size, but their design has additional drawbacks. Small modular reactors suggest a bright future for nuclear technology despite these difficulties. There is strong evidence to support ongoing research and development into them because they have the potential to offer a route toward readily accessible, safe, and sustainable energy. Realizing the full potential of this novel approach to nuclear power requires stakeholders to carefully weigh the benefits and drawbacks of small modular reactors, even though it is challenging to compare SMRs to larger reactors. Figure 2 shows the comparison of mean fuel cost and nuclear waste of PWR, LWR, and SMR reactors.

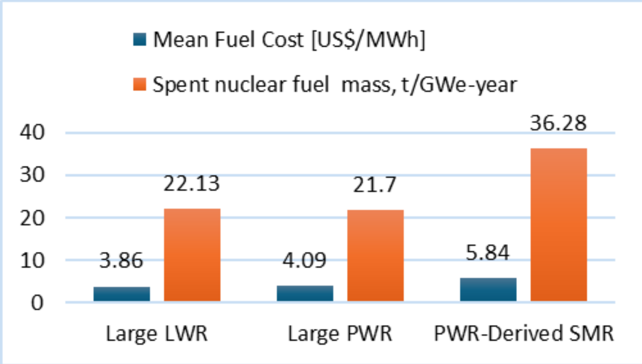

Fig. 2 Comparison of Mean fuel cost (Pannier and Skoda, 2014) and nuclear waste (Keto et al., 2022) of PWR, LWR and SMR Reactor.

7. Conclusion

With the present study, it has been concluded that SMR reactors have the potential to play an essential role in the future of nuclear energy by offering several benefits, including improved safety, flexibility, and cost-effectiveness. Several obstacles must be overcome, including public acceptance, regulatory barriers, and the implementation's financial viability. SMRs can produce up to 40% more nuclear waste than other reactors. Two possible solutions for efficiently and securely handling SMR waste are deep geological repositories and dry cask storage. Those reactors have the potential to contribute to a reliable and sustainable energy future with continued innovation and cooperation. These reactors' off-site production makes them more economically viable, and their average fuel cost is 20% lower than that of conventional reactors. Passive safety features are also incorporated into SMR designs to reduce the need for active systems and the likelihood of system failures. Including renewable energy sources such as solar and wind energy in a diversified energy portfolio is likely necessary. Concerns about cost, legal frameworks, and public acceptability impede the integration of SMR with renewable energy sources. Ensuring the safe and secure functioning of SMRs is essential for successfully integrating renewables. SMR reactors represent a promising avenue for advancing the future of nuclear energy, but their full potential will require careful consideration of both their advantages and challenges.

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