IEEE Power and Energy Magazine

The Race to Realize Small Modular Reactors

Rapid Deployment of Clean Dispatchable Energy Sources

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Abstract

Small modular reactors (SMRs) are currently touted as the next evolution of nuclear energy. They are a type of nuclear reactor designed to be smaller in size than a traditional reactor. Nevertheless, they are based on the same fission technology that splits atoms to create heat which can then be used to generate electricity. SMRs can offer clean, reliable power and heat at manageable costs for both on- and off-grid communities. Currently, there are more than 100 proposed SMR reactor designs worldwide participating in the race toward commercialization. This article presents a comprehensive review of the different SMR technologies that are currently being developed. The technical characteristics of the SMRs have been evaluated to provide insights into their complementary role in a renewable energy system and highlight how they can accelerate the journey toward a deeply decarbonized world.

Introduction

Nuclear power is experiencing a renaissance worldwide as one of the key solutions to achieve fossil-free electricity generation. In particular, the geopolitical effects on energy prices, the unprecedented demand for clean, abundant energy, and the desire to reach net zero emissions by 2050 are among the driving forces. Institutions such as MIT[1], IPCC[2], and IEA[3] acknowledge the role of nuclear power in the journey toward a deeply decarbonized world. According to the International Energy Agency (IEA), the Net Zero by 2050 scenario (NZE) predicts that the electrical power generation from nuclear power will increase two-fold by 2050, which is a median value of investigated scenarios. Nevertheless, up to 97 scenarios have been assessed by the IPCC to limit global warming to 1.5 °C. One scenario considers nearly an eight-fold increase in nuclear power. According to the U.S. Department of Energy (DOE), nuclear power has by far the highest avoided carbon dioxide emissions per energy source.[4]

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[1] D. Petti, J. Buongiorno, M. Corradini & J. Parsons, "*The Future of Nuclear Energy in a Carbon-Constrained World*", **MIT Energy Initiative**, 2018; https://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/.

[2] IPCC Report, WG3, AR5, Chapter 7: Energy Systems, **Intergovernmental Panel on Climate Change (IPCC)**, pp. 511 – 597, 2018; https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter7.pdf.

[3] "*Nuclear Power and Secure Energy Transitions: From Today's Challenges to Tomorrow's Clean Energy Systems*", **International Energy Agency (IEA)**, 2022; https://www.iea.org/reports/nuclear-power-and-secure-energy-transitions.

[4] "*Carbon Dioxide Emissions Avoided by Energy Source",* **Office of Nuclear Energy, U.S. Department of Energy**, 2019; https://www.energy.gov/ne/articles/carbon-dioxide-emissions-avoided-energy-source-2019.

Small modular reactors (SMRs) represent the latest innovation in nuclear power plant technology. Unlike traditional reactors, which have a capacity of around 1000 MW, SMRs are smaller, with a capacity of approximately 300 MW, one-third of standard-size reactors, according to the IAEA. There are also some recent large modular reactor (LMR) designs (e.g., Westinghouse AP1000) that can go up to 1000 MW.

This article provides further details about SMRs and their advantages. One of the primary benefits of SMRs is that they are produced using pre-fabricated reactor modules, which have the potential to significantly lower construction costs compared to onsite construction. This modern factory-based approach enables faster learning, and it reduces regulatory requirements, shortens construction times, and minimizes quality issues related to onsite construction. The smaller size and shorter construction times of SMRs are also expected to reduce project risk significantly and, consequently, reduce capital costs, which have historically been a major obstacle for traditional nuclear power plants.

The transition to SMRs represents a departure from the history of nuclear energy, which has been dominated by large-scale, centralized, highly productive, baseload power plants. Nonetheless, smaller nuclear power plants, comparable to SMRs in size, have existed for over 50 years. Although they have traditionally had lower financial risks, their lack of economies-of-scale meant they were never a viable alternative to large-scale power plants, as the costs of small nuclear reactors were too high in relation to the electricity they produced. However, modern manufacturing techniques have changed this situation. The principle of economies-of-mass-production now has the potential to produce SMRs at much lower costs than was possible in the past. This transformative shift is expected to have a significant impact on the future deployment of nuclear power, departing from the paradigm of large centralized power plants.

SMRs are an evolved technology with several advantages that make them useful in situations where larger grid-connected reactors may not be feasible or in remote areas where there is no grid at all. They are smaller in size, both physically and in terms of land footprint. They are modular, which means components are constructed as modules and then transported to the site for assembly. In many cases, they are delivered already fueled and can operate for many years on the initial load of fuel. They also have applications beyond electricity generation, as their excess heat can be used for non-electrical purposes such as district heating for commercial and residential needs, hybrid energy systems, water desalination (e.g., freshwater production), or heavy industry applications. SMRs can operate more flexibly than traditional reactors, enabling the integration of intermittent renewable technologies and supporting environmental and climate change goals.

The deployment of SMRs is gaining momentum globally, highlighted by Canada's Darlington New Nuclear Project planning four GE Hitachi BWRX-300, 300-MW SMRs, with the first one scheduled to be complete in 2028, and Poland's Orlen Synthos Green Energy's decision to order 24 BWRX-300.[5,6] Moreover, Ukraine's nuclear energy company Energoatom plans to build up to 20 Holtec SMR-160, 160-MW SMRs, with the first deployment in 2029. Figure 1 illustrates the global activities toward SMR deployment and

