ANALYSIS OF SMALL MODULAR REACTORS

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Abstract: Nuclear energy is currently the only technology that has potential to expand at a large scale and efficiently replace fossil-burning power plants. However, for this to happen particularly in the countries with undeveloped nuclear infrastructure, several important issues need to be addressed: financial, technological, and regulatory risks; nuclear reactor safety and security; cost and duration of construction; secured fuel supply infrastructure; development of acceptable spent nuclear fuel disposal options and radioactive waste forms; non-proliferation and threat reduction; public perception, and long-term sustainability. The advanced Generation IV reactor concepts, particularly Small Modular Reactors (SMRs), are far from commercialization and deployment. A reasonable estimate is that for most of these advanced reactors real deployment might not happen before the end of 2030s due to issues with the HALEU fuel, testing and qualification of new fuel and advanced materials under extreme conditions, regulatory processes that are still not streamlined, as well as development of acceptable spent nuclear fuel disposal options and radioactive waste forms. In addition, these new reactor concepts need to demonstrate increased safety and security, and reduction of non-proliferation risks. Having this in mind, the question arises regarding the choices that the countries with undeveloped nuclear infrastructure should make if they would like to add nuclear power plants to their energy mixture. This paper will analyze several SMR designs and a possibility of their inclusion in the near-term planning for nuclear power expansion.

Key words: small modular reactors; nuclear power; electricity production

1. INTRODUCTION

Nuclear energy is currently the only technology with a secure base-load electricity supply and no greenhouse gas emissions that has potential to expand at a large scale and efficiently replace fossil-burning power plants. However, for this to happen several important issues need to be addressed: reduction of financial, technological, and regulatory risks, nuclear reactor safety and security, cost and duration of construction, secured fuel supply infrastructure, development of acceptable spent nuclear fuel disposal options and radioactive waste forms, non-proliferation and threat reduction, public perception and long-term sustainability.

The need for electric power is constantly increasing in the USA and around the world. At the end of 2024 there were 417 operating reactors in 31 countries providing total nuclear power capacity of 377 GWe, while 62 reactors (64.5 GWe) were under construction in 15 countries [1]. Since 2014, 72 new reactors were connected to the grid, most of them in Asia (51 reactor), while China added 38 new reactors. Existing fleet of nuclear reactors is getting old. Out of 417 nuclear reactors in operations, 152 reactors are older than 40 years (30%) [1]. Average age of commercial US reactors is 42 (as of April 2024). In China, most of operating reactors are younger than 10 years. In the US, Nuclear Regulatory Commission (NRC) has been issuing the initial operating license for 40 years, with extension for additional 20 years. Several US reactors received NRC operating license extension to 80 years. However, there are issues with refurbishing, maintenance, steam generator replacements, etc. for the existing nuclear power plants (NPP). Even with additional extension of operating license, most of the US current nuclear reactor fleet will be retired by the end of 2030s. In addition to aging NPPs, over the last several years the Artificial Intelligence (AI) bubble has been rapidly expanding, and some estimate that the US might need 100 – 200 GW of new capacity over the next decade, or 10 – 20 new large nuclear reactors or more that 150 natural gas plants [2]. Thus, there is an urgent need for the replacement of aging NPPs, and exponentially increasing demand for electricity due to the need of AI centers, which generates a dilemma: (1) should the US focus on refurbishing some of prematurely shutdown NPPs (the cheapest option); (2) should it built large advanced reactors Generation III+ with passive safety (such as AP-1000), or (3) should it accelerate the development and construction of Small Modular Reactors (SMRs) while advanced reactors of Generation IV are been developed and deployed?

The author of this paper is somewhat skeptical regarding a rapid expansion of nuclear power, having in mind that previous three "nuclear renaissances" were either stopped or delayed by three nuclear accidents - Three Mile Island (TMI) -USA in 1979, Chernobyl-SSSR in 1986, and Fukushima Daiichi-Japan in 2011), as shown in Figure 1. For example, *Energy Policy Act of 2005* (George W. Bush Administration) tried to restart "nuclear spring" after almost 3 decades of stagnation due to the TMI accident, only to be stopped by the Fukushima Daiichi accident in 2011.

