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Small Modular Reactors for the European Clean Energy Transition: An Introduction and Comparison of iPWR, HTGR, and MSR Technologies

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Abstract. Europe's clean energy transition is rekindling interest in nuclear power, particularly in tiny modular reactors (SMRs), due to their ability to provide secure baseload electricity and flexible support for intermittent renewable energy sources. SMRs address the limitations of traditional large reactors by shortening construction time, lowering upfront costs, and enhancing operational flexibility for grid services. This article reviews three primary SMR development paths,integrated pressurized water reactors (iPWRs), high-temperature gas-cooled reactors (HTGRs), and molten salt reactors (MSRs),and assesses their suitability for Europe's energy needs. iPWRs are small, light-water reactors that prioritize near-term deployability and safety through an integrated design, while operating at moderate temperatures. HTGRs utilize helium coolant and TRISO fuel, achieving temperatures of approximately 800-950°C, which enables industrial heat applications and hydrogen production while maintaining inherent safety. Molten salt reactors (MSRs) circulate liquid fuel in molten salt, allowing for high-temperature, low-pressure operation and improved fuel utilization; however, material corrosion remains a challenge. Each type of small reactor (SMR) offers unique advantages for grid integration: iPWRs can employ familiar technology for load following, HTGRs can switch between electricity and process heat, and MSRs offer the potential for integrating thermal energy storage. Given these complementary characteristics, a diversified SMR strategy can improve grid reliability, provide flexible baseload power to support renewables, and advance Europe's decarbonization goals.

Keywords: Small Modular Reactors (SMRs), Integral Pressurized Water Reactors (iPWRs), High-Temperature Gas-cooled Reactors (HTGRs), Molten Salt Reactors (MSRs).

1. Introduction

Europe’s move to cleaner energy in recent years has come under pressure due to geopolitics, aging infrastructure, and the need for secure baseload power. Although the share of renewables, such as wind and solar power, has expanded rapidly, they are naturally intermittent, making it challenging to maintain grid reliability and guarantee long-term energy security. Nuclear power, especially in its new iteration as small modular reactors (SMRs), is reemerging as a positive option in this context.

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So-called big nuclear reactors, which have been a source of low-carbon electricity for decades, are the focus of one thread of research. However, they often have long lead times, high initial investment rates, limited flexibility, and difficulty operating with complex (safety) systems, relegating them as economically risky and politically sensitive [1]. These weaknesses have prevented the development of new large reactors in Europe over the past 15 years. Furthermore, they have a weak load-following capability and are not fit for the contemporary variable renewable-based power systems. That is where small modular reactors (SMRs) were born. SMR is often mentioned here, as it is a direct way to improve reliability on a profile that follows load well or can be created more quickly. In brief, SMRs are nuclear plants that aim to borrow the best aspects of existing nuclear power, which do not emit anything when running, and extend them to allow the reactor to adjust its output as needed or be paired with heat storage or hydrogen production when there is excess power [2, 3]. SMRs are generally considered nuclear reactors with an electrical output of up to 300 MWe per module, designed for off-site fabrication, shipping, and on-site assembly. The modular plan looks fugly, but it is supposed to be much better for financing and building projects than the gigawatt-scale plants of old [4]. Moreover, many SMR concepts aim to provide both process heat and low-carbon hydrogen (when coupled with electrolysis, as here, or for high-temperature processes), which is critical not just for lowering industrial emissions but also for decarbonizing heating, far beyond the scope of electricity generation [4-6]. However, the SMR “universe” is also a large and diverse one. There are dozens of SMR designs at varying stages of maturity, and numerous cross-cutting issues, including licensing, supply chains, and financing, highlight the importance of prudently crafted policies. This dashboard is a helpful, technology-agnostic indicator of what is in the pipeline and its current progress [7]. This paper is devoted to a study of three example SMR schemes: iPWRs, HTGRs, and MSRs. Before exploring the engineering aspect, I will investigate whether and how these pathways meet the needs of European power as a driver of electricity demand growth, the extent to which they are interconnected with wind or solar energy, their coupling with thermal storage, and their relationship with hydrogen, among other factors. This article does not develop a new techno-economic model. Instead, it selects continuous technical parameters (such as minimum power level and ramp rate) and closely matches them to numbers from recent reviews and larger international reports [3, 8, 9].