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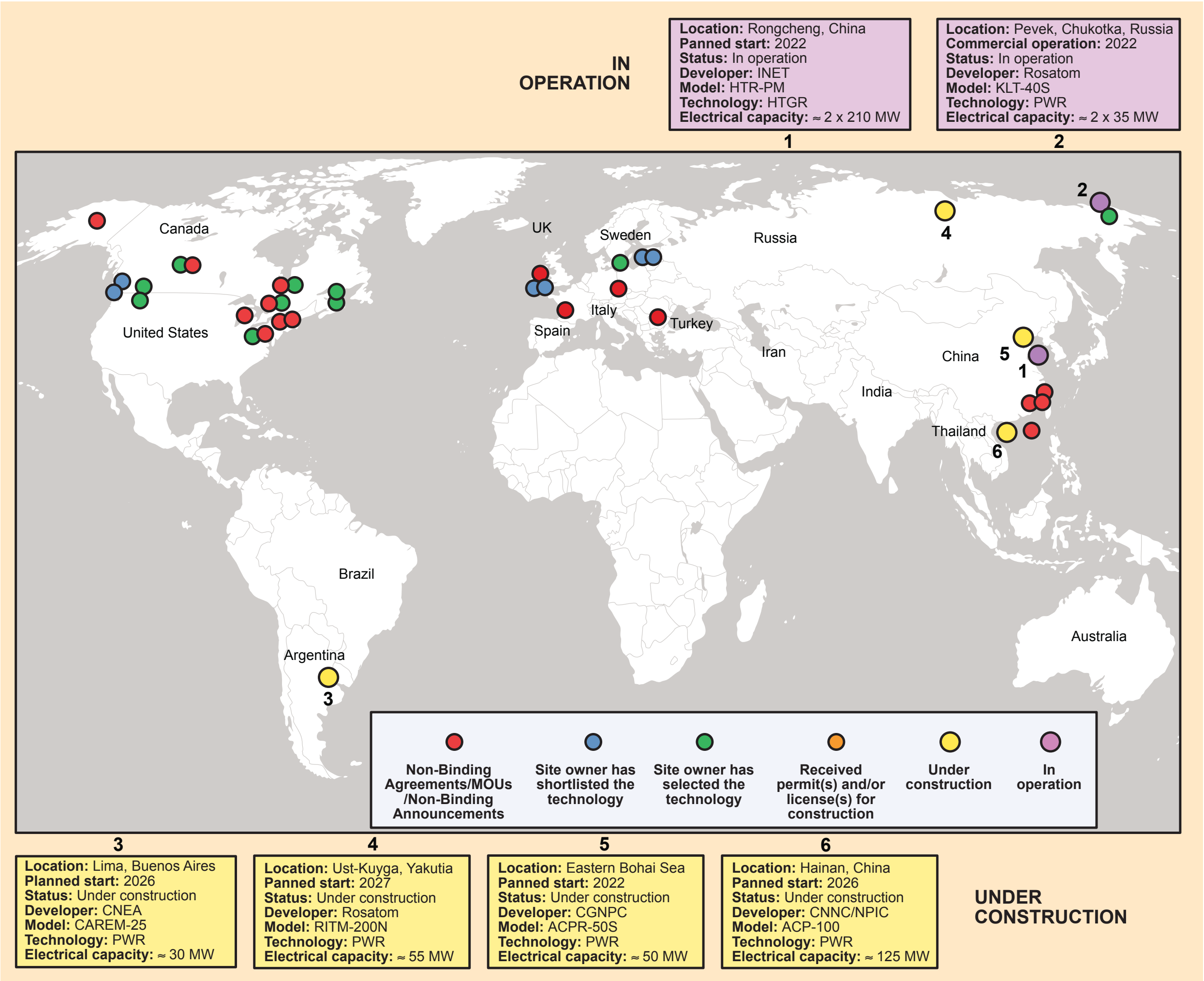
[5] "Darlington new nuclear project", **Ontario Power Generation (OPG)**; https://www.opg.com/projects-services/projects/nuclear/smr/darlington-smr/

[6] "*Six SMR power plants approved in Poland*", **World Nuclear News (WNN)**, 2023; https://world-nuclear-news.org/Articles/Six-SMR-power-plants-approved-in-Poland

rollout. Notably, China is currently constructing a 125-MW SMR at the Linglong One power plant.[7] The ACP100, developed by the China National Nuclear Corporation (CNNC), was the world's first generation III+ SMR to pass the safety review of the IAEA[8] , and it is expected to begin operation in 2026. As of today, Russia has two operational 35-MW, Generation III, floating SMRs based on conventional light-water reactor (LWR) technology[9], while China has two operational 210-MW, Generation IV, land-based SMRs[10] which utilize high-temperature gas-cooled reactor (HTGR) technology. These are the world's first HTGRs.



Location: Rongcheng, China
Panned start: 2022
Status: In operation
Developer: INET
Model: HTR-PM
Technology: HTGR
Electrical capacity: ≈ 2 x 210 MW

Location: Pevek, Chukotka, Russia
Commercial operation: 2022
Status: In operation
Developer: Rosatom
Model: KLT-40S
Technology: PWR
Electrical capacity: ≈ 2 x 35 MW

Location: Lima, Buenos Aires
Planned start: 2026
Status: Under construction
Developer: CNEA
Model: CAREM-25
Technology: PWR
Electrical capacity: ≈ 30 MW

Location: Ust-Kuyga, Yakutia
Panned start: 2027
Status: Under construction
Developer: Rosatom
Model: RITM-200N
Technology: PWR
Electrical capacity: ≈ 55 MW

Location: Eastern Bohai Sea
Panned start: 2022
Status: Under construction
Developer: CGNPC
Model: ACPR-50S
Technology: PWR
Electrical capacity: ≈ 50 MW

Location: Hainan, China
Panned start: 2026
Status: Under construction
Developer: CNNC/NPIC
Model: ACP-100
Technology: PWR
Electrical capacity: ≈ 125 MW

***Figure 1** – Locations of sites of a collection selection of small modular reactors (SMRs). Some of the information are adopted from "The NEA Small Modular Reactor Dashboard: Volume II", Nuclear Energy Agency (NEA), 2023; https://www.oecd-nea.org/jcms/pl_83555/the-nea-small-modular-reactor-dashboard-volume-ii.*

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[7] "*ACP100, an innovative nuclear reactor under construction in China*", **Energynews**, 2023; https://energynews.pro/en/acp100-an-innovative-nuclear-reactor-under-construction-in-china/.

[8] "*IAEA and CNNC Sign Agreement on Generic Reactor Safety Review for the ACP100*"**, International Atomic Energy Agency (IAEA)**, 2015; https://nucleus.iaea.org/sites/gsan/news/Pages/Signing-of-the-Agreement-for-the-IAEA-GRSR-for-the-ACP-100-Reactor-Design.aspx

[9] "*More nuclear heat for Arctic town*", **World Nuclear News (WNN)**, 2022; https://world-nuclear-news.org/Articles/More-nuclear-heat-for-Arctic-town.

[10] "*China's demonstration HTR-PM reaches full power*", **World Nuclear News (WNN)**, 2022; https://www.world-nuclear-news.org/Articles/China-s-demonstration-HTR-PM-reaches-full-power

In the near future, small modular reactors (SMRs) are expected to become commercially available. This article provides a comprehensive overview of SMRs, covering the following topics:

- ✓ First, the article presents an overview of the key technical and economic properties of SMRs.
- ✓ Next, the different generations of SMRs are described. The discussion starts with the *evolutionary Generation III+* SMR technologies, which are based on incremental improvements of existing light-water technology, such as boiling water reactors (BWR) and pressurized water reactors (PWR).
- ✓ The article then presents a separate section on *revolutionary Generation IV* SMRs, which are based on radically new reactor technologies, including liquid metal-cooled fast reactors (LMFR), molten salt reactors (MSR), and high-temperature gas-cooled reactors (HTGR).
- ✓ Finally, the article concludes with an overall assessment of the SMR technology, evaluating all proposed SMR designs and exploring the potential applications of future SMRs. This is followed by a brief section describing the safety features of SMRs, leading to the final conclusions.

