REEVALUATION OF NUCLEAR POWER BEGINS AROUND THE WORLD

— PROSPECTS FOR NEW NUCLEAR REACTORS UNDER DEVELOPMENT —

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SUMMARY

- Nuclear power is being reevaluated around the world as a decarbonizing power source. Key countries with nuclear power plants have announced increased support for nuclear development. In response, reactor manufacturers have announced plans to develop new types of reactors with enhanced safety features and to start operating them from around 2030.
- The new reactors fall into two categories: (1) improved versions of existing light-water reactors (LWRs), and (2) reactors other than LWRs (Generation IV reactors). Small modular reactors (SMRs) are also becoming a trend. However, there are some challenges, including the acceptability of reactors with limited operation records by electric power utilities and the current lack of a certification process by regulatory authorities with regard to (2).
- For the time being, the latest large LWRs will become mainstream, but SMRs and Generation IV reactors could also play a part in power generation and eventually contribute to hydrogen production and heat utilization in industry.

1. THE RECENT ENVIRONMENT SURROUNDING NUCLEAR POWER GENERATION AND NEW TECHNOLOGIES

In recent years, nuclear power has received increasing attention as a promising decarbonization technology. In Japan, the non-fossil value trading market, on which the decarbonized value of electricity is traded, began handling nuclear power in 2020, while in Europe, nuclear power was added to the EU taxonomy for sustainable activities[1] in 2022. There is also a debate, particularly in France, over whether hydrogen derived from nuclear power should be considered clean hydrogen. Although the price of nuclear hydrogen is higher than that of green hydrogen derived from renewable energy sources, it could be price-competitive depending on institutional design, and could affect the project trends of existing renewable energy sources.

Reactor manufacturers around the world are developing new types of reactors that are safer than existing reactors. The US and other key countries with nuclear power plants have announced increased support and additional financial resources for development (Figure 1). However, the new reactor types are diverse, and their development progress and prospects differ, such that they cannot be considered identical.

[1] A classification system in the EU that encourages green investment by setting standards for environmentally sustainable corporate economic activity.

Figure 1 Policy support of key countries for the development of large LWRs and new reactors

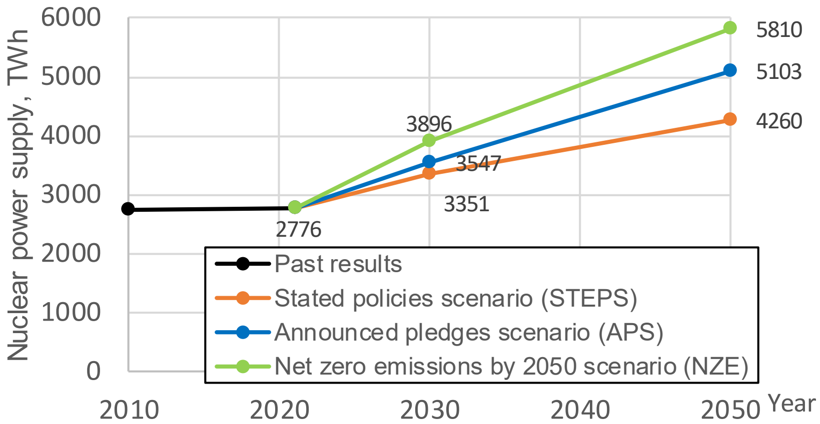
Country	Support for large LWRs	Support for new reactor development (primarily other than large LWRs)
Japan	**Existing reactors** - GX Decarbonization Power Supply Bill enacted (2023): After the Fukushima nuclear accident, the maximum plant operating period was set at 60 years, but the Bill allows for extensions equivalent to periods of shutdown due to safety reviews and other reasons. The Bill clearly states that the country will work on the development and construction of advanced next-generation reactors that incorporate new safety mechanisms.	**GX transition bonds** - Preparation of a business environment for development and construction of large LWRs, etc. - Promotion of development and construction of HTGR and fast reactors (JPY 89.1 billion over 3 years)
US	**Existing reactors** - Financial assistance (crediting) for existing reactors in financial difficulties totaling USD 6 billion over 5 years **New construction outside the US** - Poland and Ukraine adopt AP1000 large-size reactor from Westinghouse (US)	**Advanced Reactor Demonstration Program (ARDP)** USD 4 billion total (2021) ARDP 1 - TerraPower (fast reactors): USD 2 billion - X-energy (HTGRs): USD 1.2 billion ARDP 2&3 - Advanced reactor manufacturers, etc. **Technical development and operational support for SMRs** - NuScale Power (small LWRs) R&D: USD 530 million Business support: USD 1.36 billion total
UK	**New construction** - Support for new construction of large reactors up to GBP 1.7 billion (2021) - GBP 700 million in support decided for Sizewell C nuclear power station (2022) **Planned new construction** - Up to 8 units planned for construction by 2030	**Advanced Nuclear Fund (2020)** - SMR development: GBP 215 million - HTGR development: GBP 170 million **Future Nuclear Energy Realization Fund (2021)** - New construction support: GBP 120 million
France	**New construction** - Human resources support: EUR 110 million; SME support: EUR 200 million - 100% nationalization of ailing power company EDF **Planned new construction** - Began construction of 6 new large LWRs and considering construction of 8 more	**France Relance (2020)** - NUWARD (SMR, LWR): EUR 50 million **France 2030 (2021)** - NUWARD (SMR, LWR): EUR 500 million - Development of reactors with easy waste management: EUR 500 million
Canada	–	**Development and installation of a new type of reactors centered on SMRs** CAD 970 million - GE Hitachi Nuclear Energy (SMR, LWR) and other advanced reactor manufacturers, etc.