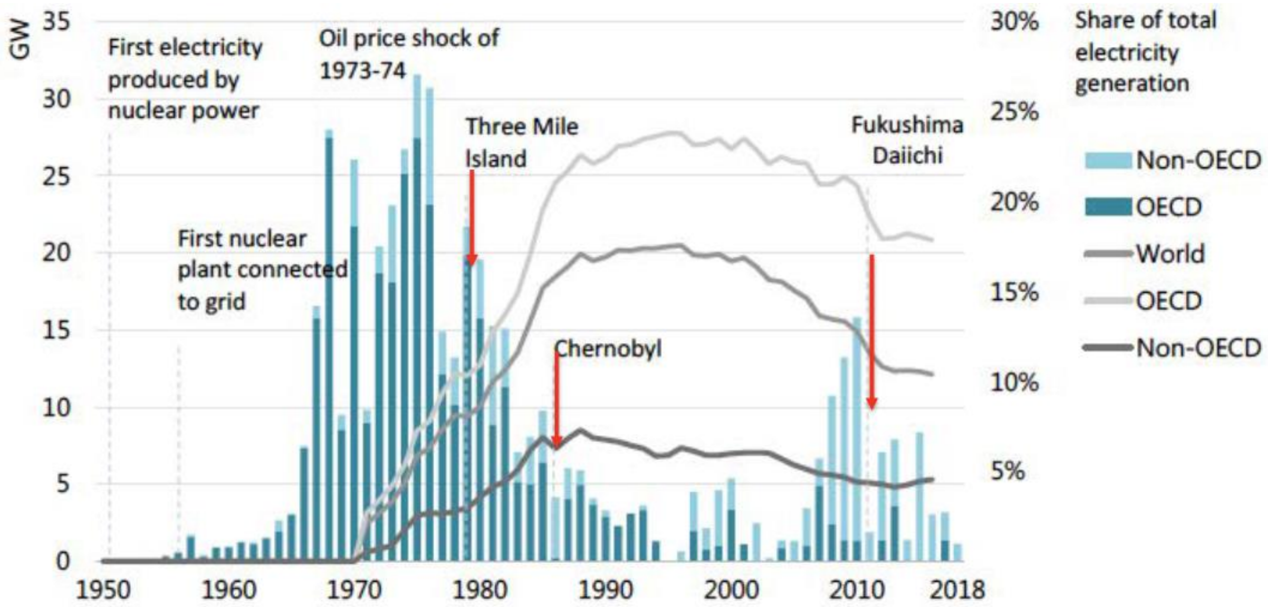

Figure 1 Reactor construction starts and share of nuclear power in total electricity production. (OECD – Organization for Economic Co-operation and Development). [3, 4]

New revival happened during the first Donald Trump administration (2017-2021) when two acts were passed: *Nuclear Energy Innovations Capabilities Act - NEICA* (2018) [5], and *Nuclear Energy Innovations and Modernization Act – NEIMA* (2019) [6]. In addition, during Joe Biden administration (2021 – 2025), a third act was passed: *Inflation Reduction Act of 2022* [7], as well as *The Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy (ADVANCE) Act* in 2024 [8]. The decision was made to invest in the development of next generation of SMRs, to speed up their prototype construction, to direct the Nuclear Regulatory Commission (NRC) to speed up licensing process, as well as to resolve issues in availability of the HALEU uranium fuel that majority of these reactors require. In addition, a private-public partnership is encouraged, and the private sector obtained authorization to construct and operate privately-funded reactor prototypes at the Department of Energy (DOE) sites. This next generation of nuclear reactors are required to have significant improvements over the most recent generation of nuclear reactors, including: inherent safety features, lower waste yields, greater fuel utilization, superior reliability, resistance to proliferation, increased thermal efficiency, and ability to integrate into electric and nonelectric applications. The DOE is then directed by NEICA to establish and fund 3 programs [9]:

(1) *Advanced Reactor Demonstration* awards: $160M initial funding for cost-shared demonstration of two reactor designs that have potential to be operational in five to seven years

following award finalization. In October 2020, the DOE selected TerraPower and X-energy to develop and construct two advanced nuclear reactors.

(2) *Risk Reduction for Future Demonstration* awards: $30M initial funding to support 2-5 additional, diverse advanced reactor designs that have a commercialization horizon that is approximately 10 to 14 years in the future. In December 2020, the DOE selected five teams: Hermes Reduced-Scale Test Reactor by Kairos Power, eVinci Microreactor by Westinghouse, BWXT Advanced Nuclear Reactor, Holtec SMR-160 Reactor, and Molten Salt Chloride Reactor Experiment by Southern Company Services Inc, based on TerraPower design.

(3) *Advanced Reactor Concepts (ARC-20)*: $20M for a new solicitation for at least 3 new public-private partnerships focused on advancing reactor designs moving toward demonstration phase. In late December 2020, the DOE selected three concepts for longer term development: Inherently Safe Advanced SMR by Advanced Reactor Concepts, Fast Modular Reactor Conceptual Design by General Atomics, and Horizontal Compact High Temperature Gas Reactor by MIT.

On May 23, 2025, President Trump issued 4 Executive Orders (EXOs) directing the U.S. Department of Energy to start a new pilot program to accelerate the testing of advanced nuclear reactors in/or out of national laboratories, and streamlining the advanced reactor pathway from demonstration to fast-track licensing [10].

Most of the above mentioned advanced nuclear reactors require fuel that significantly differs from standard LWR fuel. In order to restore domestic nuclear fuel supply chain and accelerate the development of advanced fuel, the U.S. DOE announced *The Fuel Line Pilot Program* of 2025 [11] and selected four companies for this program: Oklo Inc. (Santa Clara, California), Terrestrial Energy Inc. (Charlotte North Carolina), TRISO-X Inc. (Oak Ridge, Tennessee) and Valar Atomic Inc. (Hawthrone, California) [12].

By allowing companies to build and operate a fuel fabrication facility under DOE authorization—a faster if unconventional alternative to Nuclear Regulatory Commission licensing—the DOE's aim is ensuring "a robust supply of fuel is available for research, development, and demonstration purposes—including the 11 reactors initially selected to participate in DOE's Reactor Pilot Program."