Technical Features, Roles, and Services of the SMR

SMR technologies are highly promising from a commercial standpoint as they build on experiences and overcome many challenges from conventional nuclear reactors. The term "Small Modular Reactor" refers to the following distinctive features:

1. **Small** physically means that they are a fraction of the size of a conventional nuclear power reactor (e.g., 300 MW compared to 1000 MW);
2. **Modular** indicates that the reactor systems and components, to a large degree, are pre-made in factories and transported onsite for assembly and that the installed power can be scaled by combining multiple SMR units; and,
3. **Reactors** harness nuclear fission to generate heat to produce electricity.

In an evolving energy market, the SMRs have unique technical characteristics and flexibility to provide revenue from a variety of services, such as:

- ✓ Firm baseload power;
- ✓ Dispatchable power (e.g., due to changes in variable generation by renewable sources);
- ✓ Load-following power (e.g., due to changes in demand);
- ✓ Heat generation for non-electrical applications (e.g., district heating and water desalination at approx. 100 °C, and preheat or heat in process and heavy industry applications at ≥ 400 °C);
- ✓ Combined heat and power (CHP) cogeneration applications (e.g., hydrogen production via steam electrolysis at 150-200 °C, e-fuels production at ≥ 500 °C) for hybrid energy systems;
- ✓ Ancillary grid services (e.g., load-following, inertial response, reactive power dispatch, ramping capability, black-start and short-circuit capacity, etc.); and,
- ✓ Grid expansion deferral (e.g., reducing grid expansion needs by co-locating with demand).

Compared to *Generation III+* SMRs, *Generation IV* SMRs have the unique ability to generate high-temperature heat, which enhances their potential non-electrical services for thermal loads and energy buffering. SMRs can produce clean heat and stable power in close proximity to the end-user. This results in reduced transportation needs, including both external electrical power for backup and chemical fuel delivery, as everything is produced and consumed locally. Figure 2 illustrates how SMRs could be integrated into the future energy system, supplying both electric and non-electric demand.

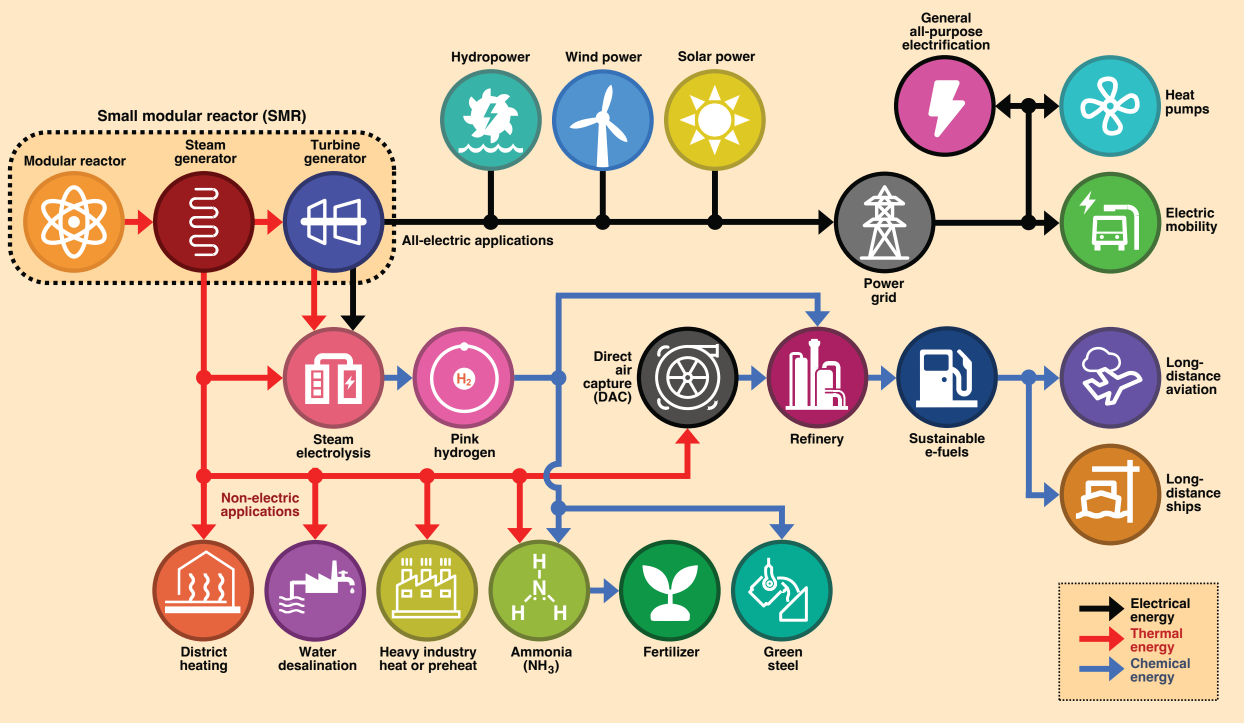

Figure 2 *– Overview of SMRs integrated into the future energy system, including electric and non-electric applications. Note that “pink hydrogen” refers to hydrogen produced by nuclear power, while "green steel" is expected to be manufactured using clean hydrogen as a reducing agent.*

Modes of Load-Following

The power management flexibility and fast response rates of SMRs should be emphasized, which widens their potential application as opposed to traditional nuclear power. In particular, light-water SMRs have three different modes of load-following options, including:

1. Taking one or multiple reactor modules offline for extended periods during low demand or high production from variable renewables (e.g., longer time intervals of several days or more);
2. Maneuver the reactor power by control rods in one or multiple power modules to compensate for hourly changes (intermediate time intervals of hours); and,
3. Bypass the steam turbine to the condenser in one or multiple power modules for rapid responses to changes in demand or generation (i.e., shorter time intervals in range of seconds or minutes).

Figure 3 illustrates the three modes of load-following. While these dispatchable capabilities are promising, it should also be emphasized that they have technical limitations and constraints. Taking reactor modules completely offline and online again will take several hours. Frequent use of control rods can contribute to thermal fatigue and aging of reactors components. Similarly, bypassing the turbine system also causes wear and tear as well as economic losses that would have to be compensated for by the provided load following service. With an increasing share of intermittent energy on the grid, however, such flexible operation will be in higher demand. Not considering these additional services, it makes more economic sense to operate the power plant continuously to maximize the return on investment. Load-following mode will also reduce the capacity factor of an SMR, which means that the levelized cost of electricity (LCOE) increases and provision of firm dispatchable power need to be valued in other ways to compensate for higher operating costs.

Figure 3 illustrates the schematic interface between the SMR and the power grid. In addition to firm dispatchable power, the synchronous generator provides other valuable system-bearing services, including reactive power for maintaining the grid voltage, rotating inertia that naturally provides fast power reserves, and short-circuit capacity that is needed for securing black-start capability. Figure 3 also highlights the steam extraction valve that takes usable heat between the high-pressure and low-pressure steam turbines. This thermal loop can supply thermal loads fully or partially. For non-electrical applications that need higher temperatures, SMR provides a preheat service from ~ 20 °C to ≥ 120 °C to reduce the energy needs from other heat sources in an industry cluster. There is also a turbine bypass valve from the steam generator in the case of fast load-following mode.

