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Global Situation of Small Modular Reactor Development and Deployment

Edited by

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List of Abbreviations

AECL	Atomic Energy of Canada Ltd.
AMR	Advanced Modular Reactor
ARDP	Advanced Reactor Demonstration Program
ASEAN	Association of Southeast Asian Nations
BAPTEN	Nuclear Energy Regulatory Agency (Indonesia)
BATAN	National Atomic Energy Agency (Indonesia)
BEIS	Department for Business, Energy & Industrial Strategy (United Kingdom)
BIS	Department for Business, Innovation and Skills (United Kingdom)
BNPP	Bataan Nuclear Power Plant
BWR	Boiling Water Reactor
CANDU	Canadian Deuterium Uranium (reactor)
CfD	Contract for Difference
CNL	Canadian Nuclear Laboratory
CNSC	Canadian Nuclear Safety Commission
COG	CANDU Owners Group
COL	Combined Construction and Operating Licence
CV	Containment Vessel
DCA	Design Certification Application
DECC	Department of Energy and Climate Change (United Kingdom)
DOE	Department of Energy (United States or the Philippines)
EA	Environment Agency (United Kingdom)

EU	European Union
EBR-II	Experimental Breeder Reactor-II
EBTKE	(Directorate General of) New Renewable Energy and Energy Conservation (Indonesia)
EFWG	Expert Finance Working Group (United Kingdom)
EIP	Energy Innovation Programme
EPR	European Pressurised Water Reactor
ERIA	Economic Research Institute for ASEAN and East Asia
ESBWR	Economic Simplified Boiling Water Reactor
FOAK	First-of-a-Kind
GAIN	Gateway for Accelerate Innovation in Nuclear
GDA	Generic Design Assessment
GW	Gigawatt
HALEU	High-Assay Low-Enriched Uranium
HTGR	High-Temperature Gas-Cooled Reactor
HTR	High-Temperature Reactor
HTTR	High Temperature Engineering Test Reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IEEJ	Institute of Energy Economics, Japan
IFNEC	International Framework for Nuclear Energy Cooperation
IMSR	Integral Molten Salt Reactor
INL	Idaho National Laboratory
IPP	Independent Power Producer
JAEC	Jordan Nuclear Regulatory Commission

LCOE	Levelised Cost of Electricity
LTS	Licensing Technical Support
LWR	Light Water Reactor
M	Metre
MMR	Micro Modular Reactor
MoU	Memorandum of Understanding
MW	Megawatt
MWe	Megawatt Electrical
MWth	Megawatt Thermal
NEA	Nuclear Energy Agency
NIC	Nuclear Industry Council (United Kingdom)
NICE Future	Nuclear Innovation: Clean Energy Future
NIP	Nuclear Innovation Programme
NNL	National Nuclear Laboratory (United Kingdom)
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission (United States)
NRCan	Natural Resources Canada
NSSS	Nuclear Steam Supplying System
NuPEA	Nuclear Power and Energy Agency (Kenya)
OECD	Organisation for Economic Co-operation and Development
ONR	Office for Nuclear Regulation (United Kingdom)
PE	Practically Eliminated
PEP	Philippine Energy Plan or Energy Policy of Poland
PWR	Pressurised Water Reactor

R&D	Research and Development
RAB	Regulated Asset Base (model)
RPV	Reactor Pressure Vessel
SMR	Small Modular Reactor
STUK	Radiation and Nuclear Safety Authority (Finland)
TRISO	Tristructural Isotropic
TWh	Terawatt Hour
UK	United Kingdom
US	United States
UAMPS	Utah Associated Municipal Power Systems (United States)
VDR	Vendor Design Review

Executive Summary

Small modular reactors (SMRs) are expected to offer a lower initial capital investment, greater scalability, and siting flexibility for locations unable to accommodate more traditional large-scale reactors. Their modularised design and inherent safety features would enhance the competitiveness of nuclear energy.

Because of such innovative features, many countries are considering the development and deployment of SMRs. In particular, the United States, the United Kingdom, and Canada are taking intensive policy measures to support the private sector in developing SMRs. What is important is that the governments of these countries are not only securing huge budgets but are also providing the sites, facilities, and technical data of national laboratories. The regulatory bodies of these countries are also having many discussions to prepare flexible and predictable regulatory schemes for SMR (and other advanced reactor) vendors, such as the Pre-Licensing Vendor Design Review in Canada.

Not only such leading countries but also other countries, including those who do not have nuclear power plants today, are considering the deployment of SMRs. The smaller generating capacity and lower investment costs of SMRs make them more suitable than conventional large-scale reactors for developing countries, which have small-scale grid systems and limited financial capacity.

It is true that SMRs would bring many advantages, but there remain problems to be solved not only regarding technical issues but also in financing and licensing, as many international experts have pointed out. Due to such problems, as of 2021, no SMRs have been commercially deployed in the world. Keeping in mind the fact that customers finally decide whether to purchase a product or not, it is crucial to make a business environment that facilitates the decision-making of potential customers. To this end, this study makes the following policy proposals:

1) For the leading countries:

•Continue the current development and deployment projects for SMRs.

•Clarify the timescales for their projects and make efforts to follow them.

•Provide enough data so that potential newcomer countries can consider closely whether SMRs are suitable for their electric power systems.

•Promote international efforts to harmonise the regulatory requirements for SMRs around the world.

•Promote international cooperation with potential newcomer countries in the fields of energy planning, feasibility studies, infrastructure development, and so on.

2) For countries that are considering the deployment of SMRs:

•Clarify their future energy plans and their needs for clean energy.

•Develop attractive business environments for vendors and investors.

•Develop and improve infrastructure, including regulation, which is necessary for the deployment of SMRs.

•Conduct open discussions in the countries about the future utilisation of nuclear energy, including SMRs.

Chapter 1

Introduction

1. Background

The nuclear energy industry is facing great difficulties, especially in countries such as the United States (US), France, and Japan. Some construction projects have been seriously delayed (e.g. Vogtle 3 and 4 in the US and Flamanville 3 in France) and others have ended in failure (e.g. V.C. Summer 2 and 3 in the US and Wylfa Newydd in the United Kingdom (UK)). On the other hand, many countries need huge amounts of low-carbon energy to implement their environmental policies. To enhance the competitiveness of nuclear energy in the clean and low-carbon energy market, advanced reactors with innovative features have been developed in some countries.

Amongst those advanced reactors, small modular reactors (SMRs) are expected to meet various demands that have not been satisfied by conventional large-scale reactors because of their design features: small generation capacity, modular construction technology, safe and low risk of radiation exposure, etc. (World Nuclear Association, 2021) Because of these advantages, SMR development projects are being conducted in some leading countries, such as the US, the UK, Canada, and so on. At the same time, some new countries that have not utilised nuclear energy have come to consider the deployment of SMRs.

Of course, there are many barriers to deploying nuclear power plants (NPPs). However, all countries are seeking various options to meet their energy and environmental policy demands. SMRs could become an important option. Most of the Economic Research Institute for ASEAN and East Asia (ERIA) member countries are also at an important phase in deciding their future energy options because they are experiencing rapid economic development and are expected to have continuously increasing energy demand.

2.Purpose

This research focuses on the innovative efforts in leading countries and on considerations in the ‘newcomer’ countries to provide the East Asia Summit member countries with useful insights and information to consider for their future nuclear energy policies.

3.Study Method

1) Literature survey

First, the report summarises the technical features of SMRs and clarifies from where these features stem. Then, it presents surveys of the current status and plans for the development and deployment of SMRs (or other advanced reactors) in leading countries such as the US, the UK, and Canada. The surveys focus on the technical features of the reactors and the perspectives of economic feasibility and regulatory schemes. At the same time, the surveys also provide insights on the status of planning, feasibility studies, and international cooperation and agreements related to the deployment of SMRs in other countries such as Indonesia, the Philippines, Poland, the Czech Republic, Estonia, Finland, Jordan, and Kenya.

2) Summary of SMR adoption in the international context

Besides the information on the status in each country, it is important to understand what is being discussed by experts in the international context. As many countries are interested in SMRs today, they are often mentioned in international conferences and reports. Therefore, the Institute of Energy Economics, Japan (IEEJ) follows and summarises these discussions. This can help to gain additional information that cannot be found by a literature survey. During the period of this research project, the COVID-19 pandemic has become serious around the world. Therefore, the IEEJ has virtually participated in international conferences, with webinars held on 2, 9, 16, 23, and 30 June via Zoom meetings.

An expert on the global nuclear energy market writes her view on SMRs for this research project, which is cited after the summary of the webinars and reports.

Chapter 2

Safety and Economics of Small Modular Reactors

1. What Are Small Modular Reactors?

Small modular reactors (SMRs) are expected to offer a lower initial capital investment, greater scalability, and siting flexibility for locations unable to accommodate more traditional large-scale reactors. These expectations are not new, since they have been repeatedly researched, developed, and proposed in various international conferences and academic reports over several decades (e.g. International Atomic Energy Agency, 1996). SMRs also have the potential for enhanced safety and security compared to earlier designs. The deployment of advanced SMRs can help drive economic growth.

The US Department of Energy (DOE) describes SMRs as follows: 'Advanced Small Modular Reactors (SMRs) are a key part of the Department's goal to develop safe, clean, and affordable nuclear power options. The advanced SMRs currently under development in the United States represent a variety of sizes, technology options, capabilities, and deployment scenarios. These advanced reactors, envisioned to vary in size from tens of megawatts up to hundreds of megawatts, can be used for power generation, process heat, desalination, or other industrial uses. SMR designs may employ light water as a coolant or other non-light water coolants such as gas, liquid metal, or molten salt. Advanced SMRs offer many advantages, such as relatively small physical footprints, reduced capital investment, the ability to be sited in locations not possible for larger nuclear plants, and provisions for incremental power additions. SMRs also offer distinct safeguards, security and non-proliferation advantages.' (DOE, n.d.)

Even SMRs are not perfectly safe, as none of the nuclear reactor concepts are 100% free from the possibility of accidents. One of the major issues concerning the safety of SMRs compared to large-scale light water reactors is 'inherent safety'. SMR vendors often state that SMRs have an 'inherent safety' feature; however, it depends. First of all, the technical term 'inherent safety' should be strictly defined before discussing the inherent safety.

2. Inherent Safety

It can be said that 'inherent safety' means that the possibility of danger itself has been eliminated. There are two possible approaches to realising this concept in nuclear power:

(a) Even if a core meltdown occurs and the radioactive materials inside the reactor diffuse outdoors, radiation is generated only to the extent that it does not affect health at all.

(b) Although there is a considerable amount of radioactive material, the core does not melt down, or even if it does, the radioactive material remains in the containment vessel and does not diffuse into the environment. This is called 'practically eliminated' (PE), short for 'the possibility of the radioactivity release could be practically eliminated'.

More detailed explanations of the two approaches are given below.

(a) Control the output

If the output of the core is small, i.e. the amount of radioactive material contained within is small, the amount of radioactive material released during an accident would be extremely limited, and the probability of endangering the health of people outside the site would be extremely low. For example, an experimental reactor with a thermal output of a few kilowatts that is far enough from the site boundary could meet such a condition.

However, how far the output should be reduced to achieve PE or effectively negate the possibility of a large release of radioactive material depends on the characteristics of the core and the design concept of the safety equipment, and it is not clearly determined at present. In other words, just because the amount of radioactive material contained in a nuclear reactor system is small, it does not necessarily mean that the risk of radioactive material release is reduced in proportion to the amount. It is still under debate amongst experts as to what kind of core characteristics and safety designs can be considered as PE.

(b) Eliminate meltdowns

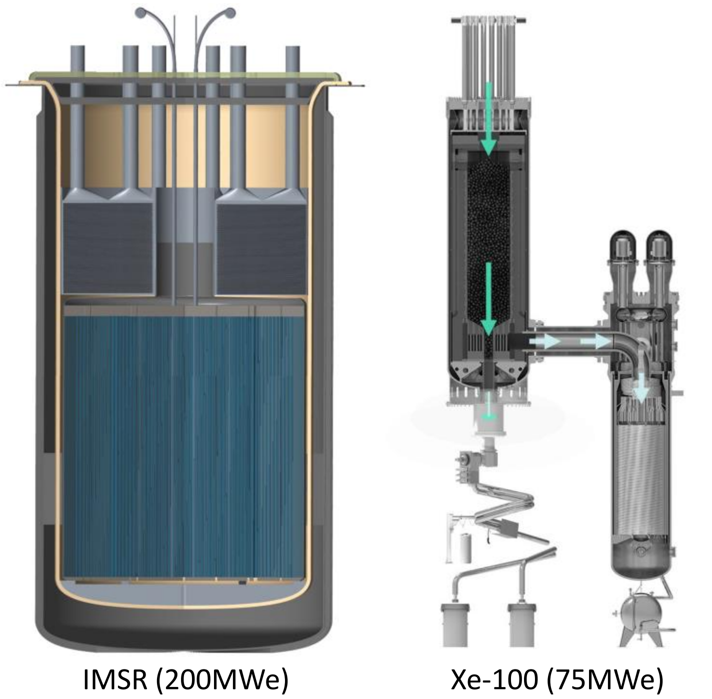
The reactor accidents that have occurred so far can be roughly divided into two categories: reactivity accidents and loss-of-coolant accidents.

Reactivity accidents

The reactors currently in operation run continuously for more than a year, during which no fuel is supplied. The fuel in the reactor is gradually depleted by nuclear fission. Fission becomes critical and continues when there is a certain amount of neutrons, but since the neutrons are generated by the fission of the fuel, the amount of neutrons decreases when the fuel is depleted, and criticality cannot be maintained, which makes continuous operation impossible. To avoid this, a larger amount of fuel is loaded, which generates more neutrons, and the amount of neutrons above criticality is absorbed by burnable poisons, control rods, and boron in water, and the amount of these absorbers is reduced as the amount of the fuel decreases. In the case of control rods, the amount of absorption is adjusted by extracting from the core the rods that have been inserted into it. A reactivity accident is a situation in which such a control device that absorbs neutrons malfunctions or is accidentally removed for some reason, causing a sharp increase in the nuclear reaction, leading to an output surge and sometimes a runaway reaction. Some SMRs, however, are not confined to the existing light water reactor (LWR) concept of 'no fuel supply during operation', but have the concept that fuel supply during operation is possible. Since such reactors are not overloaded with fuel, there is no possibility of a reactivity accident even if there is a failure in the control devices.

For example, Terrestrial's Integral Molten Salt Reactor (IMSR) is a molten salt reactor that can continue operating by adjusting the concentration of liquid nuclear fuel. The IMSR has completed the assessment of compliance with regulatory requirements (Phase 1) of the Canadian Nuclear Safety Commission's (CNSC) pre-licensing vendor design review (VDR) and is continuing with the assessment for any potential fundamental barriers to licensing (Phase 2) starting in 2018. In addition, X-energy's Xe-100 is a pebble-bed high-temperature gas-cooled reactor (HTGR), which is based on the concept of supplying spherical nuclear fuel, called tristructural isotropic (TRISO), during operation. The VDR of the CNSC for this reactor also started in 2020. Figure 2.1 shows the design concept for the IMSR and Xe-100.

Figure 2.1. Design of the Integral Molten Salt Reactor and Xe-100



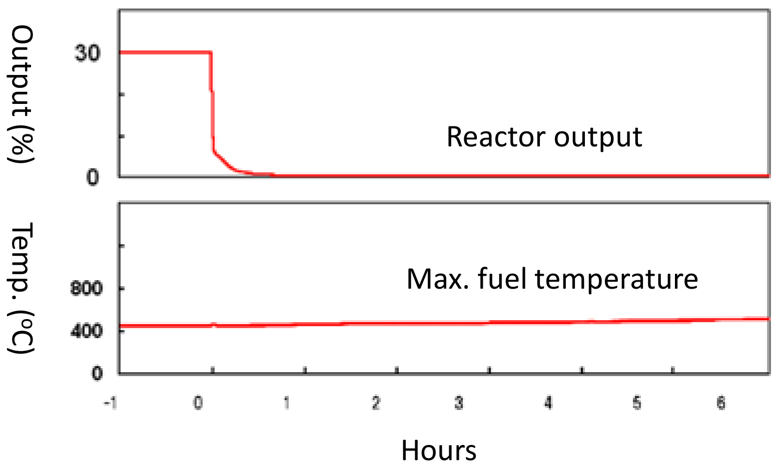
Source: Terrestrial Energy website (https://www.terrestrialenergy.com/technology/molten-salt-reactor) and the X-energy website (https://x-energy.com/reactors/xe-100), accessed 5 April 2021.