Source: Compiled by MGSSI based on data from the METI Nuclear Energy Subcommittee, Advanced Reactor Working Group and various media reports
https://www.meti.go.jp/shingikai/enecho/denryoku_gas/genshiryoku/kakushinro_wg/pdf/001_06_00.pdf
(accessed July 7, 2023)

1-1. Increase in Volume of Nuclear Power Generation and Activation of Related Business

In its World Energy Outlook 2022, the International Energy Agency (IEA) projects that global nuclear power generation will grow by 1.5 to 2.1 times 2021 levels by 2050 (Figure 2). This corresponds to an increase of approximately 200 to 400 large reactors. The primary reason for this increase is the rising energy demand, particularly in Asia. As a result, many countries are currently making progress in their plans for new nuclear reactors to address this situation. China accounts for much of these planned developments. Meanwhile, some aging, uneconomical nuclear facilities are expected to be upgraded in Japan, the US, and Europe. As new construction and renewal of nuclear power plants continue, the trade of new nuclear power related equipment and nuclear fuel will increase, as well as the demand for maintenance services.

Figure 2 IEA estimates of global nuclear power generation



Source: Compiled by MGSSI based on IEA "World Energy Outlook 2022"

1-2. Conventional and New Reactors

The most popular form of conventional commercial nuclear reactor is the light water reactor (LWR), in which ordinary water (light water[2]) is heated by nuclear fuel and the steam generated is used to drive turbines and generators to produce electricity.

On the other hand, new reactors fall into two categories: (1) improved versions of existing LWRs and (2) reactors other than LWRs (such as fast reactors, molten salt reactors, and high-temperature gas-cooled reactors (HTGR); also known as "Generation IV reactors[3]") (Figure 3). In addition, small reactors that incorporate the concept of modularization (SMRs[4]) are also becoming a trend. These reactors are expected to have high safety and be extremely economical.

The concept of Generation IV reactor and SMR technology has existed for a long time and has been developed in the past. Many of these developments have not been commercialized due to funding difficulties, technical challenges, and lack of economic viability compared to the mainstream large LWRs. However, due to the international appetite for development and unprecedented levels of investment in decarbonization technologies, demonstration reactors are beginning to be built. In Japan, the Advanced Reactor Working Group, an industry-academia-government collaboration led by the Ministry of Economy, Trade and Industry, presented a roadmap for the development of new nuclear reactors and a strategy to capture the market in 2020 (Figure 4). The roadmap illustrates the construction of large commercial LWRs and Generation IV demonstration reactors in the 2030s. In addition, overseas manufacturers of new reactors have announced construction plans for around 2030, earlier than Japan, and production of some new reactors has begun (Figure 5).