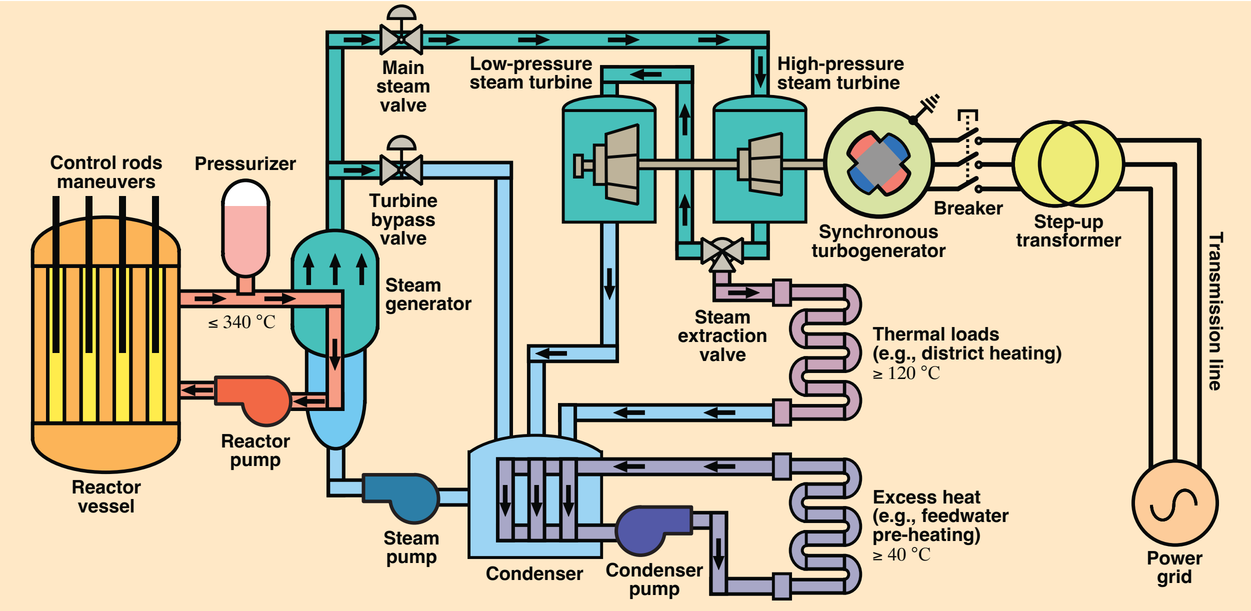

Figure 3 *– Schematic drawing of a PWR-type SMR module based on the thermodynamic Rankine cycle, including control rods, turbine bypass valve, steam extraction valve, thermal loads, and electrical breaker off-lining the generator from the power grid.*

Economic Drivers

Some SMR designs will be mass-produced in manufacturing facilities, while others, such as the GE Hitachi BWRX-300, will utilize an existing supply chain of vendors. Power plant modules are shipped to the location where they are stacked together, requiring only the final assembly to be conducted onsite. This is different from many reactors around the world, which are mostly built onsite. The modular construction method has the potential to make SMRs cheaper to build and promotes better learning than traditional nuclear power, similar to the advancements seen in the airline industry. Figure 4 illustrates the LCOE curve of traditional nuclear power against SMR technology, highlighting the economic drivers for the promised cost reduction.

In the nuclear power industry, just as in every other industry, there is value in replicating existing designs instead of making new ones from scratch. This benefit was observed with the four Barakah reactors in the United Arab Emirates (UAE), which are direct replicas of two reactors built in South Korea by Korea Electric Power Corporation (KEPKO), using the same supply chain. Comparing Barakah 1 and Barakah 4, the extrapolated capital costs were reduced by more than 50 percent, from \$5500/kW to \$2300/kW, in just over a three-year period between the initiation of each reactor project.[11,12] Lessons learned by the construction workers on the first unit were carried on to the subsequent units, resulting in an estimated 50 percent drop in labor costs for units 3 and 4. In summary, the lessons have emphasized the benefits of reusing the same reactor design and building multiple units at the same site with a well-planned and focused construction program, including an experienced supply chain and construction contractor.

Without understanding how nuclear power can be deployed well, employing a technology-agnostic approach, nuclear will be a missed opportunity to address net-zero targets. UAE's nuclear power program is a success story for the world to see and a great opportunity for replication throughout the world.

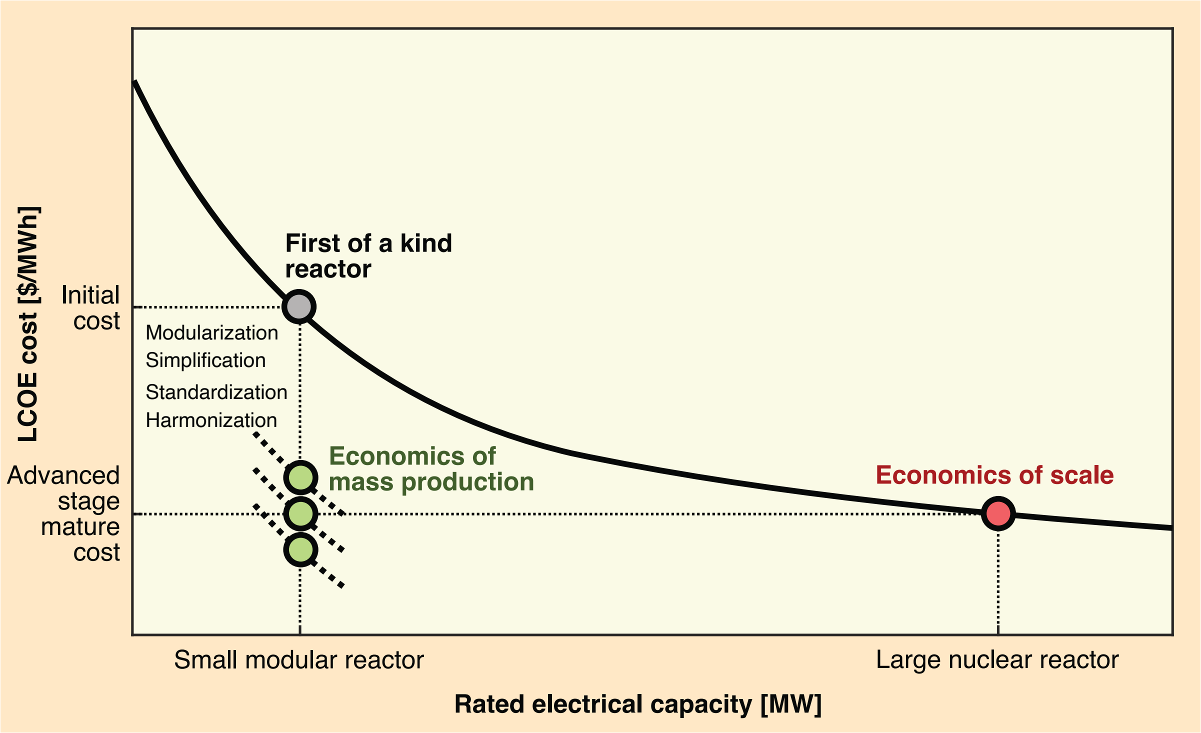

Figure 4 *– Key drivers for small modular reactors (SMRs) to compensate for diseconomics-of-scale, ensuring significant cost savings.*

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[11] "*Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders*", **Nuclear Energy Agency (NEA)**, 2020; https://www.oecd-nea.org/upload/docs/application/pdf/2020-07/7530-reducing-cost-nuclear-construction.pdf.