Loss-of-coolant accidents

In nuclear power generation, the fuel continues to emit heat, due mainly to fission during operation and the decay heat of radioactive materials generated after fission during shutdown. To remove this heat, the cooling system is always working during both operation and shutdown. If for some reason cooling is not possible, the fuel temperature will continue to rise, and eventually the core will melt, and the radioactive materials locked in the materials and components that make up the fuel will leach out. The high-temperature core raises the temperature of the surroundings. The surrounding materials begin to change into gas, which further expands, causing the pressure inside the containment vessel to build up. If the pressure in the containment vessel exceeds the strength limit, radioactive materials will be released. For this reason, not only the cooling system but also multiple devices to suppress the pressure increase are installed.

One way to prevent such accidents is to use natural convection, i.e. cooling that does not rely on mechanical devices. One example is the High Temperature Engineering Test Reactor (HTTR) (30 megawatts thermal (MWth)) in Japan, where even at 30% power with zero coolant flow, the reactor shuts DON automatically without the insertion of control rods, and heat can be removed without mechanical means by radiation and natural convection to the water-cooled cooling panels outside the reactor. Figure 2.2 shows the results of the zero-coolant test.

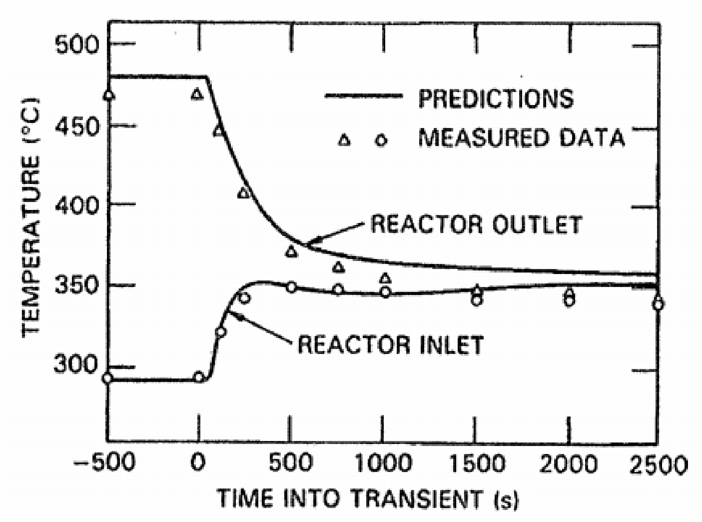
Figure 2.2. Test Results of the High Temperature Engineering Test Reactor



Source: JAEA website (https://httr.jaea.go.jp/S/safe.html), accessed 5 April 2021, translated from Japanese.

The US metal-fuelled fast reactor, the Experimental Breeder Reactor-II (EBR-II, 19 megawatts electrical (MWe)), shows similar results to the above when the coolant flow is set to zero. In addition, it is emphasised that even when the cooling source for the coolant itself is disconnected, the reactor shuts down automatically with the coolant temperature constant at a certain level and the fuel is not damaged. Aurora (4 MWth) by Oklo, which applied for a Combined Construction and Operating License (COL) in 2020, has the same characteristics as the EBR-II.

Figure 2.3. Test Results of the EBR-II



Source: OKLO (2016).

3.Features of Small Modular Reactors

A document published by the International Atomic Energy Agency, *Advances in Small Modular Reactor Technology Developments*, was issued in 2020 and lists 72 designs of SMRs (IAEA, 2020). These can be grouped into four reactor types with different coolants and core structures as shown in Table 2.1. In addition, some of them are already in operation, some are under review by regulatory agencies, and some are not. Typical examples are as follows:

Existing reactors: KLT-40S (Russia), HTTR (Japan)

Pre-reviewed by the US Nuclear Regulatory Commission (NRC): 4S (Japan), eVinci (US)

Under review by the US NRC: Nuscale (US), Aurora (US)

Phase 2 of the VDR by the CNSC, Canada, or in preparation for it: BWRX-300 (Japan), Xe-100 (US), IMSR (US), SSR-W (US)

Table 2.1. Classification of SMR Designs Mentioned in IAEA (2020)

Reactor Type	Number of Designs Listed	Representative Products
Light water reactor	Land-based: 25 Offshore: 6	NuScale, GE Hitachi BWRX-300, Russia KLT-40S
High-temperature gas-cooled reactor	SMR: 14 MR: 2	X-energy Xe-100, Japan High Temperature Engineering Test Reactor
Fast reactor	SMR: 11 MR: 1	Toshiba 4S, Oklo Aurora
Molten salt reactor	SMR: 10 MR: 1	Terrestrial Integral Molten Salt Reactor, Moltex SSR-W
Others	MR: 2	Westinghouse eVinci

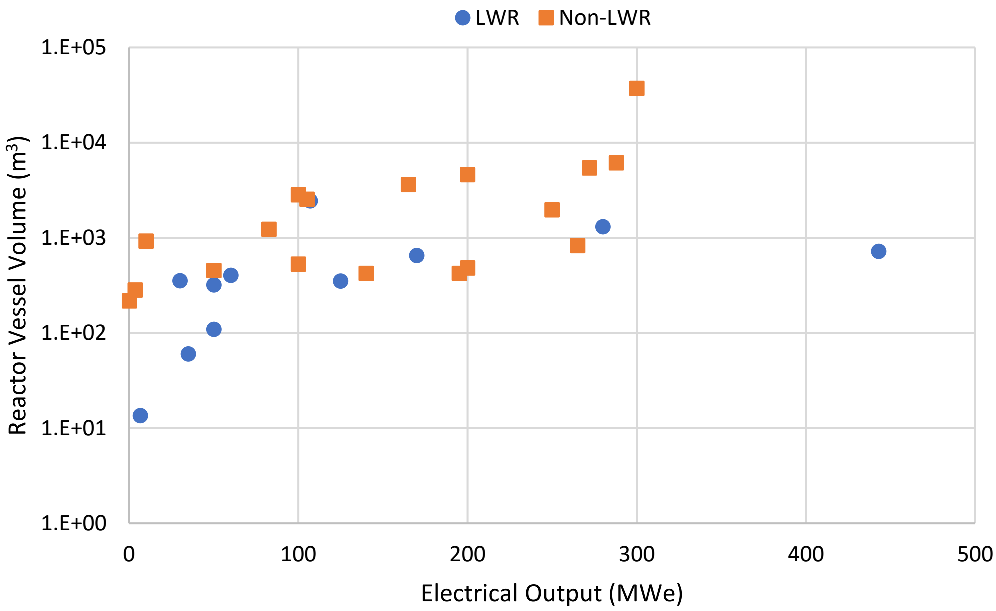
MR = microreactor, SMR = small modular reactor.
Source: IAEA (2020).

Challenges for economies of scale

The IAEA (2020) lists the specifications for a total of 35 SMRs, including eight land-based LWRs, four offshore LWRs, six HTGRs, five liquid metal cooled fast reactors, seven molten salt reactors, and five microreactors. For these 35 SMRs, this research investigated the relationship between the volume of each reactor vessel, which approximates to a cylinder, calculated from the diameter and height and the electric power output (Figure 2.4). It was found that the average reactor vessel volume per unit power output was about 3.05 m^3/MW for the LWRs (12 units), whilst it was about 25.86 m^3/MW for the non-LWR SMRs (23 units). The difference is almost one order of magnitude. The standard volume per unit power output of the third-generation large LWRs is 0.5‐0.7 m^3/MW, so the volume per generation capacity of SMRs, even LWRs, tends to be larger.

Non-LWR SMRs have larger reactor vessels for technical reasons, i.e. the use of graphite as a moderator in the case of HTGRs, and the need for structural materials to prevent chemically active molten salts and liquid metals from coming into contact with air and water in the case of molten salt reactors. A larger reactor vessel has a negative impact on cost, not just because it is harder and more costly to manufacture but also because it is more likely to face transportation constraints. The challenge for the development of non-LWR SMRs will be how to limit the increase in the size of the reactor vessels, which would otherwise offset the advantages of small-size reactors.

Figure 2.4. Electric Power Output and Reactor Vessel Sizes of SMR Designs Mentioned in IAEA (2020)



LWR = light water reactor.
Source: IAEA (2020).

Challenges for modularity of construction

Amongst the equipment of existing LWRs, the typical large-sized items that are manufactured in factories and transported rather than assembled on site are reactor vessels of boiling water reactors (BWRs) and steam generators of pressurised water reactors (PWRs) (the reactor pressure vessels (RPVs) of PWRs are smaller than steam generators). Therefore, the size of NuScale's integrated containment vessel (CV), which is considered transportable, as well as the size of the BWR reactor vessel and the PWR steam generator, will be a guideline for determining whether modularisation, or factory production, will be possible:

- Example of BWR reactor vessel size: diameter 7.1 m, height 21 m
- Example of PWR steam generator size: diameter 4.1 m, height 21 m

(Example of RPV: diameter 4.4 m, height 12.9 m)

The list of SMR specifications by the IAEA (2020) mentioned previously shows the height and diameter of the reactor vessel of each reactor type. The maximum height is about 30 m, and the diameter is generally within 8 m, except for the Russian BREST-OD-300, which is outstandingly large at about 26 m. Therefore, the reactor vessels of SMRs can be about the same in size as the reactor vessel and steam generator of a large LWR. Therefore, it is unlikely that size will be a technical obstacle to modularisation.

Meanwhile, the largest equipment in an NPP is the containment vessel. Containment vessels are generally much larger than reactor vessels. With a diameter of more than 10 m and a height of more than 30 m, they cannot be transported by ordinary means, such as by trucks on public roads. Although a containment vessel is important equipment for preventing the release of radioactive materials in the event of an accident, it is possible to have a design concept without a containment vessel if the NPP has other equipment that has equivalent functions or safety characteristics. The presence or absence of a containment vessel is another guideline for determining whether modularisation can be achieved.

4.Brief Summary

In this chapter, the research focused on some of the technological issues of SMRs, such as inherent safety, economies of scale, and modularity. As IAEA (2020) shows, there are various designs for SMRs. Many SMR vendors are making efforts to improve the safety, economic efficiency, and modularity of their products. The approaches for improvement are not the same amongst vendors, and the optimal solution for a potential customer could be different from another because of differences in demand and other conditions. Therefore, it is important for customers to make clear their own requirements and to conduct feasibility studies as early as possible. This gives vendors the opportunity to make attractive propositions for their customers.

Chapter 3

Status of Small Modular Reactor Development and Deployment in the World

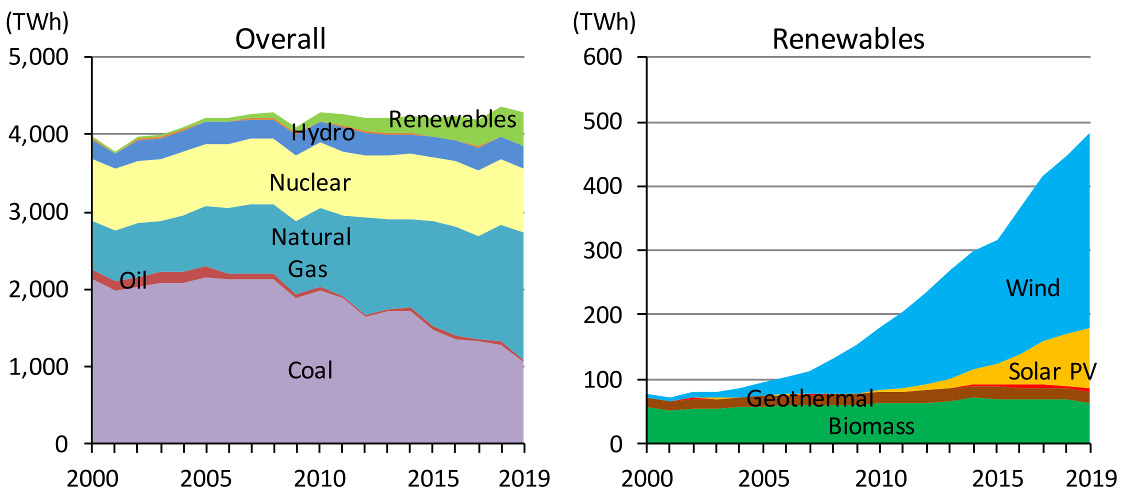
This chapter discusses nuclear energy policy and the status of small modular reactor (SMR) development in the leading countries in Europe and North America and several emerging economies in Asia and Africa, etc. The leading countries mentioned in this chapter are selected because of the efforts carried out by their governments and vendors to develop and deploy SMR technology. The emerging economies are selected based on their recent activities related to SMR feasibility studies.

1.SMR Development in the World

1.1. United States

(1) Nuclear energy policy

Figure 3.1. Electricity Generation by Source in the United States



PV = photovoltaics, TWh = terawatt hour.
Source: IEA (2020).

In the United States (US), nuclear energy provided about 19% of total electricity generation in 2019, which was the largest share amongst clean energy sources (Figure 3.1). Nuclear energy has been a reliable low-carbon energy source and has supported the country's energy security for more than 60 years. Therefore, the Department of Energy (DOE) of the Federal Government has promoted nuclear energy to meet the needs for energy supply, environmental protection, and energy security. The US electricity market is liberalised in many states today, and nuclear power generation is facing difficulties in its competitiveness and economic profitability because of the extremely low generation costs of natural gas and renewable energy (solar photovoltaics (PV) and wind). For this reason, some of the nuclear power plants (NPPs) have been closed before the expiration of their operating licence. However, the DOE has not changed its fundamental view that nuclear energy is important as a reliable low-carbon energy. It is trying to reinforce the competitiveness of nuclear energy by focusing on the development of advanced nuclear technologies. SMRs might be one of the most promising technologies amongst them. Compared to other advanced countries, there is a small number of large-scale electric power utilities in the US. For medium- or small-scale utilities that do not have enough budget to build a large-scale (around 1 GW) reactor, some of the features of SMRs would be very attractive because the total investment costs are relatively smaller than those of large-scale reactors (the total investment cost is calculated from the unit cost (US$/MW) multiplied by installed capacity (MW), and generally speaking, the total installed capacity of SMRs would be much smaller than 1 GW). The short construction time means they can soon begin power generation and collect their investment.

(2) SMR development

(a) Support for SMR research and development by the DOE

As mentioned above, the development of SMRs and other advanced reactors is an important objective for the US Federal Government. Formerly, the DOE provided the SMR Licensing Technical Support (LTS) programme to support advanced reactor development, but this has already ended. After the LTS programme, the DOE established a funding opportunity, Gateway for Accelerated Innovation in Nuclear (GAIN), for the promotion of advanced reactor development, in November 2015.

It can be said that GAIN is a form of public-private partnership. The main objective of the GAIN programme is to provide private companies with access to national research facilities, financial support, and regulatory process support. Therefore, selected companies can use experimental and testing facilities, modelling and simulation tools, important data, sample materials, and the sites of state-of-the-art national laboratories of the US. The DOE and the GAIN programme also give private companies instructions on the safety regulation of the Nuclear Regulatory Commission (NRC) so that the applicants can properly understand the regulatory process.

In addition to the GAIN programme, the DOE launched the Advanced Reactor Demonstration Program (ARDP) in May 2020 in accordance with the recommendations of the Nuclear Fuel Working Group, which was established by the Federal Government to restore US leadership in the global nuclear energy market (DOE, 2020). The ARDP identifies three pathways for support funding:

- Advanced reactor demonstrations, which are expected to result in a fully functional, advanced nuclear reactor within 7 years of the award.
- Risk reduction for future demonstrations, which will support up to five additional teams resolving technical, operational, and regulatory challenges to prepare for future demonstration opportunities.
- Advanced Reactor Concepts 2020, which will support innovative and diverse designs with the potential to commercialise in the mid-2030s.

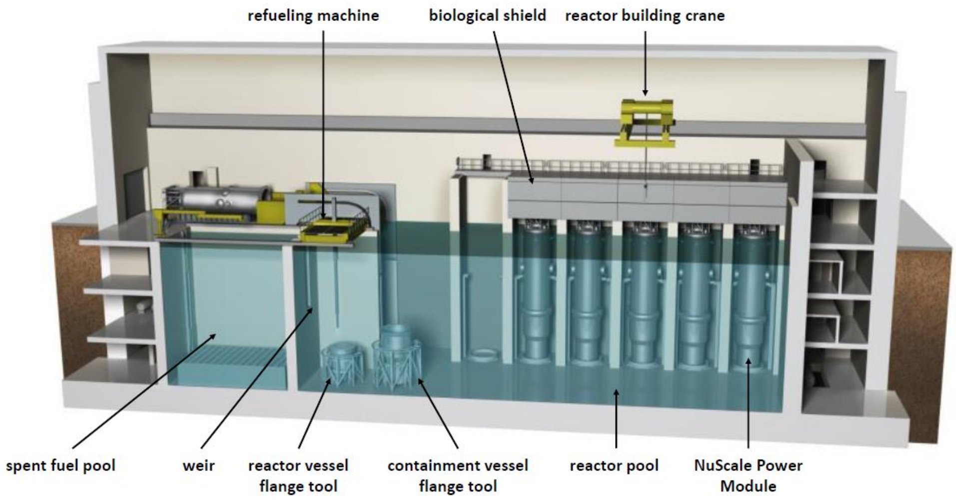
The DOE has already announced that the Natrium reactor (a sodium-cooled fast reactor) developed by TerraPower and GE-Hitachi and Xe-100 (a high temperature gas-cooled reactor) developed by X-energy were awarded US$80 million each under the ARDP scheme.