Regardless of the long-term commitment and financial support of the U.S. government, the advanced reactors and SMRs of the 4th generation will not be available on time to solve the problem of aging nuclear power fleet, as well as increasing demands imposed by AI Data Centers. Thus, a decision was made to also invest in accelerated construction of advanced LWRs, such as AP1000 (Westinghouse). In October 2025, the Trump administration announced a partnership with Westinghouse Electric Company (and its co-owners, Cameco and Brookfield Asset Management) to invest at least $80 billion in construction of new AP1000 nuclear reactors (1110 MWe) [13]. Two reactors of this type were the first new reactors built in the U.S. after more than 30 years of dry period. The units 3 and 4 at the Vogtle nuclear plant in Georgia were completed in 2023 and 2024, seven years behind schedule with the cost that was twice as much as planned (about $35 billion), reflecting a serious mismanagement and Westinghouse filing for Chapter 11 bankruptcy protection. It is estimated that 5 AP1000 could be constructed, assuming about $16 billion per unit, which may not be enough to resolve the future energy demands [13].

This short introductory analysis of the situation in the U.S. shows that a long-term government legislative and financial support is necessary for the revival of nuclear power, as well as a government-private industry partnership, regulatory process simplification, and the development of domestic infrastructure.

2. TECHNOLOGICAL DEVELOPMENT OF SMALL MODULAR REACTORS

There are various definitions of Small Modula Reactors (SMRs). The following International Atomic Energy Agency (IAEA) definition is widely accepted: "*Small modular reactors (SMRs) are advanced nuclear reactors that have a power capacity of up to 300 MWe per unit, which is about one-third of the generating capacity of traditional nuclear power reactors*." [14] IAEA definition of reactor categories is shown on Figure 2. In addition, Micro Modular Reactors (MMRs) have a power capacity of up to 10 MWe.

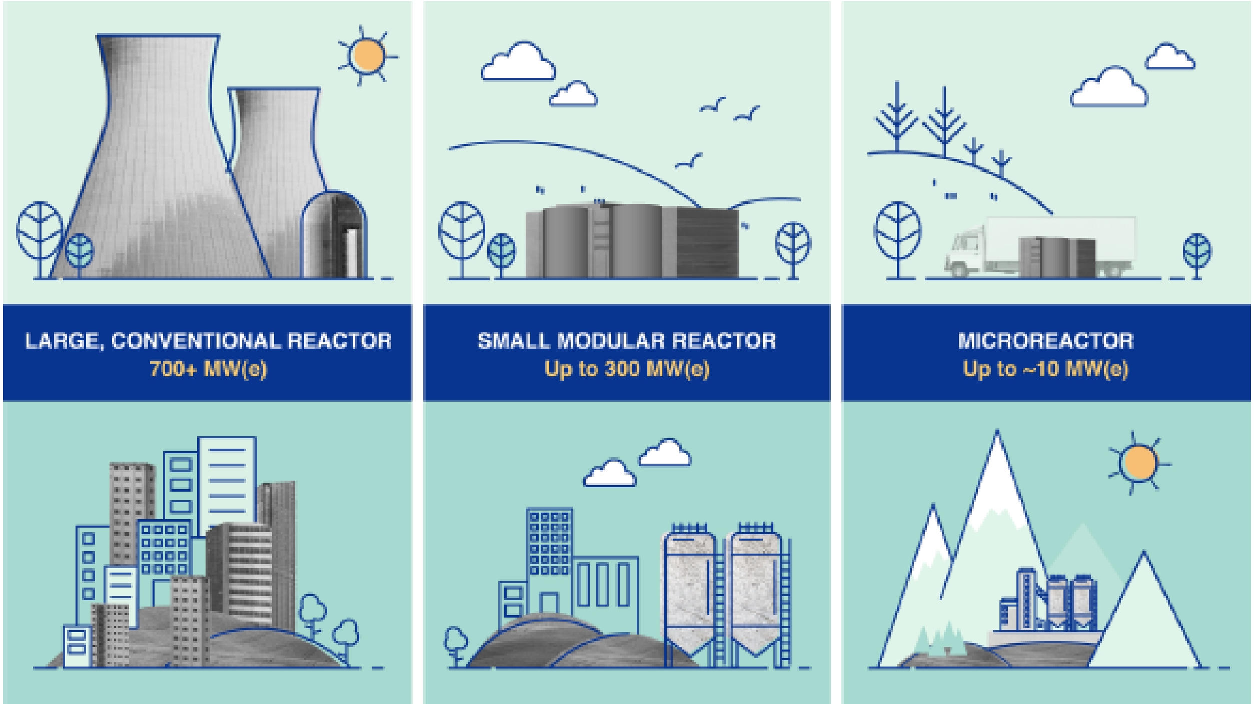

Figure 2: Definition of large conventional reactors, small modular reactors and micro-modular reactors [14]

While large conventional reactors with a power capacity around 1000 MWe could power a large city of more than a million people, SMRs could power small towns or various industrial facilities, while MMRs could be used for special purposes for military, mining, etc.

The initial development of SMRs in the USA dates back to early late 1940s and 1950s, and included Naval Nuclear Power Propulsion Program and Aircraft Nuclear Propulsion program [15]. The first nuclear-powered submarine, USS Nautilus, was built in 1954, had Westinghouse PWR reactor, and operated for 26 years. The US Air Force (USAF) explored SMRs to power long-range bombers. This program was terminated by US President Eisenhower. The first nuclear-powered merchant ship, NS Savannah, was built in 1962, had 69 MWt PWR reactors, and travel over the world visiting 78 domestic and foreign ports. It was also a part of US President Eisenhower initiative "*Atoms for Peace*".