[12] "*The ETI Nuclear Cost Drivers Project – Full Technical Report*", **LucidCatalyst**, 2020; https://www.lucidcatalyst.com/_files/ugd/2fed7a_917857d4f3544323a84f163e5e904c23.pdf.

The SMR's modular construction makes it easier to scale the power generation to the energy needs of the regions where they are located. Over time, the pool of SMRs can be expanded or reduced to match demand, helping to keep operational costs as low as possible. They are envisaged to be more affordable partly because the factory that produces the modules can be granted a license to build the reactors, which applies to any prequalified site, instead of licensing each reactor individually onsite. This is another concept borrowed from the airline industry.

Some designs intend to let the SMRs operate for decades before they are refueled. In this period, the radioactive fuel is always kept inside the reactor core, which minimizes land proliferation risks and safety issues. In several of the concepts, the reactor itself is placed underground in pools, making it less vulnerable to terrorist attacks or natural disasters as they are protected from the SMR's outer façade on the earth's surface. SMRs rely on passive safety systems that do not require timely human intervention.

Similar to classical nuclear power plants, the SMRs are based on Gen. III+ technology that produces energy by the fission of uranium atoms and electricity through closed-loop steam-turbines and turbogenerators.

Generation III+ Evolutionary SMRs

There is a total of 33 light-water SMRs currently being developed for deployment and on the pipeline to commercialization, according to the September 2022 update from IAEA.[13] They represent the Generation III+ nuclear power technology, which is an incremental, evolutionary step from existing LWR technologies. Some of the developed Generation III+ SMRs are listed in Table 1, including boiling water reactors (BWRs) and pressurized water reactors (PWRs). The table includes levelized cost of electricity (LCOE) estimates derived from the SMR supplier's announced overnight costs for their Nth-of-a-kind (NOAK) reactors,[14] following initial pilot projects, assuming a 5 percent interest rate and $25/MWh operational cost (OPEX).

Boiling Water Reactors (BWR)

Four boiling water designs are currently being developed by GE Hitachi Nuclear Energy in USA/Japan and by the Dollezhal Research and Development Institute of Power Engineering (NIKIET) in Russia. There are two conceptual and two detailed designs. BWRs turn water into steam directly to drive a steam turbine.

One of the latter designs is the 10th generation BWR by GE Hitachi. Their BWRX-300 is an evolution of their U.S. NRC-licensed 1520-MW ESBWR. GE Hitachi will design their BWRX-300 with a load-following power range between 50 to 100 percent of the installed capacity and a ramping capability of 0.5 percent per minute, which comes in addition to baseload operations. In addition to flexible power generation, district heating capability will be another opportunity. It is expected to be cost-competitive with gas around the world, often employed as a reliable, but not carbon-free, provider of firm dispatchable power.

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[13] "*Advances in Small Modular Reactor Technology Developments*", **International Atomic Energy Agency (IAEA)**, September 2022; https://aris.iaea.org/Publications/SMR_booklet_2022.pdf

[14] "*Nuclear power in Norway (Kjernekraft i Norge)*", **Rystad Energy**, November 2023; https://www.nho.no/contentassets/220ef13d98a3415abc745b7ec5e88939/20231121-kjernekraft-i-norge.pdf

***Table 1** – Overview of some Gen. III+ evolutionary SMRs (LCOE estimates assume a 5 % interest rate and $25/MWh in OPEX).*

	GE Hitachi	Rolls Royce	NuScale	Electricité de France	Holtec	Westing-house	KAERI
Model name	BWRX-300	SMR	VOYGR	NUWARD	SMR-160	AP300	Smart SMR
Country	United States/Japan	United Kingdom	United States	France	United States	United States	South Korea
Reactor type	BWR	PWR	PWR	PWR	PWR	PWR	PWR
Thermal power	870 MW	1358 MW	4x / 6x / 12x 250 MW	2x 540 MW	525 MW	900 MW	365 MW
Electrical power	300 MW	470 MW	4x / 6x / 12x 77 MW	2x 170 MW	160 MW	300 MW	107 MW
Electrical efficiency	34.5%	34.6%	30.8%	31.5%	30.5%	33.3%	29.3%
Load-following range	50 – 100%	50 – 100%	20 – 100%	20 – 100%	n/a	n/a	n/a
Ramping capability	0.5% per minute	3% – 5% per minute	0.8% per minute	5% per minute	n/a	n/a	n/a
Capacity factor	≥ 95 %	≥ 95 %	≥ 95 %	≥ 90 %	≥ 98 %	≥ 93 %	≥ 95 %
Annual electricity	≥ 2.50 TWh	≥ 3.91 TWh	4x / 6x / 12x 0.64 TWh	≥ 2.68 TWh	≥ 1.37 TWh	≥ 2.45 TWh	n/a
Outlet temperature	288 °C	325 °C	316 °C	307 °C	321 °C	324 °C	322 °C
Overnight cost (NOAK)	≥ $2400/kW	≥ $5400/kW	≥ $3000/kW	n/a	≥ $3800/kW	≥ $3500/kW	n/a
Levelized cost of electricity	≥ $42/MWh	≥ $64/MWh	≥ $46/MWh	n/a	≥ $50/MWh	≥ $50/MWh	n/a
Construction time	24 – 36 months	48 months	30 – 39 months	36 months	30 – 36 months	36 months	n/a
Plant footprint	32.7 m^2 per MWe	85.1 m^2 per MWe	151.5 m^2 per MWe	10.3 m^2 per MWe	175.0 m^2 per MWe	288.9 m^2 per MWe	841.1 m^2 per MWe
Designed lifetime	60 years	60 years	60 years	60 years	80 years	80 years	60 years
First deployment	2028	2030	2029	2030	2032	n/a	n/a
Design status	Detailed design	Detailed design	Licensed design	Conceptual design	Preliminary design	Conceptual design	Detailed design

Pressurized Water Reactors (PWR)

In contrast to the BWRs, the pressurized water reactor (PWR) separates the primary loop of water in contact with the radioactive fuel and the secondary loop that creates electricity (see Figure 3). Water in the first loop is kept liquid at high pressure and usually works at slightly higher temperatures than BWRs (e.g., 286 °C —> 318 °C), which is beneficial for higher Carnot efficiency but at the expense of higher construction costs since the reactor vessel and the other components in the primary system operate at about 160 bar pressure.