The DOE also promotes the research and development (R&D) of nuclear fuel for advanced reactors. The DOE aims to provide high-assay low-enriched uranium (HALEU) to private vendors. HALEU could be used in some advanced non-light water reactors (LWRs) that would be adopted by SMR vendors. In January 2019, the DOE announced the result of an environmental assessment which said that using DOE-owned HALEU stored at the Idaho National Laboratory (INL) will not result in a significant impact on the environment. Since this DOE-owned HALEU was produced from used fuel from the Experimental Breeder Reactor-II (EBR-II) which was already shut down in 1994, the amount is limited. On the other hand, in November 2019, the DOE signed with Centrus Energy, a nuclear fuel and services supplier, a three-year contract to deploy a cascade of centrifuges to demonstrate the production of HALEU fuel. Urenco USA, a supplier of uranium enrichment services and nuclear fuel cycle products, has also announced that they are exploring the construction of a dedicated HALEU production unit at their facility.

(b) NuScale SMR project

NuScale Power is one of the most famous reactor vendors engaged in SMR design development in the US. NuScale's SMR (Figure 3.2) consists of 60 MW power modules and adopts conventional light-water reactor technology, but it provides many advanced features, such as stability, small land usage, incremental power to match load growth, integration with renewable energy, and reduced capital costs and Levelised Cost of Electricity (LCOE) compared to large NPP and multiple commercial applications so it can decarbonise more than just electricity production.

Figure 3.2. Reactor Building Design of the NuScale SMR



Source: Reyes and Hopkins (2018).

NuScale Power is conducting a construction project for its SMR at a site at the Idaho National Laboratory (INL). It is planned to begin operation of the first module by 2029. This SMR plant consists of 12 reactor modules of 60 MW, and the total generation capacity will be 720 MW. Utah

Associated Municipal Power Systems (UAMPS), an electric power utility in the state of Utah, is the owner of the reactors. The generated electricity in the INL will be transmitted to Utah, and one of the NuScale reactor modules will provide electricity to meet the energy demand of the INL according to the agreement between UAMPS and Battel Energy Alliance, the manager of the INL. The DOE also provides a lot of funding support for NuScale. In 2013, through the LTS programme, the DOE awarded US$226 million to their five-year SMR project. In addition, in 2018, after the LTS programme, the DOE provided US$40 million in cost-sharing financial assistance for NuScale.

In December 2016, NuScale Power submitted a design certification application (DCA) to the NRC, which was the first DCA for an SMR. The DCA review by the NRC consists of six phases, and the fourth phase (advanced safety evaluation report) was completed in December 2019. NuScale Power is taking action not only in the US but has also submitted an application for a pre-licensing vendor design review by the Canadian Nuclear Safety Commission (CNSC).

(c) Other activities related to SMRs

In the US, not only the government but also lawmakers are making efforts to promote the development and deployment of advanced reactors, including SMRs. Table 3.1 shows the legislation, including bills enacted or introduced in Congress, in recent years. It is remarkable that these bills are introduced and supported by bipartisan members of Congress.

Table 3.1. Advanced Nuclear Energy Legislation in the United States

Title	Status	Main Objectives
Nuclear Energy Innovation Capabilities Act (NEICA)	Enacted in September 2018	•Provide DOE-owned sites and facilities to public parties •Cost-share grants for applicants for licences of the Nuclear Regulatory Commission (NRC)
Nuclear Energy Innovation and Modernization Act (NEIMA)	Enacted in January 2019	•Improve the predictability of NRC review for advanced reactors •Secure enough budget for the NRC to conduct new activities
[Bill] Nuclear Energy	Introduced in	•At least two demonstration projects led

Leadership Act (NELA)	Senate in March 2019 Introduced in House in June 2019	by the DOE of advanced reactors by 2025 •Additional 2–5 projects by 2035 •Establish HALEU transportation programme
[Bill] Integrated Energy Systems Act	Introduced in Senate in October 2019 Introduced in Senate in June 2020	•Establishment of DOE-led research and development programme that focuses on the integration of nuclear energy with other energy sources
[Bill] American Nuclear Infrastructure Act (ANIA)	Introduced in Senate in November 2020	•Prize for advanced nuclear reactor licensing •Credit allocation to certified reactors

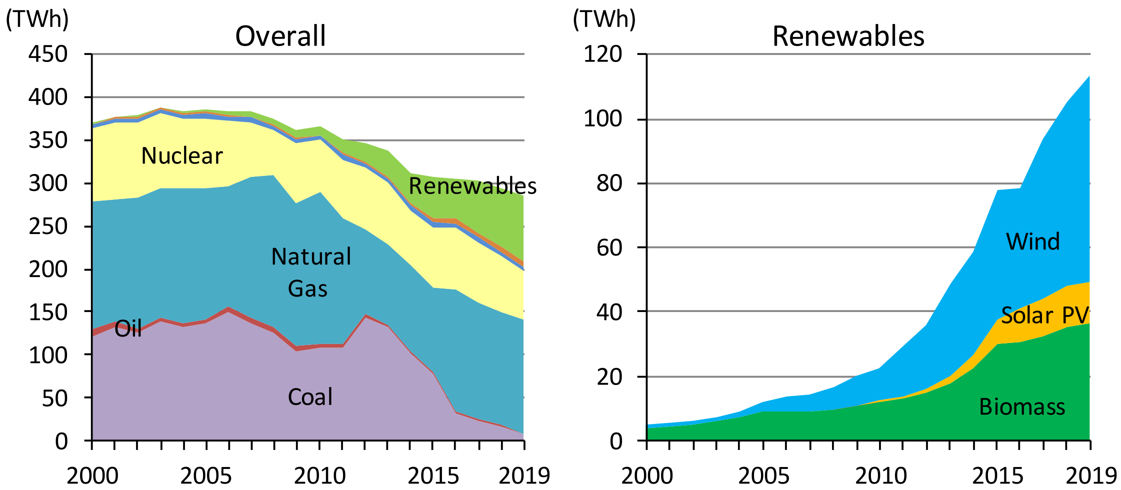
DOE = Department of Energy, HALEU = high-assay low-enriched uranium.
Note: NELA has not been passed in Congress but was partially adopted in the Consolidated Appropriations Act, 2021.
Source: Authors.

The attitude of the regulatory authority is also important for deploying advanced nuclear technology. In the US, the activities of the regulatory authority, the NRC, are supervised by Congress. As shown in Table 3.1, the NRC requires reforms so that it can cope with licensing new technologies. Therefore, the NRC has adopted a flexible and staged review process in which the NRC and applicants can intensively discuss and identify issues. The NRC is also making efforts for international cooperation. In August 2019, the NRC and CNSC signed a memorandum of cooperation that allows the two regulators to conduct common technical reviews on SMR and other advanced reactors. This will help the harmonisation of SMR regulation and encourage vendors to take action in the two countries because if they complete a review process in one country, they can easily expand their reactor to the other country.

1.2. United Kingdom

(1) Nuclear energy policy

Figure 3.3. Electricity Generation by Source in the United Kingdom



PV = photovoltaics, TWh = terawatt hour.
Source: IEA (2020).

In the United Kingdom (UK), nuclear provided 18% of total electricity generation in 2019 (Figure 3.3). The former Department of Energy and Climate Change (DECC) declared the basic nuclear energy policy of the UK government. The DECC (2013) said that nuclear energy has an important role to play in delivering its long-term objectives for a future with secure, low-carbon, and affordable energy. This attitude towards nuclear energy has not changed until today. The current government led by the Conservative Party emphasises the role of nuclear energy, and the Labour Party also insists on the need for nuclear energy.

This attitude is reflected in the contract for difference (CfD) policy scheme, one of the strategies of the Electricity Market Reform of 2011. It targets low-carbon electricity, including not only renewable energy but also nuclear energy. After introducing this mechanism, the first project for building a new NPP was Hinkley Point C. However, the National Audit Office (2017) criticised the Department for Business, Energy and Industrial Strategy (BEIS) for not sufficiently considering the costs and risks of the Hinkley Point C deal for consumers and for not assessing the potential value-for-money implications for bill-payers using alternative financing models. The BEIS then tried to introduce a new financing mechanism, the regulated asset base (RAB) model. This differs from the CfD in that it allows revenue that is not fixed but that is revised regularly and allows generators to receive revenue even before construction. The BEIS accepted a public consultation on the RAB model in 2019 and published its outcome in December 2020. Following the outcome, the BEIS (2020) said that RAB model with the high-level design principles remains a credible model for large-scale nuclear projects.

To resolve the expensive cost of building new NPPs, another policy was also launched. In 2018, the UK government published the Nuclear Sector Deal, which said that the government and industry need to make partnerships to reinforce the competitiveness of the nuclear industry of the UK. It includes a vision to reduce the costs of new construction projects by 30% up to 2030 and, thereafter, reduce them further if possible. The report mentioned that achieving this will depend on joint action on several fronts, including financing models and steps to address the main drivers of construction costs. Accordingly working groups under the Nuclear Industry Council (NIC) and the government have continued to seek cooperation between the government and industry.

(2) SMR development

The UK government's vision to develop SMRs and other advanced reactors has already been seen in the long-term strategy issued by the Department for Business, Innovation and Skills (BIS, 2013).

In 2014, the National Nuclear Laboratory (NNL, 2014) published a report on its SMR feasibility study that estimated the market potential of SMRs. According to the study, there is a very significant market for SMRs, and they fulfil a market need that cannot be met by large nuclear plants. The size of the potential SMR market is calculated to be approximately 65–85 GW by 2035, valued at £250 billion–£400 billion. In a regional assessment, the study also says that there could be a UK market for around 7 GW of power from SMRs by 2035, based on the demand for low-carbon generation and the site availability for small nuclear reactors (less than 300 MW). The study also conducts a technical assessment of some SMR designs. Their key criterion for suitability is the potential for deployment within a 10-year timescale, and they identify four reactors as promising designs that would meet both the technical and financial requirements: ACP100+ (China National Nuclear Corporation), mPower (B&W and Bechtel), Westinghouse SMR, and NuScale SMR. The NNL also shortlists two other designs by AREVA and Urenco, but they conclude that these designs should be considered in a longer timeframe.

In July 2016, the DECC and BIS were merged into the Department for Business, Energy and Industrial Strategy (BEIS). In November 2016, BEIS, advised by the Nuclear Innovation and Research Advisory Board and the Nuclear Innovation and Research Office, launched the Nuclear Innovation Programme (NIP) as a part of its Energy Innovation Programme (EIP). The EIP aims to accelerate the commercialisation of innovative clean energy technologies in the 2020s and 2030s and provides a budget of £505 million for 2015–2021, of which the BEIS allocates £180 million to nuclear innovation. The NIP provides funds for various kinds of projects, such as new-generation reactor design, advanced nuclear fuel development, fuel recycling, and technology development in advanced manufacturing and materials.

As for small-scale reactors, the BEIS focuses on advanced modular reactors (AMR) that adopt Generation IV (non-LWR) reactor technology. To this end, the BEIS announced its AMR Feasibility and Development (F&D) Project. This project consists of two phases:

Phase 1: Funding (up to £4 million) to undertake a series of feasibility studies for AMR designs. Contracts are worth up to £300,000.

Phase 2: Subject to phase 1 demonstrating clear value for money and government approval, a share of up to £40 million could be available for selected projects from phase 1 to undertake development activities. Up to a further £5 million may also be made available to regulators to support this.

BEIS revealed in September 2018 that eight companies had been awarded contracts to produce feasibility studies as part of phase 1 of the project. In July 2020, three of them were selected as successful projects for phase 2: Tokamak Energy Ltd., Westinghouse Electric Company UK, and U-Battery Developments Ltd.

The NIP also provides the Advanced Manufacturing and Materials Programme. This programme aims to reduce the capital costs and risks of advanced reactors by offering a number of benefits, including off-site fabrication which is one of the important features of SMRs. In July 2020, BEIS disclosed 11 successful projects for phase 2 (2A and 2B). Phase 2 aims to progress technologies, including those established in phase 1, towards demonstration and commercialisation.

It can be said that one of the most famous UK-based SMR vendors is the consortium led by Rolls-

Royce. They are developing a pressurised water reactor (PWR)-based design. Rolls-Royce has told the BBC that they plan to install and operate their first reactor by 2029 (BBC News, 2020).

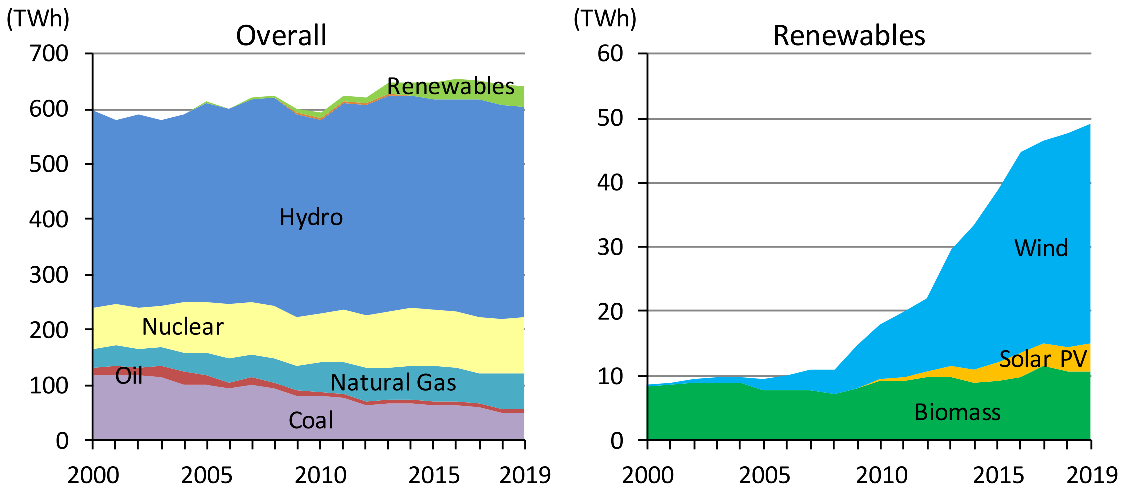
In the UK, the Office for Nuclear Regulation (ONR) and Environment Agency (EA) are responsible for nuclear safety review and licensing. The UK's regulatory scheme provides generic design assessment (GDA) in which the regulators get involved with reactor vendors and review the safety of their reactor designs at the earliest stage. As the GDA enables vendors to find any issues at an early stage, it can be said that the UK's regulatory scheme is basically favourable for new reactor vendors. The UK is also trying to improve regulatory systems so that they can deal with licensing for new types of reactors.

In October 2017, the UK government announced that it would invest up to £7 million (£5 million to the ONR and £2 million to the EA) to further develop the capability and capacity of the nuclear regulators to support and regulate the development of advanced nuclear technologies.

1.3. Canada

(1) Nuclear energy policy

Figure 3.4. Electricity Generation by Source in Canada



PV = photovoltaics, TWh = terawatt hour.
Source: IEA (2020).

In Canada, nuclear energy provided about 15% of total electricity generation in 2019, which was the second-largest amongst all electricity generation sources following hydro power (Figure 3.4).

There are four active nuclear power stations in operation, with 19 operating nuclear reactors.

The Government of Canada views nuclear energy as an important component of a diversified energy mix and a sustainable energy to meet current and future demand. Recently it has made a great deal of investment in SMRs, as the Minister of Innovation, Science and Industry said in October 2020, 'by helping to bring these small reactors to market, we are supporting significant environmental and economic benefits, including generating energy with reduced emissions, highly skilled job creation and Canadian intellectual property development'. (Government of Canada, 2020b)

The government has taken necessary measures to ensure the long-term development of nuclear energy, especially in R&D. Consequently, Canada is amongst the pioneers of nuclear power development with research efforts dating back to the 1940s and the establishment of Atomic Energy of Canada Ltd. (AECL) as a Crown corporation in 1952. AECL's National Research Universal reactor, built in 1957, is one of the oldest research reactors in the world and the most important source for medical radioisotopes for medical diagnosis and cancer therapy. Canada normally supplies approximately 75% of the world's supply of Cobalt-60 used to sterilise 45% of the world's single-use medical supplies. Additionally, Canada has exported AECL's nuclear power reactors, the heavy water-cooled and moderated pressurised-water reactors known as the Canadian Deuterium Uranium (CANDU) reactor.