Although the development of SMRs continued through decades up to now, the progress was slowed by financial instabilities, accidents (primarily the Three Mile Accident in 1979), public opposition, and luck of political/government support.

For example, in 2010 the Berkeley Nuclear Research Center (BNRC) organized *The 4th Asia-Pacific Forum on Small and Medium Size Reactors, Berkeley, CA, June 17- 19, 2010.* The innovative designs reviewed included, from USA: NuScale (NuScale), PRISM (GE), ACR-100 (ACR), PB-AHTR and ENHS (UC Berkeley), EM2 (GA), the Travelling Wave Reactor (TerraPower), Hyperion Power Module (Hyperion Power), and several SMRs from other countries were presented: SMART (KAERI, Korea), 4S (Toshiba, Japan), the Package Reactor (Hitachi, Japan), and SVBR-100 (Russia). Forward 15 years – not a single one of those SMRs has been built. These designs were summarized in the authors paper from 2012. [16].

2.1 SMR Categories

There are more than 100 different SMR designs around the world. SMRs could be characterized based on the type of fuel, moderator, or coolant that they use. SMRs could also be characterized based on predominant neutron energy spectrum: fast, intermediate or thermal, or operating temperature. Some of SMRs are transportable, while some are encapsulated and do not need fuel replacement.

FUEL: SMRs that are based on the LWR technology use standard LWR fuel – Uranium Oxide (UO_2), which is enriched in U-235 between 3-5%, and is in the form of pellets. Mixed Oxide fuel (MOX) is also used in LWRs, and represents a mixture of plutonium and uranium oxides. Future advanced reactors might use Uranium Zirconium alloy, which does not contain oxygen and is used in sodium-cooled fast reactors. Uranium Zirconium Hydride (U-ZrH) fuel, which contain hydrogen instead of oxygen, and is used in various research reactors. Tri-structural Isotropic (TRISO) fuel is in the form of spheres 1 mm in diameter, with uranium fuel in the middle surrounded by several layers of pyrolytic carbon and silicon carbide. These TRISO particles could be assembled into spherical pebbles (4-6 cm in diameter) or into cylindrical compacts. Due to its durability and superior integrity, TRISO fuel is used in high-temperature advanced reactors. In addition to fuel as solid, some SMRs use molten fuel, usually in the form of molten fluorides or molten chlorides. Regarding fuel enrichment, LWRs and SMRs based on LWR technology use Low Enriched Uranium (LEU) fuel, with enrichment in U-235 between 3-5%. However, majority of Generation IV SMRs require much higher enrichment, up to 19.75% - High-Assay LEU (HALEU), which is not yet available in commercial quantities in the U.S., and thus might slow down development of SMR designs that require HALEU.

MODERATOR: Advanced SMR designs include both fast reactors and thermal reactors. Moderators are needed for SMRs with thermal neutron spectra, because fast neutrons born in a fission event need to be slowed down to thermal energies in order to produce thermal fission. Light water (H2O) is used as a moderator in SMRs based on LWR technologies. Heavy water (D2O) is used in reactors that use natural uranium as fuel (CANDU reactors), because deuterium has much smaller probability for absorbing a thermal neutron than hydrogen, thus helping with the neutron economy. Graphite, usually in the form of solid blocs, is used in high-temperature reactors due to its better heat tolerance.

COOLANT: All nuclear reactors use coolants to remove energy released in fuel from fission and to transfer generated heat to the secondary system for electricity generation. Light water and heavy water are also used as coolants. Liquid sodium is used as coolant in fast reactors. Liquid lead or lead-bismuth is used in SMRs that require long refueling cycle. Inert gases, like helium and carbon dioxide, are used in gas-cooled reactors with graphite as a moderator. Molten salt coolant, such as FLiBe, has higher thermal conductivity and is transparent as opposite to sodium or lead. FLiBe is a molten salt made from a mixture of lithium fluoride and beryllium fluoride.

IAEA classifies SMRs in 6 categories [17]: (1) **Land-based water-cooled SMRs**. Based on proven LWR technologies. Examples: Integral PWR CAREM (Argentina), ACP100 (China), RITM-200N (Russia), NuScale VOYGR, BWRX-300 (USA), the Rolls-Royce SMR (UK); (2) **Marine-based water-cooled SMRs**. KLT-40S have been operating since 2020 on the Academic Lomonosov floating NPP (Russia); (3) **Gas-cooled SMRs**. HTR-PM pebble-bed (China) has been operating since 2021. X-Energy Xe-100; (4) **Liquid metal-cooled fast-neutron SMRs**. BREST-OD-300 lead-cooled fast reactor (Russia), Natrium – sodium-cooled fast reactor (USA); (5) **Molten salt SMRs**. One MSR under construction in USA; and (6) **Microreactors.** eVinci (USA), KRONOS MMR (USA).

Table 1 shows several representative SMR designs, with basic characteristics such as fuel type, fuel enrichment, thermal efficiency, core discharge burnup, and refueling cycle [18]. The large LWRs have thermal efficiency of 33% (PWR) and 32% (BWR), fuel enrichment from 3-5%, and refueling cycle of 18-24 months. As can be seen in Table 1, Generation IV SMRs have higher thermal efficiency (> 40%) due to higher operating temperatures, higher fuel enrichment (up to 19.75%) and longer refueling cycles that could be longer than 20 years for some of SMR designs.