Figure 3 Comparison of conventional and new reactors

Type	Characteristics	Coolant	Operating temperature	Advantages	Issues & risks	Main manufacturers
Light-water reactors (LWRs) (Generation I to III reactors)	· Current mainstream nuclear reactors · New reactors to be announced as they become available	Light water (normal water)	300℃ –350℃	· Extensive track record · Highly economical · Supply chain already established	Core damage	Mitsubishi Heavy Industries Hitachi-GE Nuclear Energy Toshiba Energy Systems & Solutions (US) Westinghouse (France) EDF etc.
Fast reactors (Generation IV reactors)	· Use of coolants that do not impede the neutrons necessary for the fission reaction · Nuclear reaction caused by fast neutrons	Sodium, molten salt, etc.	500℃ –550℃	· Suitable for fuel recycling · Possible to reduce radioactive waste · Low operating pressure	· Core damage · Measures against sodium · Establishment of maintenance technology · Establishment of economic feasibility	Mitsubishi Heavy Industries Hitachi-GE Nuclear Energy Toshiba Energy Systems & Solutions (US) TerraPower (US) GE Hitachi Nuclear Energy etc.
Molten salt reactors (Generation IV reactors)	Use salts that are solid at room temperature as a coolant	Molten salt (fluoride salts, chloride salts, etc.)	600℃ –800℃	· Core damage does not occur · Longer operation time without fuel change is possible · Low operating pressure	· Resistance to corrosion at high temperatures · Establishment of maintenance technology	(US) TerraPower (US) Kairos Power (Canada) Moltex Energy etc.
HTGR (Generation IV reactors)	· Use of high-temperature gas as coolant · Core damage cannot occur in principle even if power is lost	Helium, etc.	750℃ –1,000℃	· Core damage does not occur · Hydrogen production is possible with heat in the temperature range of 900° or higher	· Not suitable for fuel recycling · Establishment of economic feasibility	Mitsubishi Heavy Industries Toshiba Energy Systems & Solutions (US) X-energy (UK) National Nuclear Laboratory (Canada) Ultra Safe Nuclear etc.

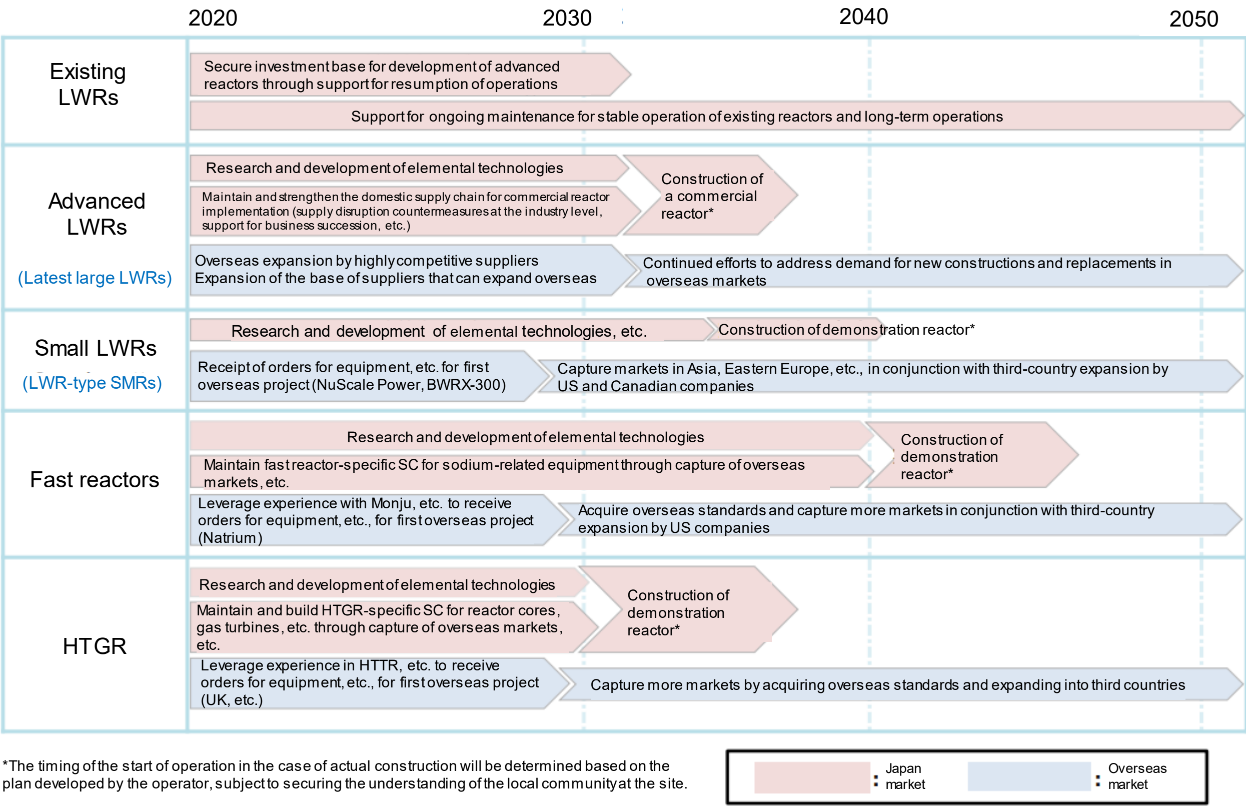
Source: Compiled by MGSSI based on various media reports