Whilst the federal government has important responsibilities relating to nuclear energy, the decision to invest in electric generation rests with the provinces. It is up to the provinces, in concert with the relevant provincial energy organisations/power utilities, to determine whether or not new NPPs should be built. Although almost all new nuclear reactor construction plans have been held back recently, there has been a notable development in nuclear energy policy in Ontario, which is the main location of the nuclear energy industry in Canada. In 2015, Ontario decided to approve the refurbishment (lifetime extension) of the four nuclear units at Darlington and the remaining six units at Bruce.

(2) SMR development

In April 2017, the Canadian Nuclear Laboratory (CNL) announced its first long-term plan, which included building a demonstrational SMR at the Chalk River site by 2026. In October of that year, the CNL reported a strong response to a request for expressions of interest on the SMR programme. According to the second report published in October 2017, approximately 80 expressions of interest were submitted, of which 51 were from Canada, 11 from the UK, 9 from the US, and 9 from other countries. It was also reported why they were concerned with SMR development in Canada:

- the higher performance of nuclear technology development in Canada;
- the nuclear regulation policy and system in Canada; and
- the convenience of operation or international procurement, such as the supply chain in Canada.

In April 2018, the actual construction and operation project of the demonstrational SMR was asked about publicly. Until the deadline in June, there were four applications.

There has been another movement in parallel with this request for expressions of interest. In June 2017, the CNL and Terrestrial Energy set out a feasibility study for the siting of the first commercial Integral Molten Salt Reactor (IMSR) at the Chalk River site to identify a suitable location to construct the plant on the basis of the memorandum of understanding (MoU) of the IMSR engineering programme in 2016. For Terrestrial Energy's IMSR, the CNL has conducted its Pre-Licensing Vendor Design Review (VDR) since April 2016. Phase 1 of the Pre-Licensing VDR was already completed in November 2017, and phase 2 is in progress. (Details of the Pre-Licensing VDR are explained below.)

In addition, there has been a movement to promote discussions on SMRs all over the country. In 2018, the SMR Roadmap was issued in Canada to foster innovation and establish a long-term vision for the nuclear industry, as well as to assess the characteristics of different SMR technologies and utilities. Such a plan is rarely seen around the world, and is established through dialogues with the federal, provincial, and territorial governments, nuclear industries, utilities, indigenous communities, and local organisations, and so on. This involves extensive engagement with industry and other stakeholders through technical workshops, initial dialogues with indigenous communities and organisations, and expert analysis by five working groups to address the key questions around SMR deployment. The roadmap says that SMR is a small, low-carbon, and low-cost source, which is a key technology for achieving the greenhouse gas emission target (30% reduction below 2005 levels by 2030 and net-zero emissions by 2050). It also declares that Canada takes world leadership for promoting SMR development and confirms the global standard. It also emphasises the importance of strategic partnerships across sectors and countries. It proposes four pillars of action – demonstration and deployment; policy, legislation, and regulation; capacity, engagement, and public confidence; and international partnerships and markets – to guide the future actions needed for various stakeholders.

In December 2020, the SMR Action Plan was revealed to follow up the SMR Roadmap. The action plan summarises the latest status of each stakeholder's actions identified in the roadmap and states that the first units of SMRs should be in operation by the late 2020s.

The Canadian Nuclear Safety Commission (CNSC) stated at the US-Canada Nuclear Energy Leadership Summit in August 2018 that the current regulation was already suitable for regulating SMRs. They have begun discussions on how to regulate SMRs with the IAEA, the US, and the UK, etc. Furthermore, the CNSC has provided a new service, called the Pre-Licensing Vendor Design Review (VDR), for vendors designing new reactors. The details of this review service are below (CNSC, 2018a, 2018b):

a. Overview

It is an optional service provided by the CNSC when vendors request it. The review has three steps, each of which is conducted against related CNSC regulatory documents and Canadian code and standards.

- Phase 1: Pre-Licensing Assessment of Compliance with Regulatory Requirements. The CNSC judges the proposed plan considering updated regulations.
- Phase 2: Pre-Licensing Assessment for Any Potential Fundamental Barriers to Licensing
- Phase 3: Follow-up

b. Current status

As of April 2021, 10 vendors are proceeding with the review process of phase 1 or 2. Two vendors have signed an agreement with the CNSC for the vendor design review. The vendors who are in phase 2 are as follows: Terrestrial Energy (IMSR), Ultra Safe Nuclear Corporation (MMR-5 and MMR-10), Moltex Energy (Molten Salt Reactor), NuScale Power (NuScale PWR), GE-Hitachi (BWRX-300) and X-energy (Xe-100).

c. Benefit for vendors

They can get reliable feedback about compliance with the regulatory requirements early in the design process, which enables them to make future plans and compensate in advance. Additionally, CNSC staff can fully understand the vendor's SMR, which results in making efficient progress for the judgment.

d. Benefit for people in Canada

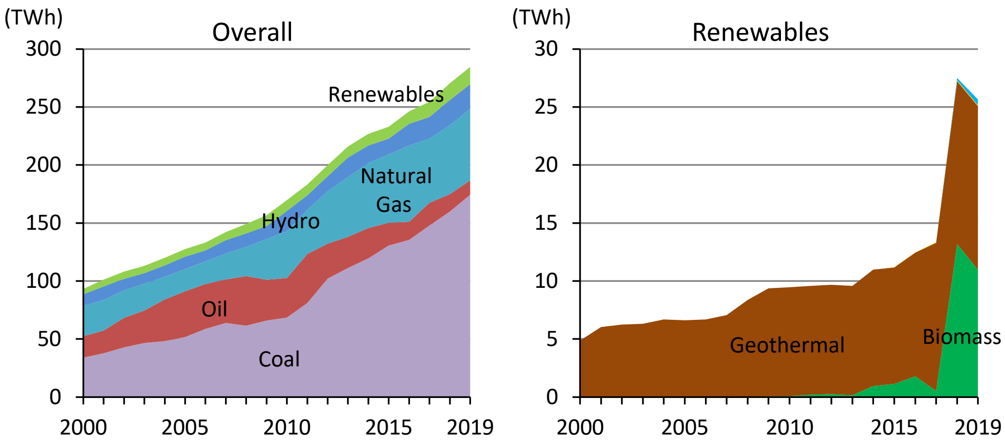
Through VDR, vendors can acknowledge their tasks clearly and make active implementation, which improves cost efficiency and safety.

2. SMR Potential in Developing and Emerging Economies

2.1. Indonesia

(1) Nuclear energy policy

Figure 3.5. Electricity Generation by Source in Indonesia



TWh = terawatt hour.
Source: IEA (2020).

Indonesia has currently no commercial nuclear reactors and most of their electricity supply depends on fossil fuels (Figure 3.5). They have long considered large-scale nuclear power deployment. In February 2014, the Government of Indonesia issued its National Energy Policy, in which nuclear is included as one of the new energy sources. The Directorate General of New Renewable Energy and Energy Conservation (2016) estimated that they would need 5,000 MW of installed nuclear capacity by 2025 to meet their growing energy demand. However, the National Energy General Plan to 2050, which was signed by the president in 2017 (Presidential Regulation No. 22, 2017), does not set a clear target for nuclear power generation capacity and regards nuclear energy as a last resort with strict attention to safety factors.

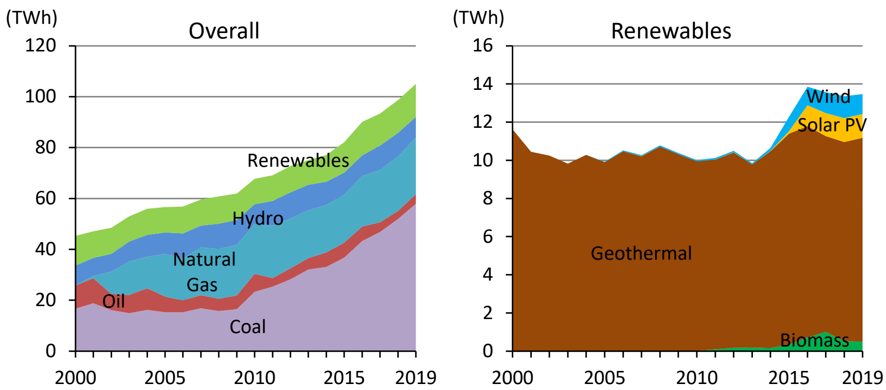
(2) Discussion on SMR development

In March 2018, the National Atomic Energy Agency (BATAN) launched a roadmap for developing a detailed engineering design for an experimental power reactor (Reaktor Daya Eksperimental, RDE), that adopts a high-temperature gas-cooled reactor (HTGR) and 10 MWth capacity. Apart from the experimental reactor, BATAN is also planning to deploy small HTGRs (up to 100 MW) in Kalimantan, Sulawesi, and other islands to supply power and heat for industrial use. A prototype unit is planned for West Kalimantan.

2.2. The Philippines

(1) Nuclear energy policy

Figure 3.6. Electricity Generation by Source in the Philippines



PV = photovoltaics, TWh = terawatt hour.
Source: IEA (2020).

The Philippines currently uses no nuclear power (Figure 3.6). However, in response to the 1973 oil crisis, they decided to build the two-unit Bataan Nuclear Power Plant (BNPP). The construction of Bataan-1 was completed in 1984, but due to financial issues and safety concerns related to earthquakes, the reactor was never loaded with fuel or operated. The government was considering converting it into a natural gas-fired power plant, but this seemed impractical, and the plant has simply been maintained without being operated. In 2010, Korea Electric Power Corporation (KEPCO) submitted a study result that said it would take US$1 billion to rehabilitate the BNPP (*The Manila Times*, 2020).

In 2016, the Department of Energy (DOE) of the Philippines reiterated that nuclear power was a live option, possibly to take over some of coal's base-load role. In March 2017, the DOE said it was exploring the potential of a small reactor in Sulu province, Mindanao, and would produce an overall nuclear programme for the country, including Bataan. The latest Philippine Energy Plan (PEP 2018–2040) includes a chapter on nuclear energy and states that they will be able to start nuclear power generation in 2027 in the earliest case.

(2) Discussion on SMR development

The DOE of the Philippines has discussed SMR technology with the Republic of Korea (henceforth, Korea). In 2019, a site characteristic survey was conducted by experts from Korean Hydro and Nuclear Power in Cagayan Economic Zone Authority. This pre-feasibility study was conducted in accordance with the MoU signed by the DOE and Korean Hydro and Nuclear Power. The final version of the study was turned over in December 2019.

Not only Korea but also Russia cooperates with the Philippines in the field of nuclear technology. The DOE signed an agreement with Rosatom in October 2019 to assess the feasibility of a small NPP, floating or on land, and probably using RITM-200 reactors.

Analysis: Advantages of SMR deployment in island countries

As the US DOE and other governments identify, there are many advantages of SMRs. They are divided into two groups: (1) modular design and (2) characteristics of the reactor.

(1) 'Modular design' includes the low capital investment and siting flexibility of SMRs. The simple design, low construction cost, and short construction period lead to lower capital investment than conventional large-scale reactors. An SMR can be built even on a small site. By adjusting the number of reactor modules, SMRs can meet the needs of a community such as in a remote area or microgrid. The number of reactor modules can be increased if energy demand in the community increases in the future. All these features of SMRs can be an attractive option for small island countries that do not have a huge budget or construction sites; they can begin with a small generating capacity and expand it in parallel with their economic growth. In such areas, however, they generally use diesel generators, etc. Therefore, it is important for SMR vendors to explain the advantages of their products compared with such conventional distributed power sources.

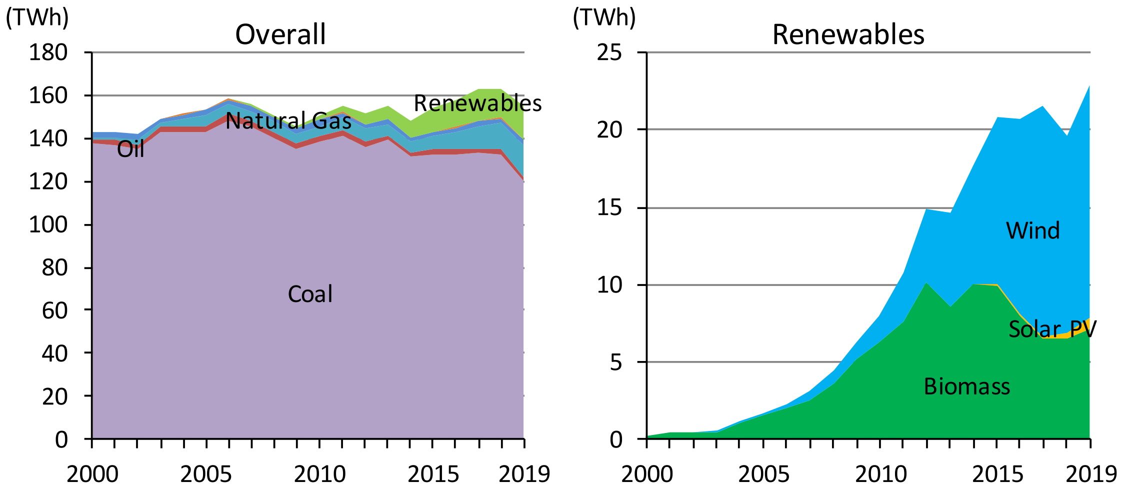
(2) The 'characteristics of the reactor' can bring high efficiency, as well as safety and security. Whilst SMRs can serve as either baseload or flexible power depending on the reactor technology adopted, in any case, they can be coupled with other energy sources to produce higher efficiency and increase grid stability and reliability. This feature of SMRs can become a great advantage, especially when a small island country has deployed huge amounts of variable renewable energy, such as solar PV or wind power generation. At the same time, many designs of SMRs have their own advanced safety features that ensure the safety of an NPP and been improved through the operating experiences of existing reactors. Moreover, some of the advanced reactors can be operated long-term without refuelling. Such designs of reactors will contribute to enhancing the security of fissile materials because they can minimise the amount of spent fuel extracted from the reactors. Long-term operation without refuelling also decreases the frequency of fuel transportation, which requires strict control and guards, which would decrease the burden on the local people.

Decreasing the frequency of refuelling and fuel transportation, however, also decreases the opportunities for related workers to move to a site, which does not have a positive impact on the local economies. It should also be kept in mind that imposing low-risk SMRs with stricter safety requirements than conventional large-scale reactors may mean losing the advantages derived from the modular design, although stricter safety requirements would increase the acceptability amongst the local people.

2.3. Poland

(1) Nuclear energy policy

Figure 3.7. Electricity Generation by Source in Poland



PV = photovoltaics, TWh = terawatt hour.Source: IEA (2020).

Poland currently has no commercial NPPs (Figure 3.7), but according to the Energy Policy of Poland until 2040 (PEP2040) approved by the cabinet in 2021, the Polish government has a plan to deploy the first one by 2033. It is planned to be a capacity of 1.0–1.6 GW, with the next ones launched within 2–3 years, which means that the entire nuclear programme assumes the construction of six units by 2043. PEP2040 also refers to the possibility of the deployment of HTGRs in the future that would be used mainly as a source of technological heat for industry.

Public support for the nuclear programme is high and even growing in Poland. PGE EJ1 (2020) shows that support for the construction of the first NPP in Poland amongst the residents of site communes (Choczewo, Gniewino, and Krokowa) was at 71% in 2019 (up from 69% in 2018).