2.2 Examples of Representative SMR Designs

In this section, several representative SMR designs will be introduced [19, 20]. Among SMR designs based on the LWR technology, we emphasize two: VOYGR (NuScale Power) and BWRX-300 (General Electric Vernova).

The VOYGR is a multi-module PWR with each module having an output of 250 MWth and 77 MWe. The VOYGR uses LEU UO2 fuel and has a refueling cycle of 21 months. The VOYGR plant can generate a different amount of power based on its number of modules. For example, VOYGR-12, which has 12 modules, generates a total output of 924 MWe. VOYGR uses a simplified design as compared to standard PWR. It has a passive heat removal system, uses natural circulation for coolant flow, and fully digital control system. NuScale design is the first and only SMR to receive design approval from the U.S. NRC in 2020 (application submitted in 2016), with the certification taking effect on February 21, 2023. In September 2025, NuScale/ENTRA1 signed an agreement with the Tennessee Valley Authority (TVA) to deploy up to 6 GW of NuScale SMRs. Figure 3 shows a diagram of a single VOYGR reactor module and multi-module facility [19].

TABLE 1 Main characteristics of representative SMRs [18]

Design	Fuel type/assembly array	Fuel enrichment (%)	Thermal efficiency (%)	Core discharge burnup (GWd/ton)	Refuelling cycle (months)
LWR land-based SMR					
NuScale	Uranium oxide (UO_2) pellet/17x17 array	<5%	30%	> 30	24
SMART	UO_2 pellet/17x17 array		30%	< 54	30
SMR-160	UO_2 pellet/square array		30%	45	24
Nuward	UO_2/17x17 array		31%	-	24
BWRX-300	UO_2/10x10 array		32%	49.5	12-24
UK SMR	UO_2/17x17 array		35%	55-60	18-24
Mobile SMRs					
KLT-40S	UO_2 pellet in silumin matrix	18.6%	23%	45.4	30-36
RITM-200	UO_2 pellet/ hexagonal array	<20%	29%	-	72-84
Gen IV and MMRs					
Aurora	Recycled HALEU fuel (EBR-II used fuel)	-	38%	-	240
eVinci	HALEU fuel	5 - 19.75%	29%	-	> 36
Natrium	HALEU fuel	-	-	-	-
ARC-100	U-Zr alloy	13.1%	35%	77	20
Energy Multiplier Module (EM^2)	Uranium carbide/hexagonal array	~14.5%	53%	130	360
Westinghouse Lead Fast Reactor	Uranium oxide, before transitioning to uranium nitrides	≤ 19.7%	47%	≥ 100	≥ 24
Integral Molten Salt Reactor (IMSR)	Circulating molten salt fuel (fluoride) with U	<5%	44%		84
Stable Salt Reactor	Static molten salt fuel (chloride) with Pu	Reactor grade Pu	40%	120 - 200	Online refuelling
KP-FHR	TRISO fuel	19.75%	44%		
U-Battery	TRISO fuel	<20%	40%	80	

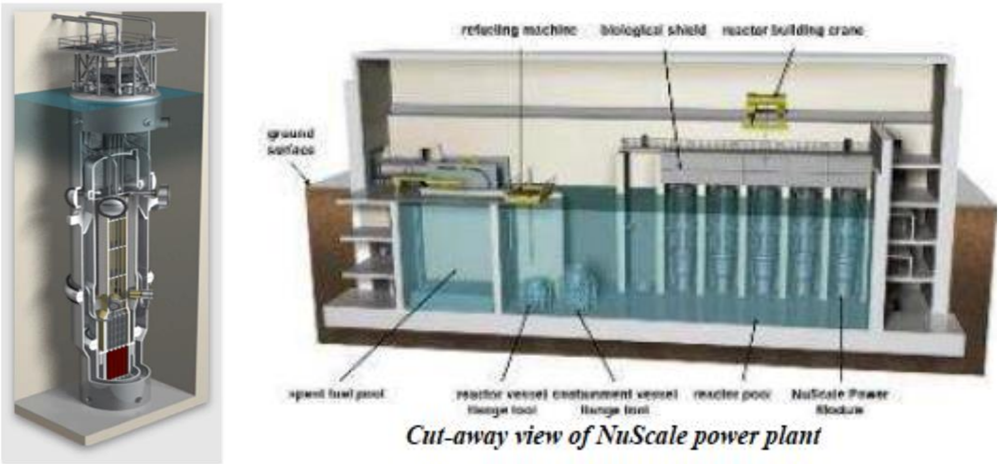

Figure 3 Single VOYGR module and a cut-away view of multi-module plant [19]

The BWRX-300 is a 300 MWe BWR, based on GE ESBWR Generation III+ BWR. It has simplified design that allows it to be built in 24 to 36 months. The BWRX-300 uses LEU, UO_2 fuel, which is readily available. It features a fully passive safety systems, natural coolant circulation, and uses proven readily available components. The BWRX-300 uses a dry containment to stop the release of any products of a Loss of Coolant Accident (LOCA), such as steam, water, or fission products into the environment. The entire BWRX-300 reactor pressure vessel is shown in Figure 4.