2 In contrast to ordinary water (light water), water with a large molecular weight due to the atoms containing more neutrons is called "heavy water." Although heavy water reactors (HWR) also exist, LWRs established their economic viability early on and became the mainstream. The introduction of HWRs is limited to a few countries such as Canada.

3 According to the definition of the Generation IV International Forum, Generation I: prototype reactor, Generation II: large commercial reactor, Generation III: improved version of Generation II reactor, Generation IV: advanced reactor other than LWR (defined by the following names by the forum: Very High Temperature Reactor, Sodium-cooled Fast Reactor, Supercritical Water-cooled Reactor, Gas-cooled Fast Reactor, Lead-cooled Fast Reactor, Molten Salt Reactor).

4 Small modular reactor. Mainly refers to reactors with a generation output of 300 MW (300,000 kW) or less, but the definition varies by country. LWR and Generation IV (non-LWR) SMRs are currently under development.

Figure 4 Japanese companies' strategic roadmap for market capture in the nuclear power industry



*The timing of the start of operation in the case of actual construction will be determined based on the plan developed by the operator, subject to securing the understanding of the local community at the site.

Source: Nuclear Energy Subcommittee, Advanced Reactor Working Group, "Technology roadmap for innovative reactor development for carbon neutrality and energy security: An interim summary" p. 29 (blue text added by MGSSI)
https://www.meti.go.jp/shingikai/ enecho/denryoku_gas/genshiryoku/kakushinro_wg/pdf/004_03_00.pdf (accessed June 14, 2023)

Figure 5 Major small LWR and Generation IV reactor construction plans of foreign reactor manufacturers

Type	Manufacturer	Name	Output (MW = 1,000 kW)	Construction site	Operation start schedule
LWR-type SMR	GE Hitachi, Hitachi-GE Nuclear Energy	BWRX-300	300	Ontario, Canada	Commercial reactor in 2028
LWR-type SMR	NuScale	VOYGR	77 x 6 units (Total 462)	Idaho, US	Reactor construction started Commercial reactor in 2029
Fast reactors	TerraPower, GE Hitachi	Natrium	345	Wyoming, US	Commercial reactor in around 2030
Molten salt reactors	TerraPower	MCFR	N/A	Experimental reactor under construction in Idaho, US	Commercial reactor in around mid-2030s
HTGR	X-energy	Xe-100	82.5	Gulf Coast, US	Commercial reactor in around 2030