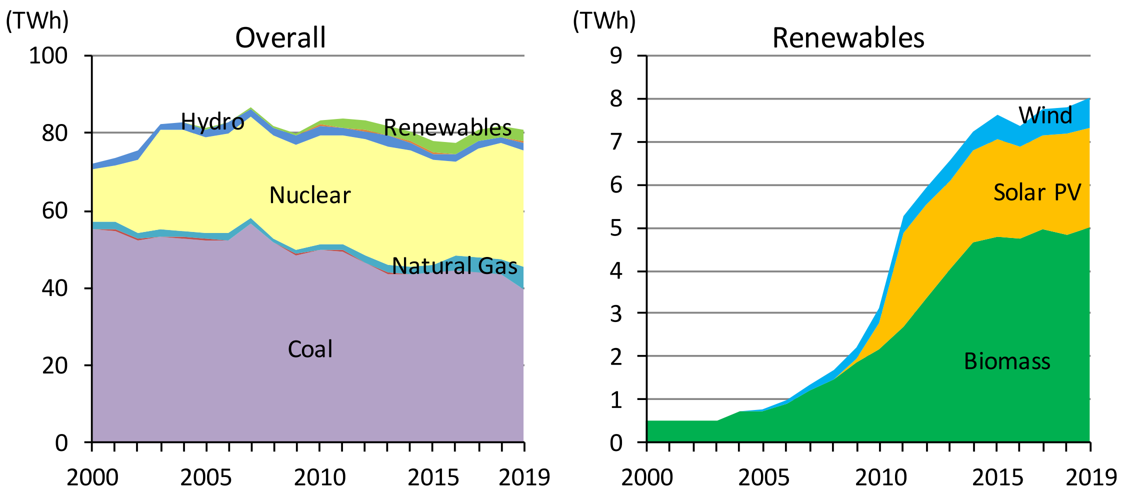
(2) Discussion on SMR development

In October 2019, GE Hitachi Nuclear Energy and Synthos SA, a chemical industry company based in Poland, agreed to collaborate on potential deployment applications for GE Hitachi's BWRX-300 SMR in Poland. Also, in November 2020, Synthos Green Energy, an affiliated company of Synthos SA, signed a cooperation agreement with Ultra Safe Nuclear Corporation to assess the feasibility of the Micro Modular Reactor (MMR) plant design to generate carbon-free hydrogen, heat, and power for use in Synthos Green Energy's chemical plants.

2.4. Czech Republic

(1) Nuclear energy policy

Figure 3.8. Electricity Generation by Source in the Czech Republic



PV = photovoltaics, TWh = terawatt hour.
Source: IEA (2020).

Nuclear energy has a large share today in the generation mix of the Czech Republic (Figure 3.8), and the government is planning to enlarge it. The 'State Energy Policy of the Czech Republic', adopted in 2015, sets the target for nuclear power generation share at 46%–58% by 2040. The policy foresees new reactors at Dukovany, and the government in 2019 gave preliminary approval for ČEZ subsidiary Elektrárna Dukovany II to build at least one new nuclear power unit. The first new reactor envisaged for the site would be of at least 1,200 MWe to replace the four units in operation there that are expected to be permanently shut down between 2035 and 2037.

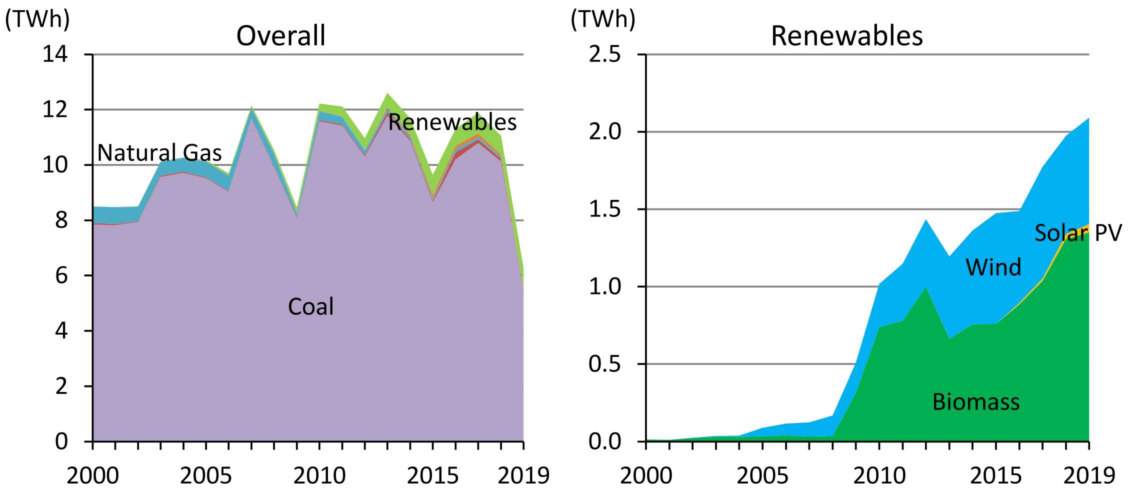
(2) Discussion on SMR development

In September 2019, NuScale Power signed an MoU with ČEZ to explore applications for its SMR in the Czech Republic. In February 2020, GE Hitachi Nuclear Energy and Czech utility ČEZ signed an MoU on examining the economic and technical feasibility of potentially constructing a BWRX-300 in the Czech Republic.

2.5. Estonia

(1) Nuclear energy policy

Figure 3.9. Electricity Generation by Source in Estonia



PV = photovoltaics, TWh = terawatt hour.
Source: IEA (2020).

Estonia has no experience of operating nuclear power generation, and most of their electricity supply depends on coal (Figure 3.9), but recently they have begun considering the option of SMRs, as stated in the next section.

(2) Discussion on SMR development

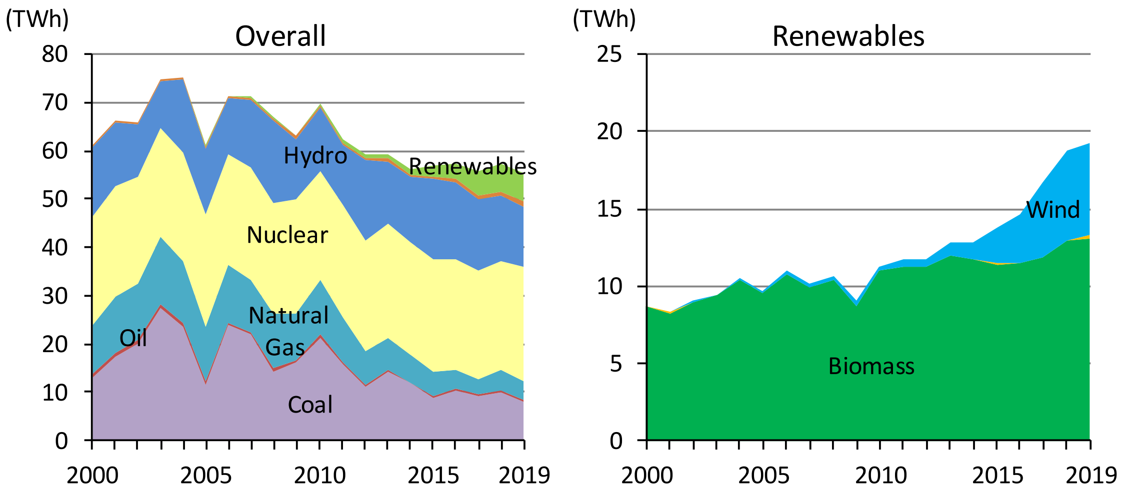
In March 2019, Fermi Energia of Estonia selected Moltex Energy as its preferred technology for its plans to establish carbon-free energy production in the Baltic region. In June 2019, Fermi Energia launched a feasibility study on the suitability of SMRs for Estonia's electricity supply and climate goals beyond 2030, following a financing round of €260,000 (US$290,076) from investors and shareholders. Fermi Energia selected four innovative SMR designs to be included in the feasibility study: Moltex Energy SSR-W300, Terrestrial Energy IMSR-400, GE Hitachi BWRX-300, and NuScale SMR. In October 2019, GE Hitachi Nuclear Energy and Fermi Energia agreed to collaborate on potential deployment applications for GE Hitachi's BWRX-300 SMR in Estonia.

In January 2020, Fermi Energia signed an MoU with Finnish power company Fortum and Belgian engineering firm Tractebel to cooperate on studying the deployment of SMRs in the Baltic country. In March 2020, Swedish utility Vattenfall participated in a study on the deployment of SMRs in Estonia.

2.6. Finland

(1) Nuclear energy policy

Figure 3.10. Electricity Generation by Source in Finland



PV = photovoltaics, TWh = terawatt hour.
Source: IEA (2020).

Finland is operating four reactors, and nuclear energy covered 35% of the electricity supply in 2019 (Figure 3.10). Olkiluoto-3, a large-scale European pressurised water reactor (EPR) is under construction, but this project faces serious delays. Another NPP is being planned in Hanhikivi, which is to adopt the Russian design VVER.

(2) Discussion on SMR development

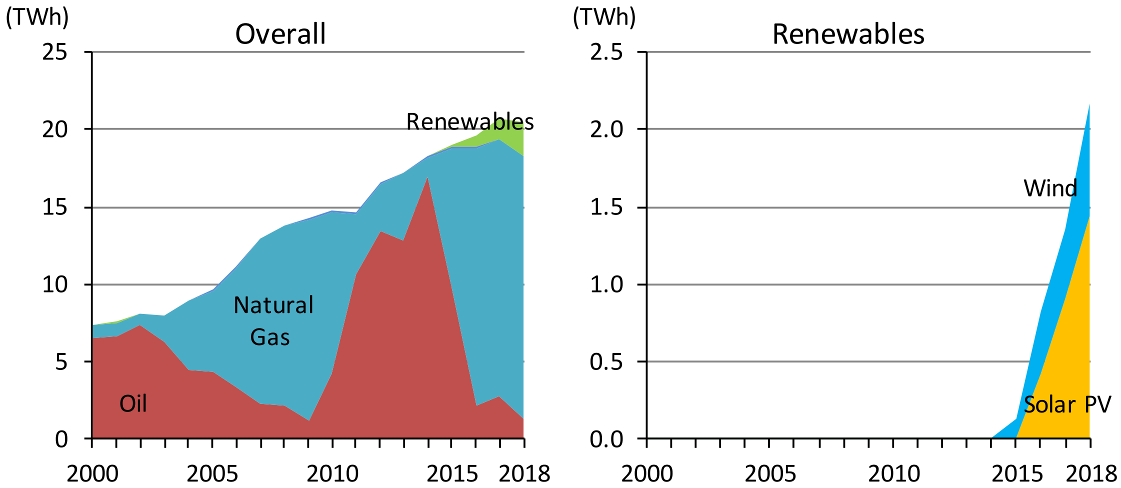
The Finnish Radiation and Nuclear Safety Authority (STUK, 2020) has published a report discussing issues related to licensing SMRs, which says: 'The current licensing procedure and safety requirements are mainly created for large, electricity generating, water-cooled reactors', and 'the needs for regulatory amendments with regard to small modular reactors must be investigated'. As for district heating, the report says: 'a plant producing heat must be located relatively close to habitation. The size of the precautionary action zone and the emergency planning zone must be considered according to need on the basis of the risk caused to the surroundings of the plant'.

In February 2020, VTT Technical Research Centre in Finland announced the launch of a project to develop an SMR for district heating. They are studying the potential use of SMRs for both district heating and electricity generation. District heating is used widely in Finland but is fuelled predominantly by coal, which is to be phased out by 2029.

2.7. Jordan

(1) Nuclear energy policy

Figure 3.11. Electricity Generation by Source in Jordan



PV = photovoltaics, TWh = terawatt hour.
Source: IEA (2020).

Jordan currently has no commercial NPPs, and the country is heavily dependent on fossil fuels (Figure 3.11). The country imports around 95% of its energy consumption, and energy independence is an important issue. In 2007, the Jordon Atomic Energy Commission (JAEC) and Jordan Nuclear Regulatory Commission were established to deploy nuclear power generation in the country. At first, they were aiming to import two 1,000 MW reactors from the export subsidiary of Rosatom. However, in 2018, JAEC cancelled the plan because of the project cost and difficulty in securing funds. Jordan is now trying to deploy SMRs.

(2) Discussion on SMR development

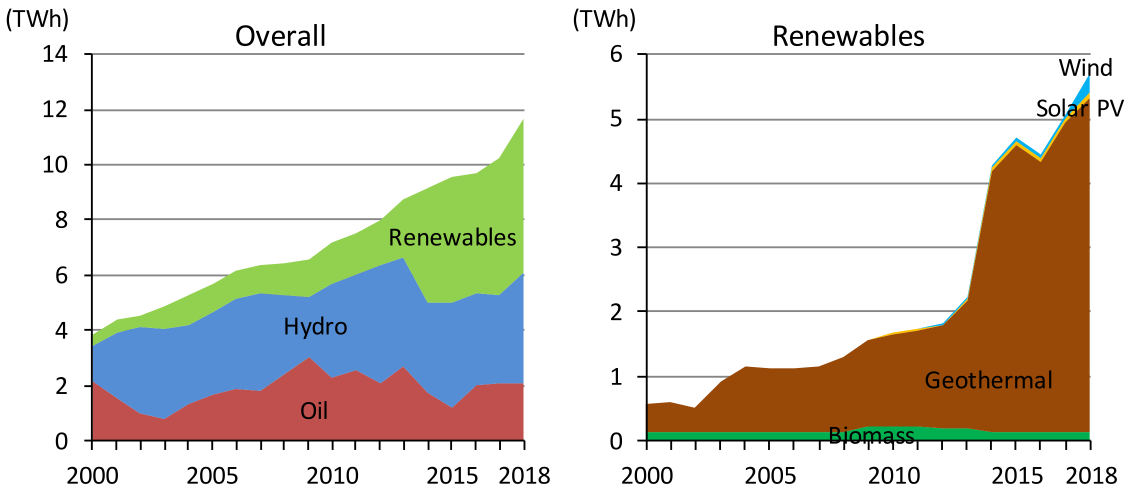
In March 2017, Jordan and Saudi Arabia signed agreements on cooperation in uranium exploration and for carrying out a feasibility study into the construction of two SMRs in Jordan. In November 2017, Rolls-Royce signed an MoU with the state-owned JAEC to conduct a technical feasibility study for the construction of SMRs of Rolls-Royce in the Middle Eastern country.

In November 2017, the JAEC signed an MoU with X-energy to assess the US company’s SMR. They will look at the potential deployment of X-energy’s Xe-100 high temperature gas-cooled pebble bed modular reactor in Jordan, and in January 2019, a joint feasibility study on the deployment of NuScale’s SMR in Jordan will be carried out through an MoU signed between NuScale Power and JAEC.

2.8. Kenya

(1) Nuclear energy policy

Figure 3.12. Electricity Generation by Source in Kenya



PV = photovoltaics, TWh = terawatt hour.
Source: IEA (2020).

Kenya currently has no NPPs, and deploys a lot of hydro and geothermal power generation (Figure 3.12). However, the country has planned to use nuclear energy as an alternative source that is stable, efficient, and reliable. In 2010, the Kenyan Ministry of Energy established a nuclear electricity project committee, subsequently transformed into the Kenya Nuclear Electricity Board in 2012. In 2019, the Energy Act was established, which transformed the Kenya Nuclear Electricity Board into the Nuclear Power and Energy Agency (NuPEA) to expand its mandate to include promoting and implementing Kenya's Nuclear Power Programme, carrying out R&D, and capacity building in the energy and petroleum sectors. In November 2020, NuPEA published its 5-year Strategic Plan 2020–2024 in order to incorporate the new mandate as well as take stock of its achievements to date.

Kenya plans to build a 1,000 MW NPP at a cost of US$5 billion. At first, they planned to complete the first construction by 2027. However, the plan faces some challenges now and it is estimated that the project will spill over into 2030. Some of the reasons are the long compliance procedures before setting up, higher costs compared to renewable energy, and the problem of radioactive waste disposal.

(2) Discussion on SMR development

NuPEA reported an initial case study of Kenya's SMR reactor technology assessment in July 2019. It concluded that most SMRs are 'first-of-a-kind' (FOAK) technology and are still in the early stages of development (conceptual and design stages). It also referred to the insufficiency of data, and with more vendor information the study could be updated.

In the Strategic Plan 2020–2024, SMRs were mentioned a few times. According to analysis through the Political, Economic, Socio-cultural, Technological, Ecological and Legal (PESTEL) model, enhancing knowledge of different reactor technologies, such as SMRs, is useful in becoming technically competitive. Additionally, according to analysis through Strengths, Weaknesses, Opportunities, and Threats (SWOT) models, the adoption of SMRs technology was mentioned as a strategic response.

3. Brief Summary

In this chapter, trends in the development of SMRs and the potential for their deployment were described through case studies. As for the leading countries (the US, the UK, and Canada), the governments are not only securing huge budgets but are also providing attractive business environments for private companies who want to develop SMRs. The regulatory bodies of these countries are also trying to prepare flexible and predictable regulatory schemes. As for the emerging countries mentioned in this chapter, they are considering the deployment of SMRs for their future energy mix, and they have begun discussions with SMR vendors.