2. Overview of SMR

Technology Pathways Another chapter in the nuclear innovation story is the Small Modular Reactors (SMRs). Not content to merely miniaturize traditional reactors, engineers and scientists are imagining new ways that reactors might be designed, built, and operated. Overall, SMRs can be categorized into three main technology paths: integral pressurized water reactors (iPWRs), high-temperature gas-cooled reactors (HTGRs), and fluidized molten salt reactors (MSRs). There are various characteristics, advantages, disadvantages, and real-life applications of these three types. There are several different routes to this destination. I will discuss them one by one in this section and present some recent research progress in their design.

2.1. The Integral Pressurized Water Reactors (IPWRs)

iPWRs are probably the one type of SMR which are easiest to understand because they are "scaled down" versions of standard, large pressurized water reactors (PWRs) (but with considerably less complexity). In iPWRs, the reactor core, steam generators, pressuriser, and pumps are integrated in a one-piece pressure vessel. This, however, minimizes the number of external pipes and leak points,

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which is beneficial from a safety perspective [10]. One of the most highly publicized iPWR designs is NuScale's VOYGR, which has been licensed in the United States and is under consideration in Eastern Europe. According to Locatelli et al., this modular architecture enables, first of all, incremental deployment to ease the management of financing and power grid integration, and second, to achieve a financial spread across multi-reactor units. One of the significant advantages of iPWRs is that they can be standardised in factory production, resulting in cost reductions over time.

Nevertheless, they have remained designed with light water as coolant and moderator, which would only allow for operation at about 300°C and lower thermal efficiency compared to more recent SMR concepts [11]. Regarding materials, there is now a high interest in the novel generation of corrosion-resistant alloys for SG tubes, as these remain relevant for PLEX [12]. Despite their deficiencies in temperature and flexibility, iPWRs are today's most deployable SMR for nations that require rapid deployment and are not as risk-averse.

2.2. First High-Temperature Gas-Cooled Reactors (HTGRS)

HTGRs are distinct because they utilize helium gas as the coolant, along with special TRISO-coated fuel particles that can withstand the extremely high temperatures and radiation. These features enable HTGRs to achieve outlet temperatures between 750 and 950 degrees Celsius; hence, they can be employed not only for electricity but also for industrial heat purposes and hydrogen production [13]. The inherent safety of HTGRs is related to the nuclear fuel - each TRISO particle includes several ceramic layers that entrap and prevent radioactive substances from moving and escaping into the atmosphere, even in cases where the reactor reaches very high temperatures. Enough, in case of an accident, however, that such reactors are passively cooled and do not require active pumping systems [6]. One real-world example is China’s HTR-PM, a twin-module HTGR project that has been grid-connected for some time. Not in Europe, but it demonstrates how HTGR can be constructed and operated safely [14]. There is one problem: Helium does not hold heat well, and it is more difficult to transfer heat with it. Recent studies are investigating the use of small heat exchangers manufactured with additive manufacturing (3D printing) to optimize this part of the design [15]. Such reactors are of particular interest to countries such as Germany and the Netherlands, which have a significant industrial heat demand and plans to move away from coal. Molten Salt Reactors (MSRs)

2.3. Molten Salt Reactors (MSRS)

Of all SMR concepts, the MSRs are the most novel and futuristic. Instead of solid fuel rods, MSRs circulate their fuel, which is a mixture of liquid medium enriched with the nuclear fuel, itself mixed into molten salts, through the reactor core. This means that continuous circulation and online refueling are achieved, fuel utilization increases, and waste is significantly reduced [16]. One of the significant advantages of MSRs is that they operate at low pressure, which decreases the likelihood of catastrophic accidents. Moreover, due to the high boiling point and large volumetric heat capacity of molten salts, MSRs can operate at very high temperatures (above 700°C) without any safety issues [17]. This renders them appropriate for combined heat and power (CHP) and possible future applications, including hydrogen production from high-temperature thermochemical cycles. MSRs do, however, have other significant technical challenges. The worst is materials corroding from the hot, chemically active salt. One way they are trying to solve this problem is through developing new structural materials, such as Hastelloy-N and silicon-carbide composites, which can better withstand these conditions [18]. Regulation is also an issue, as no MSR has been licensed for commercial

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operation in the European Union. One Danish concept project, the Seaborg Compact Molten Salt Reactor (CMSR), is targeting to have MSRs floating by 2030. If it works, it could pave the way for Europe to supply clean, flexible, and dispatchable nuclear power to coastal or island locations. Summary of Comparison: iPWRs are thus good candidates for fast deployment, as they have been proven to be feasible and easy to understand. People are now questioning the safety of HTGRs at high temperatures, which are not very dangerous and can meet industrial energy requirements. MSRs are an emerging technology, flexible and exciting, but they will also need more testing and development before any can be commercially deployed. These routes all serve different needs, and their future roles will depend on what choices Europe makes in balancing cost, safety, flexibility, and climate goals.