While VOYGR and BWRX-300, based on LWR technology, represent Generation III+, X-Energy's Xe-100 is considered a Generation-IV reactor. It is an 80 MWe/ 200 MWth modular high-temperature gas-cooled (M-HTGR) reactor using graphite as a moderator, helium as a coolant, and 15.5% enriched HALEU TRISO fuel pebbles. The Xe-100 reactor generates superheated steam at 565 °C and 16.5 MPa. Its thermal efficiency is 42.3%, much higher than for existing LWRs. Xe-100 has many redundant safety systems. TRISO fuel itself provides a passive safety system, that can contain any radioactive release. Reactor core contains 220 000 pebbles, with on-line fuel loading. The possible delay in deployment is related to the development and testing of HALEU TRISO fuel, which is not commercially available. A diagram showing the TRISO fuel pebbles and reactor core is shown in Figure 5.

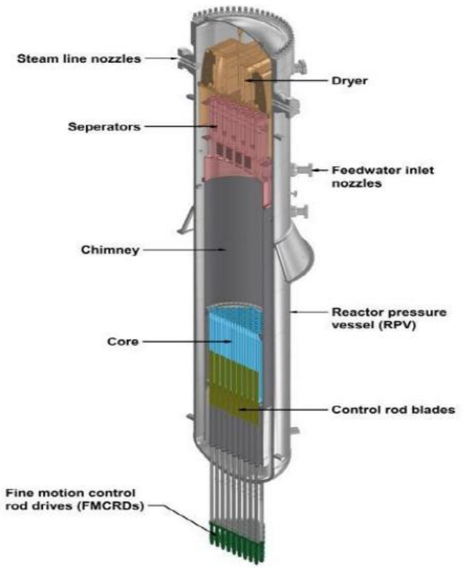

Figure 4 The BWRX-300 Reactor Pressure Vessel Internal Diagram [20]

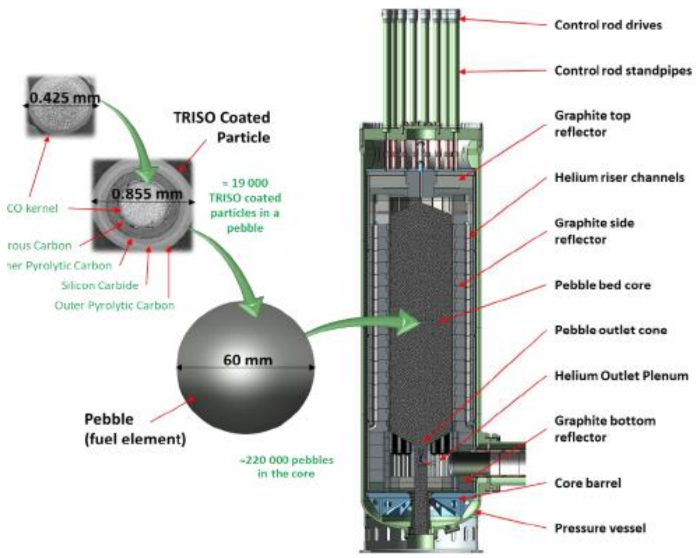

Figure 5 Xe-100 TRISO fuel pebbles and reactor core [20]

The KP-FHR (Hermes) reactor, is an SMR prototype designed to prove the viability of the Kairos Power Fluoride-Salt-Cooled High Temperature Reactor (KP-FHR). Low pressure fluoride salt (FLiBe) coolant is used to transport thermal energy to a standard steam generator system. The TRISO fuel used in the design is a pebble-type, allowing online refueling. The reactor is designed with many independent safety systems - TRISO fuel, molten fluoride salt that allows reactor to operate at low pressure, but high temperature. Kairos Power Hermes is the first non-water-cooled reactor prototype to be approved for construction in the U.S. in over 50 years. Kairos plans on building Hermes at the East Tennessee Technology. The KP-FHR reactor design is shown in Figure 6.

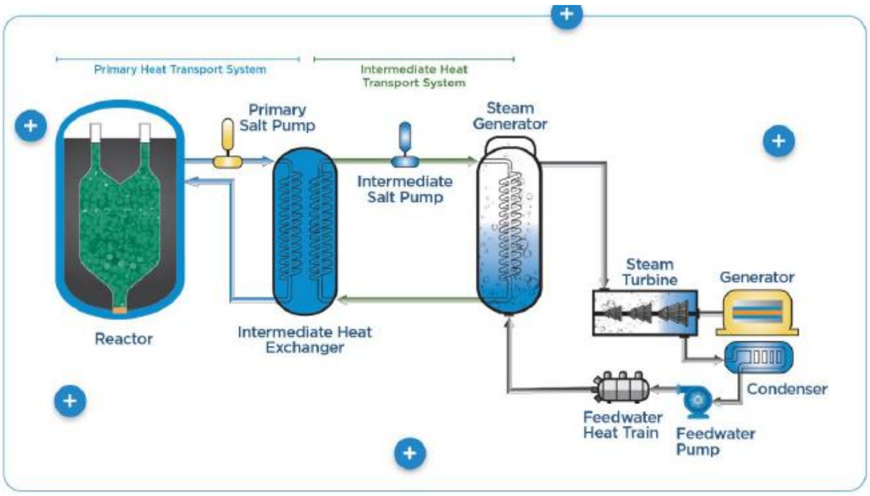

Figure 6 KP-FHR Reactor Design [20]

SEALER (Swedish Advanced Lead Reactor) is a passively safe lead-cooled reactor designed for commercial power production in the smallest possible format. Its power is 140 MWt/55 MWe. Core inlet/outlet coolant temperature is 420 C / 550 C. The fuel enrichment is 12%. It has passive safety systems. It is designed as a nuclear battery, with refueling cycle of 300 months. Five years after end of operational life, a SEALER unit will be transported back to a centralized waste management facility - either direct disposal of the entire primary vessel, including fuel assemblies encapsulated in frozen lead, or recycle of plutonium and minor actinides in SEALER reactors designed for waste transmutation. Figure 7 shows SEALER reactor vessel.