Chapter 4

Small Modular Reactor Advantages and Opportunities

In June 2020, the International Framework for Nuclear Energy Cooperation (IFNEC) held a series of webinars on small modular reactors (SMRs) to share information and discuss five issues: market perspectives, financing, licensing, the activities of vendors, and synergy with other energy sources. This webinar series showed the strong interest of many countries in SMRs and identified issues to be solved for its worldwide deployment. The webinars were held on 2, 9, 16, 23, and 30 June via Zoom meetings.

In July 2020, the Organisation for Economic Co-operation and Development/Nuclear Energy Agency (OECD/NEA, 2020) published a report titled 'Unlocking Reductions in the Construction Costs of Nuclear (REDCOST)', which identified NNP construction project cost reduction opportunities. Some parts of the report also mentioned SMRs. In April 2021, OECD/NEA published another report focusing on SMRs (OECD/NEA, 2021). This report analysed the opportunities and challenges of SMRs from various viewpoints.

It is important to understand the advantages of SMRs and the conditions to deploy them, and these international discussions give this research meaningful information. Therefore, this chapter summarises the salient features of SMRs as observed from IFNEC webinars and the OECD/NEA report.

1. IFNEC Webinar 1: National Market Perspectives Regarding SMR Market Development

Keynote speech 1

- Electricity is becoming more and more important. Not only solar and wind energy but also nuclear energy is important to securely provide electricity. Although conventional nuclear energy faces the challenge of high costs, SMRs can possibly resolve this problem.

Keynote speech 2

•China considers nuclear to be a reliable energy and places importance on SMRs, which contribute to small grids in remote areas. Recently, research on a 200 MW high-temperature gas-cooled reactor (HTGR) has been started, and research on a 100 MW pressurised water reactor (PWR) is planned.

•SMRs are important for a low-carbon future. International cooperation on technical standards and regulation systems is crucial.

Panel discussions

•Power generation in Jordan mostly consists of gas. It is a problem to import large amounts of fossil fuels. Our target is to diversify and increase domestic and low-carbon energy resources. Moreover, the planned power generation capacity will not catch up with the growing demand. That is why Jordan is trying to introduce nuclear energy.

•A small reactor (about 400 MW) is considered a realistic option because a large reactor needs 1,000 MW in demand. When a nuclear reactor is installed, it is important not only for it to be cost-competitive compared to natural gas and renewable energy but also for it to be installed by 2030. In choosing a technique, we focus on pressurised water reactors, light water reactors, and high-temperature gas-cooled reactors and exclude liquid metal reactors and molten salt reactors. The scale of the investment is limited considering Jordan's gross domestic product (GDP), and there may be a financial risk.

•To meet the growing demand, Kenya plans to introduce nuclear energy after 2035. The Kenya Nuclear Power Program (NuPEA) was started in 2010, with planned land acquisition and site characterisation and a research reactor project in 2020. Large reactors are planned to be installed first, followed gradually by SMRs. To implement the plan, it is important to reduce costs.

•Poland plans to install its first nuclear reactor based on advanced technology by 2033 and construct another five by 2043, which means 6–9 GW capacity.

•Although the priority of Poland's plan is large reactors, we understand the potential benefits of SMRs like HTGRs, especially for heat generation and co-generation. We consider

SMRs to be a contributor to climate change mitigation. To replace fossil fuels for industrial heat production, the HTGR project was started. Industry interest in SMRs is also growing.

•CO_2 prices have largely influenced oil demand. Despite the domestic oil shale resources, oil shale power generation decreased by 60% in Estonia. Intermittent capacities will be replaced.

•Amongst various reactors, GE HITACHI BWRX-300 is the most promising SMR.

•The European Union (EU) plans to achieve carbon neutrality by 2050. Considering the phasing out of fossil fuels and limitations on renewable expansion, the SMR market potential will be very large if the LCOE reaches €35 or US$35/MWh. Public acceptance of SMRs as an alternative for fossil fuels is growing.

•In 2020, various studies for SMRs (site screening, construction time, licensing models, hydrogen) were planned.

Q&A

Q: What do you think about nuclear energy or SMRs although there is strong opposition to nuclear and approval for renewable energy? What is the biggest problem for new construction?

A: Financial difficulties (high costs compared to natural gas and renewable energy), licensing, the lack of operational experience, insufficient demand growth, etc.

A: Market growth is key for SMR development. We must understand the real industry: what reactor is the most practical or which vendor has updated skills. US SMR projects are especially important because vendors in the US try to install commercial SMR.

Q: What is different in current nuclear energy from the 1960s and 1970s?

A: Small, economical, and safe products are being commercialised. If SMR technologies vendors succeed, SMRs can be introduced in any location without the need for a large environment. A different approach is needed for SMRs, especially in regulation and waste disposal.

Q: Although EU does not have a positive attitude towards nuclear now, why do you think there is potential for 300 SMRs?

A: Since energy consumption is decreasing due to COVID-19, energy investment returns are becoming more important. Renewable energy cannot produce high-temperature heat, and suitable sites are limited. The solar and wind market is getting saturated. However, SMRs can be constructed near industrial buildings and provide electrolysis and constant heat generation.

Q: Jordan is interested in SMRs but doesn't have enough research or development. How do they deploy SMRs?

A: Jordan directly approaches vendors or regulators to conduct skills and regulation processes smoothly. We send people to regulation agencies or nuclear committees in the vendor countries.

Q: How do people say about the problem of spent fuels?

A: There are some discussions on the concept of a common multinational repository. There is strong opposition to domestic repositories. A common repository should be pushed internationally.

A: It is important to communicate with stakeholders and the public in order to resolve the problem.

A: There is not much of a problem technically about the disposal of LWRs, but many challenges about social relations.

2. IFNEC Webinar 2: SMR Financing

Introduction

- Through the discussion today, we want to share the experts' attitudes on SMR finance and explore the areas in which to make great efforts in a full-spec conference. We have a hypothesis that SMR finance may be somewhere in between conventional independent power producer (IPP) finance and nuclear finance at a large scale. Whilst IPP finance has already been packaged as a commodity, nuclear finance is at an evolving stage that has many risks, such as policy, supply chain, and construction time risks.

•Can SMR finance follow the same path of renewable energy? To answer this, we should clarify what challenges we can overcome using the experience of conventional IPP finance, and what are the common challenges for finance for SMRs and large reactors and the unique challenges for SMR finance.

Public–private risk-sharing: Its contribution to lowering financing costs and enabling nuclear new builds

•Nuclear energy is a proven low-carbon source with many benefits. However, new construction of NPPs has significant risks because 80% of the costs are capital costs. Each dimension (i.e. design and development, construction, operation, decommissioning) has risks that different stakeholders owe, and they need to share the optimised risks.

•Although the category of SMRs vary from micro-reactors to 300 MW and above, most advanced projects are still large, especially multi-module plants.

•SMRs are different from large nuclear reactors in that they are easy to invest in, and some financial risks will be shifted to the vendors due to the dedicated factory assembly lines.

•Two major risks are construction risk and market risk. One of the solutions for construction risk is the regulated asset base (RAB) model, which imposes some costs on consumers as a substitute for significant financial costs. Consequently, overall costs can become lower because the risk uncertainty over long constructions is reduced. On the market risks, price volatility is challenging with capital-intensive nuclear. Regarding the various risks including these, governments play a direct role. It is also important to communicate with consumers.

Financing an SMR project: Considerations from the financial community

•Although finance is often the greatest challenge for nuclear power projects, SMRs can represent a paradigm shift.

•It is crucial for finance that the structure behind the project makes sense. It is important to answer such questions as how to trade electricity, who is the final owner for the plant, the possibility for refinancing, and policy support for clean energy.

•According to the IAEA, the time frame for research reactors is 50% less than large reactors. Although no specific milestone approach for SMRs has been reported, the time frame can be shorter, like for research reactors.

•Nuclear is basically proven technology, but newcomer countries do not have experience. There are still challenges, such as the market conditions, regulatory risk, long construction periods, high construction costs, and public acceptance. The challenges for SMRs are the FOAK risk and the need for enough volume of business and support in the early stages. If you realistically plan to introduce SMRs, government support is essential.

Financing experience of the Taishan NPP Project

•The Taishan Project planned to construct six EPRs. Two of them with a capacity of 1,750 MW have been in commercial operation since 2018 and 2019, respectively.

•Third-generation NPPs have significant risks in the form of construction costs, constructional duration, project abandonment, over-budgeting, and consumption and electricity tariffs. The project has overcome these risks because (1) significant economic growth leads to high energy demand, (2) the government has supported nuclear energy development, (3) the investors have powerful economic strength and experiences, (4) the excellent project management team has controlled the project, and (5) the credit structure for debt financing is designed well.

Government support in the design, development, financing, and deployment of SMRs: The UK experience

•According to the Expert Finance Working Group (EFWG) of the UK government, current SMR deployment lacks private sector investment. They analysed the cause and concluded that the UK could be well placed to develop FOAK small reactor projects with less than £2.5 billion by 2030.

- It is essential that governments mobilise finance in order to realise FOAK projects.
- The EFWG suggested possible financial models. One of them is a CfD/PPA model based on project finance where the government plays the role of investor. This method provides high reliability of the investment, catalysation of private finance, and help for FOAK projects. Another CfD/PPA model with governmental guarantee attracts debt and affects the weighted average cost of capital positively, but it would have a serious impact on the balance sheet if the government sets an improper guarantee rate.
- The regulated asset base model (RAB) is considered to be best suited for small and large nuclear projects. Since the Thames Tideway Tunnel project succeeded with RAB, various classes of investors or financers can be interested.

Q&A

Q: Can the Taishan project be an SMR demonstration platform?

A: The Taishan project uses a third-generation reactor, which is different from an SMR. An SMR is new technology and has a high risk. If SMRs are realised on a large scale, they may be cost-competitive.

Q: If a first SMR project succeeds, can following projects become common and practical, like renewable energy and IPPs?

A: Whilst IPP is a business model for technologies whose markets have already been established, nuclear has problems in the liberalised market. It is necessary to take account of the total cost, schedule, and nuclear benefits and the future power generation mix and decide finance.

A: SMRs will acquire finance from the private sector in the future. If made in a factory, it can be a similar technology. The government should give significant support.

A: It is necessary for the SMR supply chain to strengthen with enough investment.

A: Until SMRs becomes profitable, guarantees or subsidies are necessary from the government. If so, SMRs will become like IPPs and attract more private investors.

Comments on questions from the audience

C: 'Whether BOO or BOT is desirable for nuclear projects?' No. Nuclear is so complex that even the worldwide company TVO could not get sufficient money and the OL3 project was cancelled. To mitigate the risk, TVO had worked with the vendor for 2 years until the bid for their next reactor. They cooperated on design improvements and asked technological questions.

C: SMR has an important role in a clean energy future and meeting electrical demand due to electrification, populational growth, and water shortages. SMR needs to be a volume business before discussing the definition of 'clean energy'. The discussion should focus on how to develop each country's nuclear project rather than the right taxonomy. It is essential to generalise project elements, including technological design so that any country can make a successful nuclear project.

C: I have acknowledged the key issues to follow and consider through the discussions today. Further comprehensive discussion on SMRs will be continued.

C: The discussions today are just a starting point. I have high expectations for the next webinar on SMR licensing.

3. IFNEC Webinar 3: SMR Licensing

Introduction

•The COVI-19 pandemic has proved the need for nuclear because it supplies secure electricity for the medical industry. Nuclear also gives economic, geopolitical, environmental, social, and public health benefits.

•Canada published the SMR roadmap cooperating with many stakeholders. NRCan also announced Canada's SMR action plan.

•No country can introduce SMRs without cooperation. It is important to share the experiences globally.

Opening remarks

•Countries around the world have a strong interest in SMRs, but the assumptions of SMRs are different amongst them. SMRs has various categories, such as light water reactors or fourth-generation reactor, which leads to significant differences in regulation.

•SMRs can be successful if they can get a market everywhere in the world, like aircraft, which is different from conventional reactors that are made for each site specifically. Boeing and Airbus would make products rather for the world market than the domestic market.

•After basic rights become standardised, we should look at the technology not at specific sites to get the worldwide market. We have to licence each individual SMR technology.

•It is important for regulators to work together. Amongst many challenges, I think licensing is most important. It is also important for those countries who are interested in SMRs and do not have NPPs because SMR fits small grids without large reactor regulations. If such newcomers do not get profit, SMRs will not have a global market.

Multilateral cooperation supported by the IAEA

•SMRs have many challenges. Since accidents have no borders, all countries need to work together to get transparency and accountability.

•The nuclear industry, including SMRs, has continued to innovate, so regulatory systems must be developed too. SMRs are significantly different from existing reactors in that they are less dependent on safety systems. That is why they need a regulatory approach for safety. A regulatory framework should be developed reflecting the understanding of risk and performance.

•Through the SMR regulators' forum, we can recognise common issues. The objectives are to collaborate on technological development and deployment, propose changes to national requirements and practices, and provide inputs for the consideration of IAEA in future activities.

•There are three phases in the forum. In phase 2 (2018–2020), a new working group was established and the topics were 'design and safety analysis', 'licensing issues', and 'manufacturing, commissioning, and operation'. The publications are now available online.

•The IAEA has made a safety and licensing framework with a top-down approach applying existing knowledge from general to specific. The IAEA has a planned hierarchy of safety goals combined with a technology-neutral and specific framework.

CNSC perspectives on regulatory collaboration

•The Canadian Nuclear Safety Commission (CNSC) is a Canadian independent nuclear regulator. The CNSC always puts safety first and stays flexible to technological developments. We keep good relationships with vendors.

•Preparing for the changes to the regulatory environment, the CNSC ensures enough workforce with the right skills, and transfers valuable knowledge and experiences from veteran staff to the next generation.

•The CNSC develops collaboration with international nuclear agencies or regulators, especially with the IAEA and NEA. Bilateral cooperation is also developed, including the NRC and ONR. Furthermore, we share experiences and provide guidance on SMRs through engagement with embarking nuclear nations.

•Industry should work to harmonise engineering safety standards with international agencies. SMR development also needs a global supply chain. In conclusion, international collaboration is most important to increase the level of safety with better and quick decisions.

Regulatory infrastructure and collaboration in Indonesia

•Badan Pengawas Tenaga Nuklir (BAPETEN) has long experience as a regulatory agency with 400 personnel, including 270 technical staff. In Indonesia, some proposals for SMRs have already existed, but the government has made no clear decision.

•Regulations are actively updated in accordance with international standards. Although no vendor design reviews are in progress, BAPTEN is conducting open dialogues with applicants. International and bilateral cooperation is developed, such as with the IAEA and CNSC.

•There are many challenges: (1) the assessment and decommissioning of ageing research reactors should be considered; (2) existing regulation is mostly based on LWR, so it must be developed to deal with FOAK; and (3) we should have leadership for regulating safety and for transparent and open information because of the lessons from the Fukushima accident.

CANDU Owners Group SMR activities

•CANDU Owners Group (COG) is a platform of CANDU owners and expands SMRs. They have established an SMR forum under the COG that involves CEOs of various companies to share perspectives and address common challenges. The Canadian Nuclear Industry SMR Secretariat is going to be launched, which inputs into the Action Plan under the SMR roadmap released in 2018.

•Industry has reviewed the existing framework and benchmarks against other guidance. The COG has been collaborating on some areas, such as liability. On security, the COG SMR Security Task Team, consisting of experts from the CANDU community, have issued position papers. The COG has also developed international collaboration. It enables SMR development, but we need to consider the differences in the time frames of each country. Not only regulators but also industrial players (vendors, supply chain, operators) need to collaborate with each other, and organisations should facilitate this.

Discussion

Q: Why is it important to harmonise regulation now?

A: Many countries have declared they will be carbon neutral by 2050. This means that low-carbon technologies need to be commercially introduced in the market by around 2030, 10 years after now. So, there is a period of only 10 years for SMR development to realise this objective.

A: The economies in many countries are severely suffering. They should move forward to a clean energy future and SMRs play an important role.

A: From the long period of regulation, now is the timing for international collaboration. Isolated implementation is not enough.

A: Current challenges for nuclear are the lack of public confidence, regulatory complexity, huge initial costs, and the need for long governmental support. If SMRs can be harmonised quickly, they can solve the problems in 10 years.

Q: What can the nuclear industry apply from other sectors? How can the IAEA help us to increase international collaboration?

A: Compared with the aviation industry, SMRs have several problems. They need not only to be certificated by the regulatory bodies, but they also need to be standardised as an industrial product. To acquire a global system, there are two international agreements needed on the cooperation of vendors and technological neutrality. International organisations, including the IAEA, should lead the discussions for a global SMR roadmap.

A: Looking at the COVID-19 pandemic, nuclear can learn many lessons from the identification of a vaccine, which is needed for safety and the quick sharing of information.