Source: Compiled by MGSSI based on company websites and various media reports

2. TYPES AND CHARACTERISTICS OF NEW REACTORS

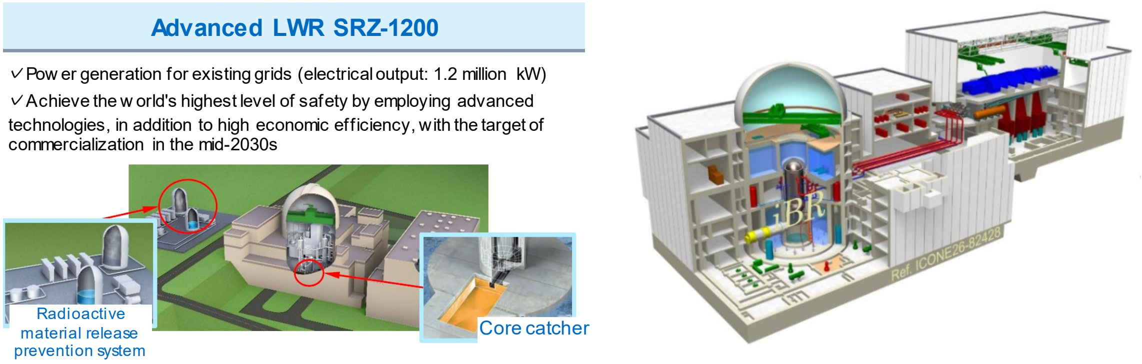
2-1. Large LWRs

The latest large LWRs are much safer than older types. Although new construction has been limited in Japan, the US, and Europe since the year 2000, manufacturers have continued to improve their designs in response to the 9/11 terrorist attacks in the US and the Fukushima nuclear accident. In the case of Toshiba Energy Systems & Solutions' latest large LWRs, the probability of core damage, as in the Fukushima accident, is estimated to be about 1% that of older models. In Japan, renewal of large LWRs is likely to begin in the 2030s

(Figure 6). In the past, Japanese manufacturers have presented concepts for large LWRs for the international market, but after fighting an uphill battle with overseas nuclear power projects until 2020, they are now focusing on orders for renewals in Japan. Overseas, EDF (France) and Westinghouse (US), as well as Chinese, Russian, and Korean manufacturers that have been successful in exporting nuclear reactors in recent years, are also continuing development, and for the time being, these companies will be engaged in the construction and renewal of large LWRs around the world.

Figure 6 Conceptual diagram of major new large LWRs

(a) Mitsubishi Heavy Industries SRZ-1200 (b) Toshiba Energy Systems & Solutions, iBR

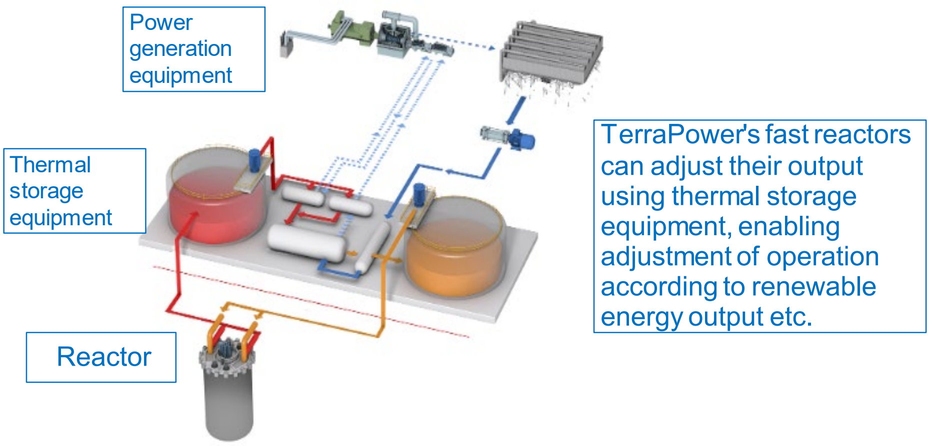


Source:
(a) Mitsubishi Heavy Industries, Nuclear Energy Segment, 5th Advanced Reactor Working Group "Mitsubishi Advanced Reactor Development Efforts" p. 2
https://www.meti.go.jp/shingikai/enecho/denryoku_gas/genshiryoku/kakushinro_wg/pdf/005_03_00.pdf
(b) Toshiba Energy Systems & Solutions website, "Advanced LWRs enabling carbon neutrality and energy security," iBR
https://www.global.toshiba/jp/company/energy/topics/nuclearenergy/iBR.html
（accessed on July 3, 2023 for both a and b）