3. A focused comparison

3.1. Grid services and "grid-friendliness"

This is a result of the fact that modern European grids require multiple types of support, including primary and secondary frequency control, ramping functions to follow net load, voltage/reactive power support, and, at times, a black-start capability. Recent reviews indicate that SMRs are being designed with operational flexibility explicitly taken into account; such reactors have lower minimum power levels, faster ramp rates, and established cycling regimes. For example, IAEA guidance covers the flexibility (non-baseload) operation of nuclear power plants, pooling operational experience and a collection of procedures for frequency control and safe load-following. The NEA specifically studies technical and economic trade-offs, such as fuel performance and component aging, associated with cycling plants [3, 19, 20]. Breaking this down into the three pathways we considered, iPWRs are the lowest-hanging fruit for near-term grid-following, as they utilize light-water technology that is already familiar to the industry and can be paired with steam-side storage to help manage power fluctuations, given the rapid movement of electric loads. HTGRs can apparently "ramp" by switching output between electricity and heat/hydrogen,so that the grid sees a fast response, but the core does not have to cycle as aggressively. MSRs could take this much further by time-shifting energy over multiple hours using hot-salt storage, but this role depends on demonstration progress and licensing outcomes [2, 3, 21].

3.2. Wind solar and storage

Wind and solar are intermittent; hence, the obvious question is how SMRs help balance the system at the least cost with the minimum curtailments. The problem with integration is that all the studies of nuclear-renewable hybrid energy systems come up with very different ways to integrate electricity generation: purely electrical coupling (the reactor ramps with the grid), thermal coupling (the reactor runs steady, a heat store plus turbine does the ramping), and product switching (the reactor serves hydrogen or district heat when power is not needed). These contours can lessen curtailment and enhance the general utilization of both assets [2, 21]. SMRs receive good grades on the island and in weak grid reviews. There are several SMR review articles that suggest increasing resilience by providing inertia, dependable capacity for microgrids, or as hybrids, which work well with various intermittent renewable energy sources. Control and sizing matter, but there is indeed a fundamental complementarity in this setting [22].

Regarding hydrogen, NEA assessments suggest that nuclear heat and electricity can be competitive for significant, centralized demand, particularly when high-temperature reactors are

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coupled with high-temperature electrolysis. On a system level, the hydrogen plant effectively serves as a large, configurable load to absorb excess power or heat from the system, balancing the grid and enabling optimal reactor operation [5, 23].

3.3. Keywords (style to use: keywords)

In power-system terms alone, iPWRs are a gridist (internal-facing), short-term solution focused on driving load-following to net demand peak-following since steam-side storage reduces primary control duties; HTGRs are a hubist (external-facing) mid-term solution for firm power, and because duty cycles can be product-based when HTGRs also need to meet process demands of heat or hydrogen generation; MSRs are a long-term storage-focused solution requiring longer demonstrations to verify the promise of enhanced ramping range. These roles align with international technical literature and technology maturity tracking that is neutral [3, 20, 23]

4. Conclusion

Today, Small Modular Reactors (SMRs) are coming as a game changer for the ageing fleet of large reactors, as well as addressing the limited contribution to baseload power of intermittent renewables in Europe’s energy transition. Uniting safety and flexibility, they can also react flexibly to changes in hydrogen or heat demand, and are a key player in decarbonized power systems. For the three routes considered,iPWRs, HTGRs, and MSRs,they have very different benefits and technical issues. iPWRs are realistic and well-known, with short-term deployment potential. HTGRs' high temperatures allow for industrial heat. MSRs offer high-temperature, multi-purpose operation and are a promising future candidate, still requiring experimental validation. Perhaps more importantly, these technologies are not just academic, but are frequently connected to industrial projects and current research. The comparison in ramping capacity, hybrid system integration, and grid services also suggests different roles that SMRs can fulfill given their configuration and development stage. If Europe is preparing to make a quantum leap in its power infrastructure, it is probably a mistake to bet everything on a single solution,but SMRs are clearly the kind of thing that should be a part of the solution space.