A: We have also started to look at other industries and will discuss regulatory activities in common with other regulators. I think countries deeply interested in SMRs should lead the cooperation in regulations and the IAEA should support them. Too many countries should not be involved at first because of the differing time frames.

A: More international workshops are needed, such as an SMR security paper workshop. This should start from a few countries and progress to many countries.

Questions from audience: (1) How do we harmonise regulation in many types of design? (2) How is SMR licensing different from GW-scale reactors? (3) Pursuing perfect harmonisation, will business progress be later?

A: (3) If the regulatory mechanism or international policy framework develop by about 15%–20% of the level of those of the aviation industry, nuclear could be a business. (1) After 3–5 years in selection, regulators will do good work. We have to care about time because much time is needed for licensing after that selection.

A: (2) SMRs and large-scale reactors have many common characteristics, but there are many differences, too. In particular, there are differences in the security measures and the liability of operators. Another challenge is for the vendor to get investment due to many designs for SMRs. Government should back up and make clear policy for clean energy, including SMRs.

A: (1) Countries differ significantly in the extent to which they introduce IAEA safety standards. It is important to consider to what extent regulatory issues are harmonised. (2) SMR licensing should be developed basically from conventional reactors. However, it is most important to consider the risks of SMR facilities. (3) I do not think so. There are common views for safety between countries that have developed their own safety principles. Identifying such common views would make national reviews in other countries more efficient.

C: A bilateral approach is more efficient and a quicker way to go on harmonisation. The CNSC has a similar opinion to the US NRC. Not only an international approach but also a bilateral approach is important.

C: Especially for embarking countries, harmonisation and standardisation are really important. Regulatory bodies have to reinforce independence and technical competency. International agencies maintain much information, and documents of specific projects can be useful for many countries.

C: Today’s summary: (1) there are only 10 years to move forward; (2) it is essential to build a global market and somebody should take leadership; and (3) to establish a low-carbon framework, regulations need to be developed.

4. IFNEC Webinar 4: SMR Vendor Forum

Introduction

- The IFNEC develops cooperation in peaceful nuclear use. We collaborate with many governmental representatives.

BWRX-300: Innovative, cost-competitive, and ready for deployment

•General Electric has pursued new nuclear technologies for decades. We focused on the large light water reactor, but we will focus on SMRs.

•To achieve decarbonisation, nuclear is getting more important. The key is cost competitiveness. BWRX-300 is designed to reduce the overall cost and is capable of load following and is ideal for industrial applications and electricity generation. The building volume is reduced by about 90% from the economic simplified boiling water reactor (ESBWR) due to loss-of-coolant accident mitigation. BWRX-300 is really cost competitive.

•Canada and the US have been prepared for licensing. In addition, many countries and companies have strong interest. Research to reduce operation costs using AI is progressing with partners, including universities. BWRX-300 is ready for near-term deployment with industrial partners, affordable design, licensing, supply chains, and after-market services.

Chinese high-temperature reactor programme

•China considers the high-temperature reactor (HTR) to be important as a supplement to PWRs replacing coal-fired power. It is expected to produce hydrogen and as co-generation. Research was started in the 1970s and commercial plants have been constructed since 2014.

•HTR-PM is being demonstrated in Shangdong. The technology is based on HTR-10 and the two reactors and two steam generators are connected with one turbine. This enables cost efficiency and high temperatures. The HTR-PM project started construction in 2012 and is almost all completed. Critical and power operations are scheduled for 2021.

•The main achievements are the standard nuclear steam supplying system (NSSS) module with a full scale-testing and licensing framework. The project has brought many facility developments, a useful supply chain, fuel fabrication capacity, and so on. Whilst HTR-PM can be constructed in bulk, an improved version of HTR-PM600 is also being developed.

The IMSR power plant – a resilient and cost-competitive clean energy alternative

•Terrestrial Energy is developing the IMSR in order to solve cost problems. The first commercial IMSR plant is to be constructed within 10 years. We have already completed CNSC Vendor Design Review Phase 1, and we are now in Phase 2.

•Conventional nuclear power has the ‘problems of 10’ (US$10 billion/GW, over 10 years of construction, and over 10 cents/kilowatt hour LCOE) and is highly complex.

•Modularity and reduced size alone are not cost effective, but IMSR is dispatchable and low-cost because research has continued over 60 years and the private sector has innovated focusing on the market.

•Nuclear has two opportunities. One is the replacement of the ageing Western fleet, and another is further deployment in replacing coal and natural gas. These can make the nuclear cost competitive.

Moltex: An overview and update

•Moltex has three features: (1) elimination of the meltdown risk, (2) recycling of its fuel and reducing radioactive waste, and (3) thermal energy storage.

•Thermal storage is much cheaper than electricity storage. Moltex uses spent CANDU fuel, which reduces the amount of waste.

•Moltex has partnered with New Brunswick to build a first reactor taking account of the local supply chain. The project finalised the CNSC Phase 1 Vendor Design Review and is preparing for Phase 2.

NuScale Power SMR overview and update

•NuScale was formed to complete the design and commercialising of the NuScale Power Module SMR. The first plant in the UAMPS Carbon Free Power Project is expected to be in operation by around 2027.

•Compared to large PWRs, the cost is significantly reduced due to the lack of a cooling system. In the advanced design, combining 12 modules enables the production of up to 720 MW. Even if a power outage occurs, safety can be maintained because the plant can shut down automatically and modules are cooled in a pool.

•Design certification application (DCA) was completed in 2016 and the NRC technical review Phase 4 was completed in 2019. We also applied for CNSC VDR Phase 1 and 2.

•Following FOAK of the 720 MW reactor, the 'nth-of-a-kind' cost is estimated at about US$2.5 billion (US$3,672/kilowatt).

Rosatom RITM series SMRs

•ROSATOM can offer a whole supply chain for nuclear. ROSATOM has already experienced over 20 small reactors, so SMR is not new. We also completed the first floating NPP (two 77 MW reactors) in the world in 2019, and it was fully commissioned.

•The RITM series uses proven PWR technology and can be transported by train and has a reduced size. RITM is prepared for many applications.

•The first kind of land-based NPP in Russia is planned, with an estimated 3–4 years of construction. The RITM series has a safety concept. The site licence is to be obtained in 2023, and it is to be commissioned in 2027.

Rolls-Royce SMR in a decarbonised economy

•We started the SMR project 3 years ago. It focuses on energy costs not only electricity but also heat. Huge financing costs make the LCOE high. The electricity market price is uncertain, which is difficult to estimate.

•We make great efforts for reducing capital costs, the construction period, and risk. For example, we reduce the size and power output and modularise whole plants. Most methods of decarbonisation require more clean electricity and SMRs play an important role.

SMART development with validated technologies

SMART is a 110 MW reactor. Not only steam but also sea water can be used to produce fresh water.

SMART has passive safety systems in preparation for an emergency. The performance and safety of SMART are evaluated by a comprehensive technology validation programme.

There is a SMART business model. The Korea Atomic Energy Research Institute and King Abdullah City for Atomic and Renewable Energy of Saudi Arabia are joint SMART technology owners. They plan to introduce FOAK SMART first in Saudi Arabia and newcomer countries. They are ready to develop optimal business model with each other for better finance, project structure, and long-term operation.

Xe-100 technology overview

•X-Energy is developing both advanced reactors and fuel.

•Reactors: They are safe and proven by technology. The fourth-generation reactor, now used, is the nearest to market. The licence approval is on track from the US and Canada.

•Fuels: Our product TRISO-X is the most robust nuclear fuel on Earth.

•Xe-100 is a fourth-generation HTGR design based on proven technology. The safe design requires no power or operator action to ensure that the fuel is not damaged. Within the next 5–6 years, it can be deployed as a cost-competitive, low-risk, and carbon-free energy source.

•X-Energy has also worked on the safety shutdown. The Reactivity Control and Shutdown System offers suitable management.

Discussion

Q: What kind of collaboration can be seen for SMR development worldwide?

A: I believe there is immense potential for collaboration. The US and Canada have collaborated on licensing. Cooperation on regulatory guidelines is a good example. Another possible collaboration is in the supply chain, which requires an international view.

A: Whilst vendors compete in the market, they can cooperate in the supply chain and licensing. This enables new SMR technology to develop and be deployed globally.

A: It is important to cooperate with the host country. Vendors should fully cooperate with the local industry when implementing a project. Another example of good collaboration is Rosatom, GE, and Framatome.

Q: How are SMRs to be applied to heavy industry requiring very high temperatures as a low-carbon option?

A: Although the current design produces about 750 degrees, it can be changed immediately to produce 900 degrees. With 870 degrees, the sulphur-iodine (SI) process can produce hydrogen.

Q: Hydrogen production can supply super high temperatures. Our SMR technology can be cost competitive in heat produced almost all by combustion.

A: SMRs can produce high-temperature heat. Our research shows that a great deal of hydrogen can be produced effectively at 860 degrees.

A: We also focus on the same approach. We replace the steam generator with a heat exchanger and combine this with an air combustion system. This can also produce a very high temperature and reduce harmful gas emissions.

Q: How can regulators who are specialised in light water reactor regulation transform to other reactors' regulation?

A: The US NRC has changed the design criteria with the DOE's support. This can be applied to advanced reactors, especially for HTGR. I was surprised at NuScale's activity in highly supporting regulators.

5.IFNEC Webinar 5: Energy Synergy and Hybrid System

Opening remarks

•Today's programme focuses on clean energy synergy between nuclear and renewable energy. The 'Nuclear Innovation: Clean Energy Future' (NICE Future) initiative established under the Clean Energy Ministerial considers it important.

Slovenia: Experience with operating 99% CO_2 free generation fleet of nuclear and hydro

•Gen group has three pillars of business, which are electricity production, development and investments (new hydro power plants), and trading and sales.

•Two-thirds of electricity generation in Slovenia are low-carbon sources. Gen group has generated 350 MW in nuclear electricity as baseload power, which accounts for 50% of nuclear in Slovenia.

•We can get synergy from the coordinated operation of Krsko and hydro power plants on the Sava River by adjusting production hours relative to electricity price fluctuations and managing high and low river flows.

Argentina: Energy transitions and the role of nuclear energy

•Most countries generate electricity mainly from fossil fuels. France and Argentina have very little amounts of fossil fuel electricity, exceptionally.

•Renewable energy, such as hydroelectricity and nuclear, are complementary relationships. Their mix can be the solution for energy transition.

•In Argentina, whilst energy demand is concentrated in or around the centre of the country, wind is concentrated in the south and solar is concentrated in the north. Renewable power generation units are far from the demand area, so Argentina has three NPPs in the centre of the country. Moreover, we are planning the SMR 'CAREM25', which is a PWR with 32 MW capacity and 100 MW core thermal power.

Integrated energy systems: Moving from models to reality with near-term nuclear-hydrogen demonstration projects

•The future energy system needs to be reliable, effective, affordable, and low-carbon. Nuclear can offer not only heat and electricity but also hydrogen. Right-sized reactors offer new options for various community sizes and demand. For example, SMRs can meet community demand and advanced reactors can supply heat at high temperatures.

•The Idaho National Laboratory (INL) has developed a graded approach to identify, design, and evaluate hybrid system architectures. They consider resource, technology, economic, and market potential.

•We have an integrated energy systems demonstration project: hydrogen production via electrolysis. Hydrogen enables energy storage and industrial use. Moreover, NPPs become cost-effective due to the second source of revenue from hydrogen. In our recent analysis, SMRs are cheaper to produce, compress, and deliver hydrogen. The LWR-H2 project is now being demonstrated in Exelon and Davis Besse.

European research and initiatives on hybrid systems, including co-generation

•Nuclear is needed to operate flexibly and to contribute to hybrid energy systems, such as in combination with renewable energy and applications for other industries than electricity.

•The EU Renewable Energy Directive endeavours to increase the share of renewable energy in the heating and cooling sector by 1.3% per year, which includes waste heat from nuclear.

•The HTGR system researched in the EU can make fertiliser, which is highly dependent on natural gas, low-carbon.

•In the future, hybrid energy systems need to develop not only in terms of innovation but also society (public acceptance), regulation (licensing and standardisation), policy, and deployment.

The role of advanced reactor systems in meeting future market needs

•The role of electricity is increasing and, consequently, demand-side management and storage are attracting much attention. Non-electrical sectors also need decarbonisation. Although the technologies are uncertain, they are becoming more important for frequency response, profile operation, and load following.

•The problem of spent fuel is significantly difficult, and advanced reactors need to manage the problem.

•Nuclear also provides heat that is being used in desalination and district heating. Nuclear can contribute to the generation of high temperature heat and hydrogen.

Implementation strategies of resilient nuclear-renewable hybrid energy systems

- Coupling electric power with thermal power enables effective energy use. Combining hydrogen provides more options, mainly in storage. Many models have been developed to produce multi-output with multiple resources.
- A micro modular reactor (MMR) for the NPP outage model is proposed. If an NPP does not work normally, it will be disconnected from the consumer side.
- As another model, the SMR is used in marine ships. Hybrid energy systems with SMR and renewable energy on ships is being considered.

Q&A

Q: How should we address the clean energy system in the discussion of taxonomy where nuclear is excluded by the European Commission?

A: Nuclear new builds need sustainable funds for investors. Whilst the EU has consulted about taxonomy, nuclear is not excluded nor included. Foratom emphasises that nuclear is a clean and affordable energy option that can generate power regardless of the weather.

A: It is important for decision makers in many countries to share the value or practice of nuclear and consider the solution for complex problems. Opportunities are needed across various organisations, such as NICE Future.

C: In Europe, each country has a different opinion on nuclear. International agencies such as the IEA say that both nuclear and renewable energy is important to mitigate climate change and for energy security and the Sustainable Development Goals.

Q: This webinar has discussed the nuclear-renewable hybrid system. From the standpoint of renewable energy, what does the system mean?

A: Although renewable energy itself cannot provide steam or high temperature heat, a hybrid system can do it, which makes other industrial processes low-carbon.

A: Renewable energy can seize new opportunities, including business or scalability by combining with SMR or MMR.

A: We believe the combination of renewable and nuclear is suitable for the future. Nuclear can help renewable energy, which is variable and unstable. We want the renewable community to share nuclear's value.

A: There might be no competition between renewable and nuclear energy. Even after much more renewable energy is deployed, nuclear will also be needed to achieve climate goals.

6.OECD/NEA Report: REDCOST

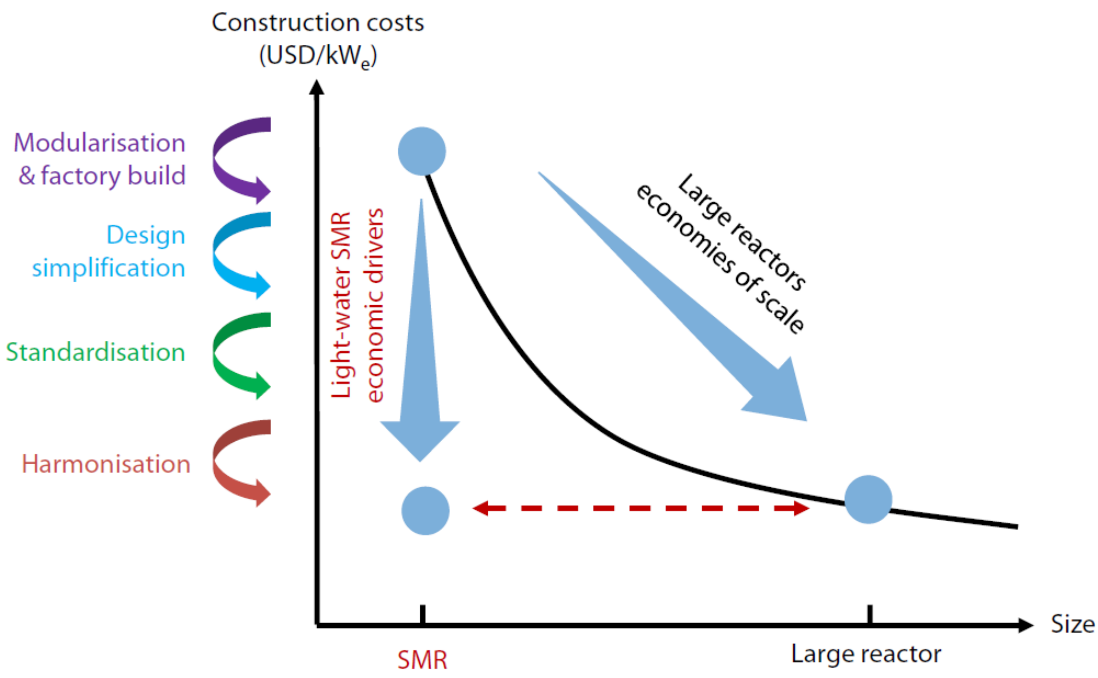
The NEA report titled, *Unlocking Reductions in the Construction Costs of Nuclear*, also known as the REDCOST report, includes some analysis on SMRs. Here is a summary of the explanation of SMRs in the NEA report:

SMRs have cost reduction potential in the long term (beyond 2030). Especially by their design, they may take greater advantage of specific cost-cutting strategies (i.e. the series effect, simplification, modularisation, etc.) to improve the economic performance of new nuclear installations. It is essential for success that governments support the timely development of demonstration projects, the licensing framework required to foster market deployment, and the talent development of highly technological expertise needed in nuclear power. At the same time, the harmonisation of codes and standards and licensing regimes may provide more cost reduction opportunities for conventional reactors, and such commercial drivers are also effective for SMRs.