2-2. Generation IV: Fast Reactors

Fast reactors mainly use coolants such as sodium or molten salt that do not impede the neutrons necessary for the fission reaction. Fast reactors using molten salt are also called molten salt fast reactors. Their major advantages are the reduction of radioactive waste and the effective use of uranium resources. However, careful handling of the coolant is required because sodium is prone to ignition due to chemical reactions with air and moisture, and molten salt is highly corrosive. TerraPower (US), in which Bill Gates has invested, is developing a sodium-cooled fast reactor (Figure 7) with a total of USD 1.2 billion in support from the US Department of Energy (DOE), and plans to build a demonstration reactor by 2027. GE Hitachi Nuclear Energy (US) is supporting this development, and there is a possibility that Japanese fast reactor manufacturers will receive orders to design and manufacture the components.

Figure 7 TerraPower's Natrium sodium fast reactor

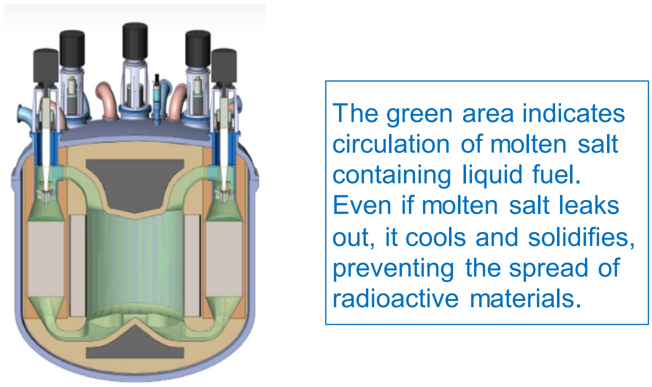


Source: TerraPower's website "THE NATRIUM™ TECHNOLOGY" (blue text added by MGSSI)
https://natriumpower.com/reactor-technology/ (accessed June 14, 2023)

2-3. Generation IV: Molten Salt Reactors

Molten salt reactors use sodium chloride, fluoride salt, etc., which are solid at room temperature, as a coolant. Due to their high operating temperatures, they are more energy efficient than LWRs. Another advantage is their high safety profile – even if the reactor loses its cooling function, as in the Fukushima nuclear accident, it should not melt down in principle. Even if molten salt leaks out of the container, it cools and solidifies, trapping radioactive materials (Figure 8). The challenges for this type of reactor are to improve corrosion resistance and establish maintenance methods. TerraPower, a leader in molten salt reactors, is working on these issues with support from the DOE, and plans to start operation of a demonstration reactor in the 2030s.

Figure 8 TerraPower's MCFR molten salt fast reactor

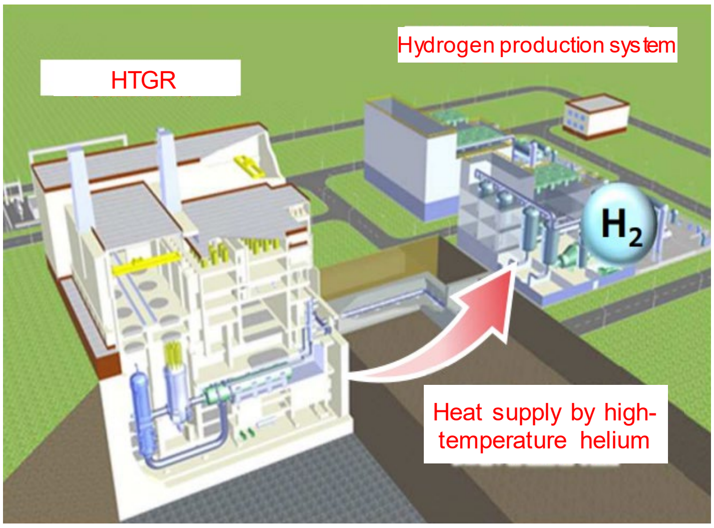


Source: TerraPower website, "MOLTEN CHLORIDE FAST REACTOR TECHNOLOGY" (blue text added by MGSSI)
https://www.terrapower.com/our-work/molten-chloride-fast-reactor-technology/ （accessed June 2, 2023)