Among land-based SMRs, there are 21 PWRs under development, with the Chinese ACP100 SMR and the Argentinian CAREM SMR currently under construction. Moreover, the NuScale VOYGR 4x/6x/12x 77-MW PWR-type SMR had it's design licensed effective from 21st February 2023. Additionally, there are eight marine-based PWR-type SMRs, including the JSC Afrikantov OKBM 2x 35-MW KLT-40s SMR, which has been in operation since 2022. A similar 325-MW marine-based PWR-type SMR, the JSC Afrikantov OKBM VBER-300, is currently at the licensing stage.

The recently licensed NuScale VOYGR SMRs are based on combining small power modules of 77 MW, including 4-pack, 6-pack, and 12-pack configurations. This is contrary to the Rolls Royce PWR-type SMR, where power output has been maximized (i.e., 470 MW) to deliver robust economics for nuclear power plant investment while also enabling modularization and standardization. The Rolls Royce SMR went through a formal design assessment by UK regulators in 2022. Their plan is to start building their first SMR in 2026.

Generation IV Revolutionary SMRs

The Generation IV SMRs are more revolutionary and experimental than the evolutionary Generation III+ SMRs. They incorporate a range of advanced technologies to improve safety, thermal output, efficiency, and sustainability compared to traditional nuclear reactors. The specific features of Generation IV SMRs can vary, but they generally aim to address some of the key challenges, such as nuclear waste, fuel supply, and safety. This is addressed by new safety features, more efficient use of fuel, reduced nuclear waste, and the ability to use alternative fuels such as thorium. The Generation IV International Forum (GIF) has chosen six reactor designs to be classified in this category. Here, we will present three of these designs, which are also well-suited for construction as SMRs.

Liquid Metal-Cooled Fast Reactors (LMFR)

SMRs based on liquid metal-cooled fast reactors (LMFR) use liquid metals as coolant instead of water. It allows the LMFRs to operate at roughly 200 °C higher temperatures (e.g., 318 °C —> 517 °C) than traditional PWRs while operating at much lower pressures. As a result, LMFR-type SMRs can achieve passive safety features in their most compact form and simplify the overall system. The higher temperature allows the SMR's electrical efficiency to increase from about 30 percent to roughly 38 percent, generating more electricity per unit of fuel. One example of an LMFR is the lead-cooled fast reactor that uses liquid lead or lead-bismuth as a coolant. This technology has historically been used in SMRs onboard submarines.

LMFRs can be designed to use a wide range of fuel types, including recycled nuclear fuel and natural uranium, which can reduce nuclear waste. LMFRs can also incorporate innovative passive safety features that can further help prevent accidents and mitigate their consequences. Nevertheless, there are also some inherent challenges and limitations associated with LMFRs. Using liquid lead or lead-bismuth as a coolant can pose technical challenges related to the corrosion and erosion of reactor components. Additionally, the development and construction of LMFRs can be expensive, which can limit their potential for widespread deployment. The use of lead or lead-bismuth can make reactor monitoring more difficult for nuclear proliferation, as the coolant can shield the nuclear fuel from detection.

Despite these challenges, LMFRs are being developed as a promising revolutionary option for future nuclear power, offering potential advantages in terms of efficiency, fuel flexibility, and safety. Further research and development are needed to address the technical challenges associated with LMFRs and to assess their potential for widespread deployment. Currently, there are 8 proposed SMR designs of LMFRs worldwide, including four conceptual designs, one preliminary design, two detailed designs, and one under construction (i.e., NIKIET BREST-OD-300, a 300-MW LMFR-type SMR).

The Swedish company LeadCold, which is a spin-off from the Royal Institute of Technology (KTH), are currently developing a 55-MW LMFR-type SMR (i.e., SEALER-55) that are based on lead as a coolant. They are working together with global utilities and partners like Uniper and OKG to deliver the first LMFR-type research reactor in Oskarshamn, Sweden. LeadCold claims to have developed an aluminum-alloyed steel exhibiting excellent corrosion resistance to deal with fundamental challenges associated with LMFRs, and it will be used to protect the SMR's fuel capsules against corrosion.

Molten Salt Reactors (MSR)

The molten salt reactor (MSR) is a reactor concept that was first introduced in the 1950s and 1960s. The first MSR experiments were conducted by Oak Ridge National Laboratory in Tennessee, USA, where an 8-MW_{th} prototype ran between 1965 and 1969.[15] A program aimed at developing an MSR operating in the fast neutron spectrum was, unfortunately, stopped due to 'budgetary reasons' and since the US nuclear energy program focused on the development of light water reactors (LWRs) with a uranium fuel cycle that produced plutonium-239 used in thermonuclear bombs.

MSRs were considered to be radical half a century ago, but today they offer many advantages that warrant a fresh look. The advanced nuclear reactor technology uses liquid fluoride or chloride salts as both coolant and fuel carrier. One of the key advantages of MSR-type SMRs is their ability to incorporate passive safety features with operation at nearly atmospheric pressures and high temperatures. SMRs are inherently stable due to its negative reactivity. They can operate at nearly 400 °C higher temperatures than PWR-type SMRs (e.g., 318 °C —> 702 °C), which can improve electrical efficiency from 30 percent to over 40

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[15] Haubenreich, P. N., Engel, J. R., "Experience with the Molten-Salt Reactor Experiment", **Nucl. Appl. Technol.**, vol. 8, no. 2, pp. 118–136, 1970; https://doi.org/10.13182/NT8-2-118.

percent. The high-temperature output makes MSRs relevant for providing high-quality heat to non-electrical applications.

MSR-type SMRs can also be designed to use thorium as a fuel source, which is three times as abundant as uranium. Compared to conventional PWR-type SMRs, the amount of waste can be reduced by up to 100 times.[16] Furthermore, the remaining waste would only require storage for about 300 years. These features that have made MSRs one of the most promising Generation IV reactors.[17]

Another beneficial characteristic of MSRs is their inherent load-following capabilities with their strong negative thermal coefficient of reactivity.[18] For example, imagine the load of the reactor is increased, meaning that more energy is drawn from the reactor. As a result, the reactor temperature decreases, and likelihood of fission increases since atoms are packed closer together, resulting in higher power output. Vice-versa is the case when the load on the reactor decreases. Conversely, when the reactor load decreases, the opposite occurs, resulting in lower power output. This natural load-following capability makes MSRs well-suited for adapting to fluctuating energy demands.