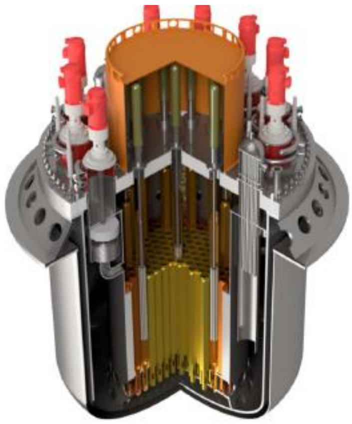

Figure 7 SEALER reactor vessel [19]

As it was mentioned earlier, there are over 100 SMR designs. Among those, SMRs based on proven LWR technology (either PWR or BWR) are closest to be deployed, probably over the next several years. However, SMRs that belong to Category IV will have much longer path to their deployment, depending on how fast the HALEU fuel is developed and tested, how long it will take for the licensing procedures of new technologies, and how are their safety and security fully developed.

3. ADANTAGES AND DISADVANTAGES OF SMALL MODULAR REACTORS

The focus of nuclear community on SMRs is related to the need to develop a nuclear power option which is more affordable, with designs that are simplified and standardized, with improved safety and security, with reduced cost and duration of construction, as well as with reduced amount of spent nuclear fuel and radioactive waste. Thus, SMRs are intended to also provide the electricity to countries with small, limited or distributed electricity grid system as well as for the countries with limited financial resources for investment into large nuclear power plants. Most of the proposed small reactors offer combined electricity and process heat to industrial complexes, water desalination, and district heating.

In order to fulfil this role, SMRs do need to offer the following advantages over the large LWRs: (1) Power generating systems for areas difficult to access or without infrastructure for transportation of fuel; (2) Modular concept that reduces the amount of work on site, makes it simpler and faster to construct, including components that are factory-assembled and transported to the desired location for installation; (3) Long life cycle and reduced need for refueling (perhaps every 10-15 years); (4) Design simplicity with passive safety systems and inherent safety characteristics; (5) Expanded potential siting options since more sites are suitable for SMRs; (6) Smaller nuclear island and footprint of the whole nuclear power plant; (7) Scalability – multiple SMR units could be installed in one location; (8) Low initial costs and risks, with low operation and maintenance costs; (9) Load following – power output that could be adjusted to electricity demands; and (10) Proliferation resistance.

However, SMRs (particularly Generation IV SMRs) must overcome a list of drawbacks if they are to be deployable in the near future: (1) Economics of SMRs needs more analysis in order to show possible advantages over large LWRs. The limited power of SMRs causes higher specific costs for construction and operation per unit of electric power as compared to large LWRs. (2) Most Gen IV SMRs require higher fuel enrichment (HALEU fuel), between 5% to up to 19.75% U-235. Currently, HALEU is only produced in Russian Federation at a commercial scale. (3) Most Gen IV SMRs are using new fuel (metallic, carbide, nitride, TRISO) that needs to be fully developed, tested and licensed. (4) Spent nuclear fuel from small reactors could be located in remote areas which will make its transport more difficult. Also, spent fuel will be spread in many more sites while nowadays it is congregated at a limited number of locations; (5) The back-end of the SMR fuel cycle has not been addressed as of yet. Longer life cycles (5-30 yrs), and new fuel types represent great challenges for spent fuel management, including possible reprocessing, and disposal of radioactive waste. (6) Obtaining design certification and license may take longer time than expected. (7) Public acceptance of new concepts might be challenging.

As shown in Figure 8, the LCOE cost for large LWRs goes down almost exponentially with the increase of installed power [18]. However, the same principle does not work for SMRs. Levelized Cost of Energy (LCOE) measures lifetime costs divided by energy production. It calculates present value of the total cost of building and operating a power plant over an assumed lifetime.

SMRs could have advantage regarding possible cost overruns, that are common during large LWR construction. The most recent example is Flamanville 3 (France, EPR, 1650 MWe gross, Areva). Construction started in 2007 and the plant got connected to the grid in Dec 2024 instead of planned 2012. Initial cost was €3.3 billion (€2434/kWe) and final cost was €13.2 billion (~€8000/kWe). Similarly, the units 3 and 4 (AP1000) at the Vogtle nuclear plant in Georgia were completed in 2023 and 2024, seven years behind schedule with the cost that was twice as much as planned (about $35 billion). EPRI study [21] specified that construction duration has a large impact on the capital cost, that could increase 3 to 5 times if duration of construction is extended 2 to 3 times. Although the EPRI study concluded that considerable reduction in capital cost between the First-of-a-kind (FOAK) as compared to NOAK could be accomplished and that a FOAK SMR could have a lover capital cost as compared to conventional LWR, it also emphasized that the study was done for an assumed SMR design, while most SMRs are in predesign and it is difficult to estimate capital cost for specific SMR types.