2-4. Generation IV: HTGRs

HTGRs are reactors that use helium or other gases as coolants. The operating temperature of HTGRs is high at 900°C or more, and this heat can also be used for hydrogen production (Figure 9). In addition, this type of reactor is very safe because the reactor core is not damaged even if power is lost. A research HTGR is in operation in Japan and a demonstration HTGR in China. In the US, X-energy has received USD 1.2 billion in DOE support and aims to begin operation of an HTGR in the 2020s. On the other hand, the plant materials include expensive alloys, and in principle, the reactors and buildings are larger than those of LWRs of the same power output, resulting in the drawback of high construction costs and high levelized cost of electricity. Therefore, many manufacturers, such as Toshiba Energy Systems & Solutions, aim to contribute to decarbonization by supplying heat to industries such as hydrogen production and steelmaking rather than for power generation.

Figure 9 Hydrogen production system using heat from a high-temperature gas-cooled reactor



Source: Mitsubishi Heavy Industries, Nuclear Energy Segment, 1st Advanced Reactor Working Group "Mitsubishi Advanced Reactor Development Efforts" p. 2
https://www.meti.go.jp/shingikai/enecho/denryoku_gas/genshiryoku/kakushinro_wg/pdf/001_08_00.pdf
（accessed June 2, 2023）

2-5. SMR (Small Modular Reactor)

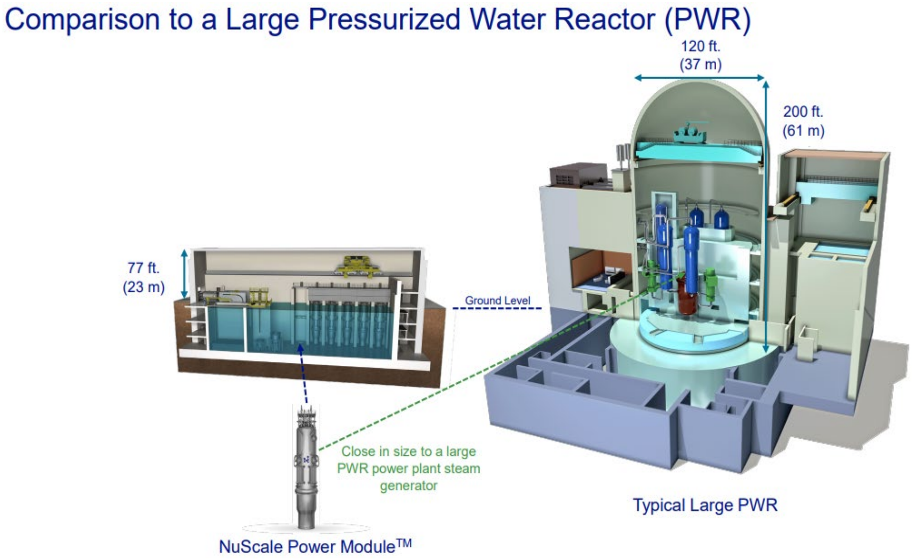
The levelized cost of electricity for nuclear power generation is heavily influenced by construction costs. Construction costs for large reactors have risen sharply due to anti-terrorism measures and the addition of design features following the Fukushima nuclear accident, as well as the rising cost of on-site construction, particularly in Europe and the US. While large reactors require on-site welding of components due to transportation limitations, SMRs are modularized at the factory to maximize the combination of components around the reactor and then transported to the site, thereby reducing on-site work and construction costs.

Among SMRs, plans for NuScale Power's (US) pressurized water LWR and GE Hitachi Nuclear Energy's boiling water LWR[5], which is being jointly developed with Hitachi-GE Nuclear Energy, are currently leading in the US and Canada, respectively, and are scheduled to start operation around 2029 (Figure 10). In addition, due to their small size, SMRs can be installed on ships, so many manufacturers are moving forward with the development of offshore power plants and marine applications.