There are also some noteworthy technical challenges associated with MSRs. The use of liquid salts as a coolant and fuel carrier can pose technical challenges related to the corrosion and erosion of reactor components, such as the graphite moderator. Additionally, the operating temperature and chemical composition of the salts limit the materials that can be used in the reactor.

The introduction of liquid fuel also poses challenges to nuclear safeguards, as much of the current IAEA inspection regimes are specifically developed for the uranium-plutonium fuel-cycle and do not apply directly to the MSR fuel-cycle. Similar challenges exist on the regulatory side where the licensing framework is currently lacking for MSRs.

Currently, there are 13 proposed MSR-type SMR designs on track to commercialization, including two pre-conceptual designs, six conceptual designs, two preliminary designs, one basic design, and one detailed design (i.e., Terrestrial Energy IMSR400, a 2x 195-MW SMR).

High-Temperature Gas-Cooled Reactors (HTGR)

High-temperature gas-cooled reactors (HTGR) uses graphite as a moderator and achieves about 500 °C higher temperatures than the conventional PWR reactor technology (e.g., 318 °C —> 815 °C). The reactor core is designed as either a "prismatic block", where the fuel core is surrounded by a hexagonal graphite reflector, or "pebble bed", where the fuel is encapsulated in spheres about 6 cm in diameter that cycle through the core. A total of 17 proposed HTGR-type SMRs are proposed worldwide, with one in operation in China (i.e., INET HTR-PM, 2 x 210 MW).

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[17] Siemer, D. D., "*Why the molten salt fast reactor (MSFR) is the "best" Gen IV reactor*", **Energy Sci. Eng.**, vol. 3, no. 2, pp. 83–97, 2015; https://doi.org/10.1002/ese3.59.

[18] Elsheik, B. M., "*Safety assessment of molten salt reactors in comparison with light water reactors*", **J. Radiat. Res. Appl. Sci.**, vol. 6, no. 2, pp. 63–70, 2013; https://doi.org/10.1016/j.jrras.2013.10.008.

HTGRs are the predecessor of the very-high-temperature reactors (VHTR). These reactors use helium gas as a coolant and graphite as a moderator. They can operate at very high temperatures and can use a variety of fuels, including recycled nuclear fuel and thorium.

Table 2 *– Overview of some Gen. IV revolutionary SMRs.*

	LeadCold	**ARC**	**Moltex**	**Seaborg**	**Terrestrial Energy**	**ThorCon**	**INET**
Model name	SEALER-55	ARC-100	SSR-U	Power barge	IMSR400	ARA SMR	HTR-PM
Country	Sweden	Canada	United Kingdom	Denmark	Canada	United States	China
Reactor type	LMFR	LMFR	MSR	MSR	MSR	MSR	HTGR
Outlet temperature	550 °C	510 °C	795 °C	670 °C	700 °C	704 °C	750 °C
Thermal power	140 MW	286 MW	40 MW	2x / 4x / 6x / 8x 250 MW	2x 440 MW	557 MW	500 MW
Electrical power	55 MW	100 MW	16 MW	2x / 4x / 6x / 8x 100 MW	2x 195 MW	250 MW	210 MW
Electrical efficiency	39.3%	35.0%	40.0%	40.0%	44.4%	44.9%	42.0%
Plant footprint	363.6 m^2 per MWe	560.0 m^2 per MWe	19.5 m^2 per MWe	17.5 m^2 per MWe	115.4 m^2 per MWe	43.4 m^2 per MWe	1219.5 m^2 per MWe
Designed lifetime	28 years	60 years	60 years	24 years	56 years	80 years	40 years
First deployment	2030	2029	n/a	2028	2031	2028	2022
Design status	Conceptual design	Preliminary design	Basic design	Conceptual design	Detailed design	Preliminary design	In operation

Other Generation IV Reactor Types

Super-critical water-cooled reactors (SCWRs) use super-critical water as both a coolant and a working fluid for the steam cycle. This offers advantages such as higher thermal efficiency and a simpler cooling system. However, they still face technical challenges and are still in the early stages of development. There are also sodium-cooled fast reactors (SFRs) that use liquid sodium as a coolant and can operate at higher temperatures than conventional PWRs. Similar to most fast reactors, they can use recycled nuclear fuel, reducing the amount of nuclear waste produced.

SMR Technology Assessment of Proposed Designs

In the technology assessment conducted in this article, a total of 73 SMR designs have been evaluated based on various performance metrics and grouped according to their reactor type (see Figure 5). The majority of the SMRs have an electrical power rating between 10 MW and 300 MW, complying with the SMR definition of the IAEA. However, there are a few outliers at both ends of the spectrum.

Figure 5 present an overview of the two groups of SMRs; The *Generation III+* and the *Generation IV* considering the two key economic drivers of outlet temperature and electrical efficiency. The revolutionary Generation IV SMRs exhibit higher electrical efficiencies and operate at 300 to 600 °C higher temperatures than the Generation III+ SMRs. The highest temperatures and efficiencies are found among the high-temperature gas-cooled reactors (HTGR).

The upper subplot of Figure 5 depicts various heat applications. Notably, all SMRs have the capacity to supply heat to the paper industry. Generation III+ SMRs are also approaching the temperature thresholds necessary for soda ash, a commonly used inorganic compound. Furthermore, the high-temperature Generation IV SMRs based on HTGR technology can provide the required temperature levels for a diverse range of applications, including heat supply to chemical industries, ammonia production, refineries, steam methane reforming, and aluminum production.

The populations of SMRs shown in Figure 5 were statistically analyzed to identify general trends. Table 3 list the mean results from all the SMR populations investigated.

Table 3 *Mean performance metrics (temperature, power density, efficiency, and lifetime) among populations of different SMR designs, including boiling water reactor (BWR), pressurized water reactor (PWR), liquid metal-cooled reactor (LMFR), molten salt reactor (MSR), and high-temperature gas-cooled reactor (HTGR)*

Reactor type	**Electrical power** (min. – max.)	**Outlet temperature**	**Spatial power density**	**Electrical efficiency**	**Designed lifetime**	**Number of designs**
BWR	47.5 MW – 300 MW	286 °C	35.88 kW/m^2	30.50%	70 years	4
PWR	6.6 MW – 470 MW	318 °C	13.18 kW/m^2	29.92%	56 years	26
LMFR	10 MW – 450 MW	517 °C	35.03 kW/m^2	37.98%	48 years	9
MSR	8 MW – 300 MW	702 °C	21.35 kW/m^2	41.67%	51 years	14
HTGR	2.5 MW – 288 MW	815 °C	31.17 kW/m^2	39.63%	46 years	20