References

[1] Locatelli, G., Mancini, M., & Todeschini, N. (2017). Generation IV nuclear reactors: Current status and future prospects. Renewable and Sustainable Energy Reviews, 74, 644–660.
[2] NREL. (2020). Hybrid Energy Systems: Opportunities for SMRs. National Renewable Energy Laboratory. Retrieved from https: //www.nrel.gov
[3] IAEA. (2024). Flexible Operation of Nuclear Power Plants for Load-Following. IAEA Nuclear Energy Series NP-T-3.Retrieved from https: //www.iaea.org
[4] IAEA. (2023). SMR Booklet 2023 Edition. International Atomic Energy Agency. Retrieved from https: //aris.iaea.org
[5] NEA. (2022). Advanced Nuclear Fuel Cycles and Radioactive Waste Management. OECD Nuclear Energy Agency.Retrieved from https: //www.oecd-nea.org
[6] IAEA. (2022). Advances in High Temperature Gas Cooled Reactor Fuel Technology. International Atomic Energy Agency. Retrieved from https: //www.iaea.org
[7] OECD/NEA. (2025). SMR Dashboard: A Framework for Assessing Deployment Readiness. OECD Publishing. Retrieved from https: //www.oecd-nea.org
[8] National Energy Administration of China. (2021). China’s Energy Transition Report. (in Chinese). Retrieved from http: //www.nea.gov.cn

DOI: 10.54254/2755-2721/2025.GL27857

[9] State Grid Corporation of China. (2014). Power Grid Development Report. (in Chinese). Retrieved from http: //www.sgcc.com.cn
[10] Ingersoll, D. T., et al. (2020). Benefits of modularity in small nuclear power plants. Progress in Nuclear Energy, 120, 103233.
[11] Liu, Q., Zhao, Z., & Feng, L. (2023). A techno-economic review of iPWR SMRs. Energies, 16(8), 3456.
[12] Latorre, M., Natesan, K., & Smith, B. (2022). Corrosion resistance of alloys for advanced nuclear systems. Nuclear Engineering and Design, 389, 111658.
[13] Tian, Y., Zhang, X., & Wang, J. (2022). TRISO fuel behavior in high-temperature gas-cooled reactors. Annals of Nuclear Energy, 170, 108960.
[14] Zhang, Y., Su, M., & He, S. (2021). Commissioning and safety assessment of HTR-PM. Nuclear Engineering and Technology, 53(11), 3497–3505.
[15] Wang, Y., Ren, X., & Duan, X. (2023). Additive manufacturing of compact heat exchangers for HTGRs. Journal of Nuclear Engineering, 4(1), 101103.
[16] Zhao, H., Lin, Q., & Xu, J. (2023). Liquid fuel behavior in molten salt reactors: Modeling and safety implications. Progress in Nuclear Energy, 149, 104201.
[17] Li, Y., Zhao, H., & Wu, Y. (2021). Thermophysical analysis of molten salts for high-temperature nuclear applications. Annals of Nuclear Energy, 158, 108254.
[18] Kissane, M., & Croteau, E. (2022). Materials for Molten Salt Reactors: Current Challenges and Future Prospects. Journal of Nuclear Materials, 562, 153538.
[19] PNE. (2024). Review of Load-Following Capabilities in Modern Nuclear Designs. Progress in Nuclear Energy, 153, 104584.
[20] Nuclear Energy Agency (NEA). (2021). Technical and economic aspects of load-following with nuclear power plants. NEA No. 7530 Retrieved from https: //www.frontiersin.org
[21] Frontiers in Energy Research. (2021). Nuclear-Renewable Hybrid Energy Systems (NR-HES): Review and Roadmap. Retrieved from https: //www.frontiersin.org
[22] Michaelson, D., & Jiang, L. (2021). System-level modeling of SMRs in isolated and weak grids. IEEE Transactions on Energy Conversion, 36(2), 1156–1167.
[23] NEA. (2025). SMR Dashboard: 3rd Edition. OECD Nuclear Energy Agency.