[5]There are two types of LWRs: the boiling water type, which was created in the early days, and the pressurized water type, which has improved safety features in comparison to the boiling water type. The boiling water type directly turns the turbine with heated water, whereas the pressurized water type exchanges heat part way, thus reducing the extent of exposure to radioactive materials.

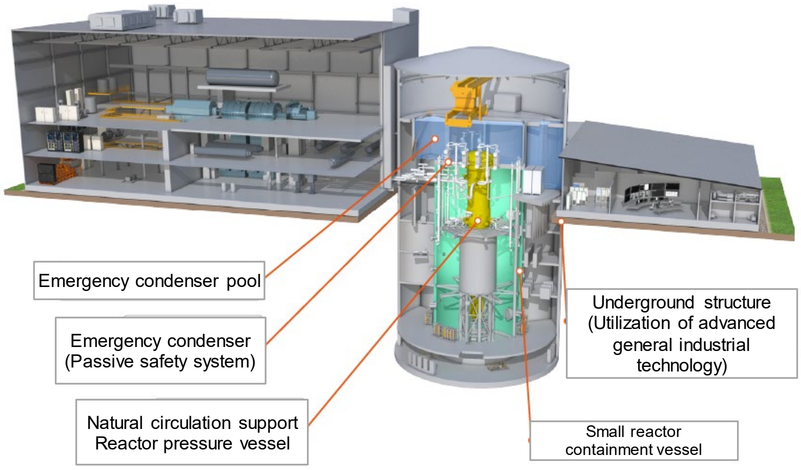
Figure 10 Leading SMR concept diagram

(a) NuScale Power's VOYGR pressurized water SMR (left) and large LWR (right)



Source: NuScale's website, "Nucala's SMR Development," https://www.meti.go.jp/shingikai/enecho/denryoku_gas/genshiryoku/kakushinro_ wg/pdf/002_06_00.pdf (accessed June 2, 2023)

(b)BWRX-300, a boiling water SMR jointly developed by GE Hitachi Nuclear Energy and Hitachi-GE Nuclear Energy



Source: Hitachi-GE Nuclear Energy website, Nuclear energy business initiatives, Research and development / new reactors
https://www.hitachi-hgne.co.jp/activities/advanced_reactor/index.html (accessed June 14、2023)

3. CHALLENGES AND FUTURE PROSPECTS FOR NUCLEAR POWER

While the demand for new LWRs and renewals is expected to increase, Generation IV reactors have the disadvantage of having no commercial track record. Electric power utilities that have operated nuclear reactors so far have no experience with commercial reactors other than LWRs. Solid benefits and a proven track record of operation are necessary to motivate electric power utilities to install Generation IV reactors. Another problem is that both conventional and new nuclear reactors generate some degree of radioactive waste, and therefore disposal sites must be selected in Japan and other countries.

Legal and regulatory provisions are also necessary for Generation IV reactors. Existing LWRs have a review process established by the nuclear regulatory authorities of each country. Although the formulation of the review process for sodium fast reactors is relatively advanced among Generation IV reactors, the further away from the mechanisms and structures of existing LWRs, the less established the process. Therefore, there is a risk that approval of the construction of commercial Generation IV reactors will take time, leading to schedule delays. However, if the operation of the demonstration reactor, which will begin around 2030, is successful and demonstrates its superiority over LWRs, Generation IV reactors will be utilized and may eventually spread beyond power generation to other fields such as hydrogen production and heat utilization in industry.

Although nuclear power was viewed negatively worldwide in the 2010s due to the 9/11 terrorist attacks in the US, the Fukushima nuclear accident, and rising construction costs in Europe and the US, capital investment is expected to increase in the future due to its promise as a decarbonized power source. In addition to reactors, demand for plant-related equipment and services related to nuclear power generation is also expected to increase.

Currently, state-of-the-art large LWRs are the mainstream, but plans are underway in North America and Europe for the construction of small commercial LWRs. Generation IV reactors may also play a part in nuclear power generation in the future, and future development trends will be watched closely.