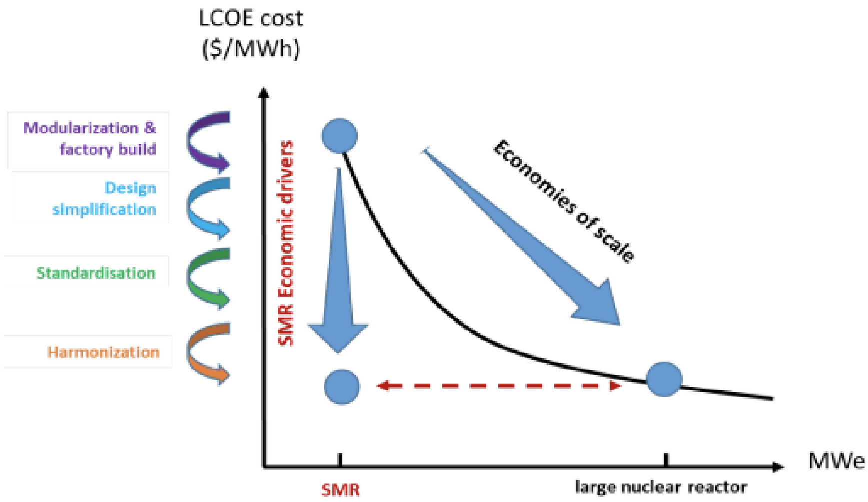

Figure 8 Economy of scale tends to disfavor SMRs [18]

The current estimates for SMR capital cost are between $3000/kWe to $6000/kWe. It was also shown that the LCOE for SMRs could be competitive with Wind and Solar, if there is a full partnership between industry and government (Table 2) [22].

TABLE 2 Comparison of LCOE for FOAK SMRs and Wind and Solar [22]

	Investor-Owned Utility (LCOE)	**Municipal Utility (LCOE)**
Dispatchable		
First of a kind SMR $/MWh (no government partnership)	98	76.7
First of a kind SMR $/MWh (full government partnership)	48.4	43.4
NGCC $/MWh	38.6-43.4	35.9-40.6
Variable		
Wind[9]	41.6	33.5
Solar[9]	51.7	40.8

Additional advantage of SMRs over renewables (Solar and Wind) is in much larger capacity factors (Table 3). While the capacity factor of SMRs is larger than 95%, the capacity factor for Wind is 35% and for Solar 25%. It means that for the same installed capacity, SMRs are producing almost 3 times more electrical energy than Wind and almost 4 times than Solar.

TABLE 3 Comparison of SMRs with Wind and Solar for 1000 MWe Plants [22]

	Nuclear SMR	NGCC	Wind	Solar
Max. Capacity factor (%)[11]	>95	90	35	25
Land requirements (acres)[12, 13, 14]	50[15] see below	343	85,240	7,900
Jobs during operation	500	50	50	-
Plant lifetime (years)	60 to 80	40 to 50	20 to 25	20 to 25

In addition, the SMR land requirements are considerably smaller, and plant lifetime is considerably longer that in the case of Wind and Solar.

4. CONCLUSIONS

Small Modular Reactors are compact nuclear reactors with electric generating capacity typically less than 300 MWe. Their modular design allows for scalable energy solutions, and offer enhanced passive safety features and flexible designs. There are more than 100 different SMR designs around the world. SMRs could be characterized based on the type of fuel, moderator, or coolant that they use. SMRs could also be characterized based on predominant neutron energy spectrum: fast, intermediate or thermal, or operating temperature. Some of SMRs are transportable, while some are encapsulated and do not need fuel replacement. This paper report examines key features of SMR designs, assessing their scalability, potential costs and benefits, economic impacts, and current deployment status.

The ideal SMR concept must satisfy requirements of sustainability, passive safety, proliferation resistance, simplicity of construction and operation, scalability, and affordability. The SMRs could be broadly used by smaller utilities, by smaller countries with financial or infrastructure constrains, in isolated regions or for distributed power needs, and for various other non-electrical application (process heat, desalination, district heating).

This paper analyzed several SMRs based on proven LWR technology and several belong to Generation IV SMRs. It is expected that SMRs based on proven LWR technology will be easier to license and more acceptable by general public. Other reviewed concepts could also become competitive, given financial support and regulatory simplification. However, there are technical and institutional challenges to be addressed with further R&D: HALEU fuel development, testing and licensing, testing and validation of technological innovations in components, systems and engineering, economy-of-scale, perceived risk factors for First-of-a-kind nuclear power plants, and regulatory and licensing issues. Additional issues to be addressed include spent nuclear fuel management, including possible reprocessing, and disposal of radioactive waste.

In conclusion, it needs to be pointed out that most of the SMR concepts are not new, but over the last several decades did not have full government financial support, appropriate regulatory framework, and inclusion in long-term plans for energy future. Thus, with the current full government support in the U.S. it is to be expected that the deployment of SMRs will accelerate, and that some of innovative Generation IV SMR would get the chance to be developed, tested and deployed.

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