The small nuclear cores will also solve technical limitations due to the size of Generation III reactors through simplification, modularisation, and standardisation. They enable enhanced passive or gravity-driven mechanisms, integral designs with all the components of the nuclear steam supplying system into a single vessel, and reduced inventories. SMR features allow below-grade siting, providing more protection from natural or man-made hazards, but these innovations may also introduce new safety issues to be assessed in more detail.

Whilst SMRs have many benefits, they have a major economic drawback because they cannot benefit from economies of scale due to their smaller size. However, their economic performance can be improved through series production and higher learning rates thanks to simplification, standardisation, modularisation, and harmonisation (Figure 4.1). These factors will be relatively more important to balance diseconomies of scale, so the cost reduction factors will not carry the same weight as other nuclear technologies. The potential of these strategies to reduce costs has been well documented in other industries, such as shipbuilding and the aircraft industry.

Figure 4.1. SMR Economic Drivers That Help Compensate for Diseconomies of Scale



SMR = small modular reactor.
Source: OECD/NEA (2020).

For timely deployment, SMRs will also require new licensing regimes. Current licensing frameworks typically rely on an extensive experience base with large single-unit LWRs, but LWR SMRs incorporate non-traditional components such as helical coil steam generators, internal control rod drive mechanisms, or new in-vessel instrumentation for which operational experience is limited. Plus, Generation IV SMRs will include features that have never been tested before. The lack of experience with these novel designs poses challenges in demonstrating and approving their safety case. Moreover, the introduction of alternative fuels and/or coolants (i.e. Generation IV SMRs) will translate into greater deviations from previous regulatory paradigms and may require more flexible licensing approaches.

In conclusion, attaining the economic competitiveness of SMRs will require a coordinated effort by the various stakeholders, a dedicated policy and regulatory framework, and, most importantly, a global market. Regulators will, therefore, need to determine how they can work together to devise more streamlined and harmonised regulatory frameworks to create a true global SMR market. It is also imperative to appropriately estimate the size of this market to establish a robust supply chain and sustainable construction know-how that results in competitive capital costs. Beyond the potential cost savings described above, SMRs also offer a different value proposition in terms of financing, ancillary services, and off-grid and non-electric applications that could also improve their economic performance.

7.OECD/NEA Report on Small Modular Reactors

In 2021, the OECD/NEA published another report that focuses on SMRs, which identifies their challenges and opportunities. Here is a summary of the discussions in this report (OECD/NEA, 2021):

According to the IAEA, approximately 70 SMR concepts are currently under development. Whilst the term 'SMR' has been adopted around the world to refer to all small reactor designs, significant differences remain across the major types of SMRs under development (Figure 4.2). Around 50% of the SMR designs under development are variants of light water reactors (LWR-SMRs), and the others correspond to Generation IV reactors (Gen IV SMR) that adopt alternative coolants and advanced fuel, etc. Generation IV-based designs do not have the same levels of operating and regulatory experience as that of LWRs, but they can benefit from an extensive history of past R&D upon which developers and regulators may draw.

Figure 4.2. Selected Reactor Designs as a Function of Power Output, Core Outlet Temperature, and Deployment Configuration

Source: OECD/NEA (2021).

Since SMRs will not benefit from economies of scale, it will be important to ensure 'series construction'. Therefore, SMR designs should be highly modularised, simplified, and standardised so that they will be suitable for mass production in factories. Factory fabrication also contributes to enhanced quality control that can reduce construction risks, foster a ‘series effect’, and enable the introduction of new manufacturing techniques, some of which have already been demonstrated in other industries. At the same time, the smaller size and the prediction of shorter delivery times could reduce upfront investment needs for SMRs compared to larger reactors. Furthermore, SMRs have flexible capabilities which enhance load-following and non-electric applications. These features could bring system-cost benefits and new market opportunities.

As these new technologies were not envisaged when the currently applicable international nuclear conventions were drafted, such conventions would need to be reviewed so that they can be adapted to the innovative SMR concepts. However, the main difficulty with the novel designs is the limited experience base that makes it challenging to demonstrate and approve the safety features of SMRs. In addition, changes to the fuel and/or coolant will translate into greater deviations from previous regulatory paradigms and may require more flexible licensing approaches.

If SMRs are mass-produced in factories, the economic benefits could be significant. This would require, however, a large global market for a single design. Higher levels of regulatory harmonisation will be needed to realise a global market, as well as a reduction in the number of designs.

SMRs have furthermore introduced a series of untested innovations that may lead to additional technology risks. However, as SMRs gain in maturity with the first demonstrators coming online, some of these risks should be mitigated. The supply chain should also be ready to support the emergence of a market for SMRs, ensuring the timely availability of factory-fabrication capabilities, high-assay low-enriched uranium (HALEU), and other innovative fuel production capacities, along with the necessary skills and R&D infrastructure. Additional challenges may arise in terms of public engagement because several concepts of SMRs attempt to minimise evacuation zones and to place the reactors closer to large population centres.

Finally, as a result of the discussions above, this OECD/NEA report identifies four key enablers for SMR deployment: (1) public engagement and international collaboration, (2) the construction of FOAK SMR demonstration units and learning, (3) harmonisation of licensing regimes, (4) development of manufacturing capabilities.

Chapter 5

Expert Views on Small Modular Reactors

In the last chapter, the Institute of Energy Economics, Japan (IEEJ) gathered expert views on small modular reactors (SMRs) by participating in and summarising the webinars and published reports. In addition to such information, Ann MacLachlan, a freelance journalist who has detailed knowledge of the global nuclear energy market, kindly wrote her views on SMRs. Here is her review.

1.SMRs: A Review of Market Prospects

The multitude of SMR designs being promoted by both large traditional vendors and start-ups recalls the line-up of nuclear technology contenders in the United States (US) in the 1950s and 1960s. Common sense tells us that, as happened then, only a handful of designs will survive to the commercialisation phase.

Undeniably, SMRs have caught on as a fashion trend in the nuclear world. But this may be due not to their intrinsic value but rather to the market failure of large light water reactors (LWRs). Faced with the reality that no utility company will order a large reactor in the foreseeable future, the US government has poured money into SMRs to support the nuclear sector. Thanks to their image as being safer than large LWRs, SMRs may also win greater public acceptance. In addition, SMRs equate with innovation – a way to keep the nuclear research community afloat and to attract young people to a sector seen as future-oriented. For some activists, they represent a way to allow nuclear energy to play an important role in decarbonising the planet.

However, **technological hurdles** remain for SMR designs, even those based on mainstream PWR technology like NuScale or France's Nuward. More innovative models like fast reactors or those based on molten salt fuel/coolant will reboot the fuel cycle, requiring regulatory adjustments (higher-enrichment fuel, use of thorium) and the adaptation of fuel cycle installations or construction of new ones. These modifications will take years.

Cost is also a major consideration. Current cost projections for power from SMRs are highly hypothetical, since experience is lacking, and are likely to be low, given the track record of cost projections for nuclear projects in the past.

Even the UAMPS NuScale demonstration project in Utah, which has US$1.36 billion in US federal financial support, upfront power purchase agreements, and a reserved site on federal land, has seen its start-up schedule slip 4 years to 2030, and several customer utilities withdrew when the projected cost rose by almost 50% to US$6.1 billion (Utility Dive, 2020).

[With cheap natural gas, no carbon tax, and high risk premiums on nuclear project financing, further US SMR projects will need significant government support.]

The capital costs, and therefore the market potential, of SMRs are highly dependent on the existence of **long series** of identical or nearly identical units. Whilst this series effect is in theory easier to achieve for SMRs (it takes more units to generate the same amount of power as a large reactor), it will not kick in until production is centralised in a small number of facilities, which may not be soon given the number of players in the field.

In addition, the series effect will not necessarily apply to balance-of-plant and conventional power systems. Site-related costs and civil works will be unique at each site.[1] NuScale is promising up to 80% local supply content to partners in its international agreements, which could dilute the standardisation effect.

It is too early to predict whether these factors – the dispersal of production plants and the time needed to reach the 'nth-of-a-kind' unit with stabilised cost and construction schedule – will be offset by lower unit costs stemming from design simplification and modular construction.

A major determinant in the feasibility and timing of SMR commercialisation is **licensing**. The US Nuclear Regulatory Commission (NRC) approved the design for a NuScale plant with 12 50-MWe modules in 2020 after working on the issue for 12 years (NRC, 2020). A planned new NRC regulatory framework for 'advanced reactors' is still 3 years away, and several key licensing issues are still open. No other SMR design is so far along in licensing at the NRC. NuScale, meanwhile, uprated its reactor module to 60, then 77 MWe, which will require fresh review by the NRC (NuScale Power, 2020).

Meanwhile, the NRC is working with regulators in Canada and the UK to 'harmonise' SMR regulation. As with commercial aircraft, the adoption of a **single regulatory framework for SMRs worldwide** is a key to develop worldwide markets. Experience suggests that will not happen easily, despite the huge international influence of the NRC. Whilst smaller countries with less

[1] Joël Guidez (2020), *French Nuclear Energy Society (SFEN) Webinar on SMRs*. 3 December.

nuclear power experience may adopt the NRC standard, traditional nuclear power countries like France, Russia, and China may be reluctant, not the least because licensing is an element of national industrial sovereignty as well as market power. The potential for resistance to US–Canadian–UK ‘global leadership’ in harmonising regulation based on US standards should not be underestimated.

2.Market Analysis

According to Xavier Ursat of Électricité de France (EDF) in late 2020,[2] the world market for SMRs could be ‘well over’ 25 GW by 2035–2040. That is still less than half the potential market projected for 2030 in a 2014 study by the UK NNL (65–85 GW). That gap suggests that the commercialisation of SMRs is receding in time, raising the possibility that SMRs will arrive in too few numbers, too late to revive the nuclear industry or contribute significantly to CO_2 emissions reduction.

A construction-operation licence for the NuScale ‘reference plant’ in Utah is not expected until 2025 at the earliest, and future financing remains to be worked out. Ed Merrow, a US-based project analyst, considers that whilst SMR projects may be less risky for financiers than larger plants, there will be no large-scale deployment in the short term because ‘it will take years’ for the designs on the table today to work through the technology hurdles, regulatory channels, and supply chain issues.[3]

Although SMRs are proposed as a replacement for coal-fired power plants in the US and China, with a potentially large market, significant deployment for **power applications** will not happen before demonstration units have provided construction and operating experience to lower the risk profile and reduce costs and construction times.

More potential could be seen in specific situations: isolated sites (military bases, remote communities such as in Canada and Russia) as well as countries or territories with small grids that cannot support large reactors. These seem however not to be a single market but rather several specific markets with different requirements that might require several reactor models, reducing the series effect.

[2] French Nuclear Energy Society (SFEN) webinar on SMRs, 3 December 2020.

[3] IFNEC-OECD Nuclear Energy Agency workshop, ‘Issues in the Financing of Nuclear New Build’, 14–15 January 2021.

The existence of a large, interconnected grid on the European continent reduces the potential market for power SMRs in that region.

The potential appears greater, in Europe and elsewhere, for **non-power applications** such as industrial heat, seawater desalination, and hydrogen production by electrolysis. The economics of such projects remains to be demonstrated and project and financing schemes designed.

Traditional nuclear vendor companies are not financially strong enough to sponsor construction, with the possible exception of integrated state-owned companies like Rosatom and its Chinese counterparts. Worldwide, the engineering, project, and construction industry has little equity and 'will not be in the market to take multi-billion-dollar risks' as it used to do, according to Merrow.[4]

Because Canada is already quite far in the evaluation process and ready to licence SMRs, I believe the chances are good for the **SMR market to develop first in Canada**, in partnership with US-based companies. Who will the customers be? Dedicated project companies would be logical, but it will be difficult to finance this kind of project without corporate backing. Perhaps large mining and/or engineering companies in a consortium would work.

It is broadly accepted that government support will be necessary for the first projects. How long must or could that support last? Will it even be allowed in Europe under state aid rules?

Even if SMRs can breach the obstacles of technology, cost, licensing, and financing, there are **other issues**, specific to nuclear projects, that could cause problems. The first, rooted in nuclear weapons proliferation concerns, is the treatment of spent fuel from SMRs, notably in emerging countries like Egypt, Kenya, or Indonesia: Are the countries whose vendors are selling these reactors prepared to take back spent fuel from the world, and will their public accept that? Will small countries buy SMRs if they have to manage spent fuel or the resulting final waste?

Another issue that has proved sticky in the past is nuclear third-party liability. Vendors will be unwilling to sell reactors to countries that have not enacted strict nuclear liability legislation and joined international liability conventions. In India, debate about shielding foreign vendors from liability has lasted for almost a decade without full resolution.

Because of the need to fulfil so many conditions, I do not think the commercialisation of SMRs will happen before the 2040 timeframe. Their success will depend on the concentration of market power in a few hands – to ensure series effects – and the harmonisation of regulatory

[4] Merrow, IFNEC-OECD NEA workshop, see above.

frameworks across many countries.

Potential customers could be any kind of industrial company that needs process heat or dedicated dependable power. Such a configuration would represent a sea of change compared to the nuclear power world we have known since the 1960s.

Chapter 6

Conclusion and Recommendations

1.Analysis

As this research has revealed, SMRs can be a new solution for world energy demand that could not be satisfied by conventional large-scale nuclear reactors. It can be said that the technical features of SMRs would be suitable for the general demand in society today because (1) low-carbon energy is required especially after the Paris Agreement of 2016, (2) advanced safety features have become important after the Fukushima Daiichi accident, and (3) modularised small-scale generation capacity is suitable for developing countries in terms of electrical grid capacity and of financial capacity. Therefore, many countries in the world recently have shown interest in investing in SMRs, as clarified in Chapters 3 and 4.

However, there are many problems to be solved, as pointed out in Chapters 4 and 5. Due to such problems, SMRs have not been commercially deployed as of 2021. You can see the concepts of SMRs referred to even in documents or articles published more than 30 years ago, which means SMRs have been researched and developed for such a long period in laboratories but have not been deployed in society yet. Therefore, what you have to do today is not only develop the technical features, but also to get rid of such problems. Keeping in mind the fact that customers finally decide whether to purchase a product or not, it is crucial to make a business environment to facilitate the decision making of potential customers (electric power utilities, in most cases). To this end, the IEEJ makes policy proposals as follows both for the leading countries of SMR development and for the potential customer countries.

2.Policy Proposal

1) For the leading countries, such as the US, the UK, and Canada:

For these countries, it is recommended that they should continue and accelerate their current development and deployment projects for SMRs. The timescales for their projects should be clarified, and they should make efforts to follow the schedules because if they take too much time, potential customers around the world will lose interest in SMRs. At the same time, it is important to provide enough data so that potential customers can consider closely whether SMRs are suitable for their plans. Besides the efforts taken by individual countries or vendors, there should be international efforts to harmonise the regulatory requirements for SMRs in the world since regulatory harmonisation is a crucial method for promoting the mass production of reactor modules and accelerating deployment all over the world. Finally, to expand the potential global SMR market, international cooperation with potential newcomer countries should be promoted in the fields of energy planning, feasibility studies, infrastructure development, and so on.

2) For the countries considering the deployment of SMRs in Asia or Africa who need stable and reliable clean energy but currently have small grid systems:

First, these countries should clarify their future energy plans and their needs for nuclear energy to attract the interest of exporter countries of SMRs, which would lead to cooperation agreements and joint feasibility studies. This is the very beginning of a nuclear energy programme. At the same time, they should develop attractive business environments for vendors and investors. After they decide the deployment of SMRs (or even large-scale reactors), they should develop and improve infrastructure for the utilisation of nuclear energy, including the regulatory schemes that are necessary for the deployment of SMRs. Besides all of these processes, it is also important to conduct open discussions in their countries about the future utilisation of nuclear energy, including SMRs, to improve public understanding and acceptance of nuclear energy.

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