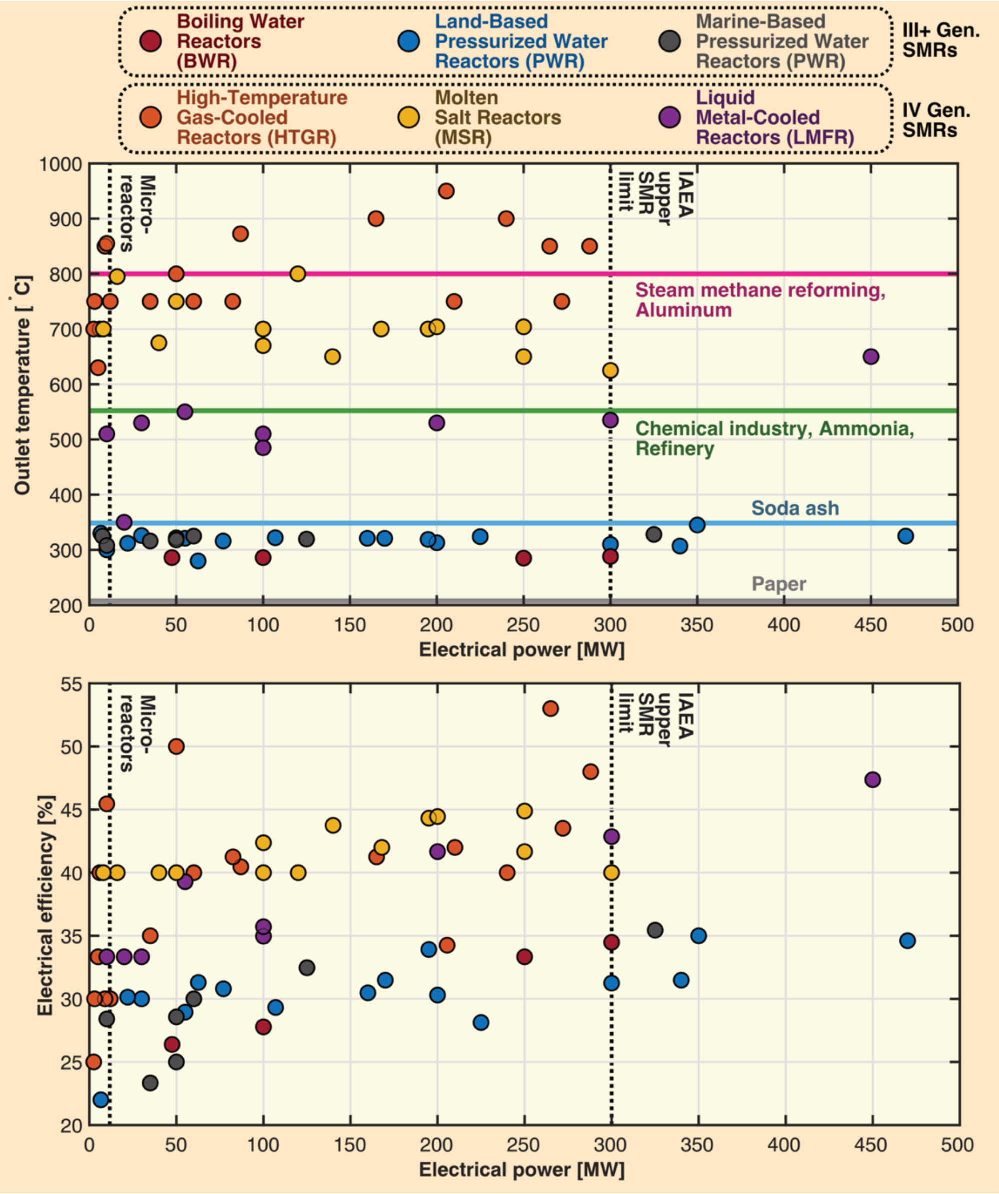

Figure 5 *– Upper plot shows the range of sizes and temperatures for heat applications. Lower plot shows range of electrical efficiencies among the small modular reactors that are under development.*

Inherent Safety Features of SMRs

Generation III+ SMRs, such as the GE Hitachi BWRX-300, are considered passively safe due to their use of natural circulation and passive cooling isolation condenser systems. According to GE Hitachi, the BWRX-300 design can "*passively cool itself for seven days without power or operator action during abnormal events, including station blackout*".[19] Similarly, NuScale's smaller 77-MW VOYGR modules, with

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[19] "BWRX-300: One of the most economical SMR designs available", **GE Hitachi Nuclear Energy**, 2021; https://www.gevernova.com/content/dam/gepower-nuclear/global/en_US/documents/product-fact-sheets/GE%20Hitachi_BWRX-300%20Fact%20Sheet.pdf

significantly lower decay heat post-shutdown compared to larger reactors, could offer enhanced environmental safety. NuScale emphasizes their modules' ability to shut down passively in worst-case scenarios and isolate the containment vessel, eliminating the need to add water for cooling or external AC or DC power. Control rods that stop the reactor's fission reactions are pulled by gravity in emergency situations, and the SMR is able to handle the decay heat that occurs in the aftermath of the reactor shutdown. In addition to the safety features of Generation III+ SMRs, the emerging Generation IV SMRs promises even greater safety advancements, if successful. These SMRs are designed with advanced safety systems that make them considered "walk-away-safe", resistant to meltdowns, and operate at lower pressures than conventional light water SMRs.

Conclusions

This article has provided an overview of the new small modular reactor (SMR) paradigm in the nuclear energy sector. In general, there are two types of evolutionary Generation III+ SMRs being proposed and three types of revolutionary Generation IV SMRs. Both generations of SMRs have similar deployment paths, with most deployments expected at the end of this decade. However, Generation III+ SMRs have a lead in the race since they are based on already mature technologies. Nonetheless, it remains unclear how the envisaged series-fabrication of SMRs will work out in reality and how modern manufacturing technologies will impact the economics and the learning rate of these developments.

The Generation IV technologies offer many benefits in terms of efficiency and thermal outputs but should rather be considered as the outsiders in the race to realize SMRs by the end of this decade. This is not only attributed to the lower maturity levels of the Generation IV technologies. The current nuclear regulatory frameworks and inspection regimes are not ready to accept a commercial fleet of Generation IV SMRs. The novel waste-streams from Generation IV reactors also require new approaches to waste management, safeguarding, and final disposal.

Ultimately, as the nuclear energy landscape continues to evolve, ongoing research and development, coupled with public trust, will be critical to addressing the challenges and harnessing the potential advantages of emerging SMR technologies. Collaboration between industry, regulators, and researchers will be essential in driving forward progress and ensuring a successful future for different generations of SMRs.

For Further Reading

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Acknowledgements

The authors would like to acknowledge Magnus Korpås (NTNU) for valuable comments, and the funding of the NERES-project (ntnu.edu/web/iel/neres), “*Nuclear Energy’s role in a Renewable Energy System*”, to support the effort needed to write this article.

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