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Small Modular Reactor (SMR) Deployment: Advantages and Opportunities for ASEAN

Edited by

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List of Abbreviations

AECL	Atomic Energy of Canada Ltd.
AMR	Advanced Modular Reactor
ARDP	Advanced Reactor Demonstration Program
ARFEM	(Expert Group on) Advanced Reactor Systems and Future Energy Market Needs
ASEAN	Association of Southeast Asian Nations
BATAN	National Atomic Energy Agency (Indonesia)
BEIS	Department for Business, Energy & Industrial Strategy (United Kingdom)
BIS	Department for Business, Innovation and Skills (United Kingdom)
BPPT	Agency for the Assessment and Application of Technology (Badan Pengkajian dan Penerapan Teknologi) (Indonesia)
BWR	Boiling Water Reactor
CfD	Contract for Difference
CNL	Canadian Nuclear Laboratory
CNSC	Canadian Nuclear Safety Commission
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)
EBTKE	(Directorate General of) New Renewable Energy and Energy Conservation (Indonesia)
EIP	Energy Innovation Programme

EPR	European Pressurised Water Reactor
ERIA	Economic Research Institute for ASEAN and East Asia
GAIN	Gateway for Accelerated Innovation in Nuclear
GDA	Generic Design Assessment
GW	Gigawatt
GWe	Gigawatt Electrical
HALEU	High-assay Low-enriched Uranium
HTGR	High-temperature Gas-cooled 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
JAEC	Jordan Nuclear Regulatory Commission
LCOE	Levelised Cost of Electricity
LTS	Licensing Technical Support
LWR	Light Water Reactor
MCA	Maximum Credible Accident
MMR	Micro Modular Reactor
MoU	Memorandum of Understanding
MW	Megawatt
MWe	Megawatt Electrical
NDRC	National Development and Reform Commission (China)

NEA	Nuclear Energy Agency (Organisation for Economic Co-operation and Development)
NIC	Nuclear Industry Council (United Kingdom)
NIP	Nuclear Innovation Programme
NNL	National Nuclear Laboratory (United Kingdom)
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission (United States)
NuPEA	Nuclear Power and Energy Agency (Kenya)
OECD	Organisation for Economic Co-operation and Development
ONR	Office for Nuclear Regulation (United Kingdom)
OPG	Ontario Power Generation
PEP	Philippine Energy Plan or Energy Policy of Poland
PV	(Solar) Photovoltaic
PwC	PricewaterhouseCoopers
PWR	Pressurised Water Reactor
R&D	Research and Development
RAB	Regulated Asset Base (Model)
RAI	Request for Additional Information
SMR	Small Modular Reactor
SNPP	Small Nuclear Power Plants
SNPTC	State Nuclear Power Technology Corporation (China)
SSC	Structure, System, and Component
STUK	Radiation and Nuclear Safety Authority (Finland)
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. Recently, China and Russia have also been making great efforts to deploy SMRs. The governments have taken strong leadership in technology development in the two countries.

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 2022, no SMRs have been commercially deployed in the world. Keeping in mind the fact that customers ultimately decide whether to purchase a product or not, it is crucial to create 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 SMR vendors:

- Make an attractive proposal for customers (electric power utilities, in most cases).
- Have intensive discussions with the regulatory authority and follow regulatory guidance.
- Promote discussions in Asian or African countries that are considering the deployment of SMRs.

3) 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, this report presents surveys of the current status and plans for the development and deployment of SMRs (or other advanced reactors) in leading countries: the US, the UK, Canada, Russia, and China. The surveys focus on policy support for technology development and regulatory schemes in each country. At the same time, the surveys also provide insights into 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, and some SMR vendors have begun discussions with regulatory bodies. 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.

Chapter 2

Status of Small Modular Reactor Development and Deployment in the World

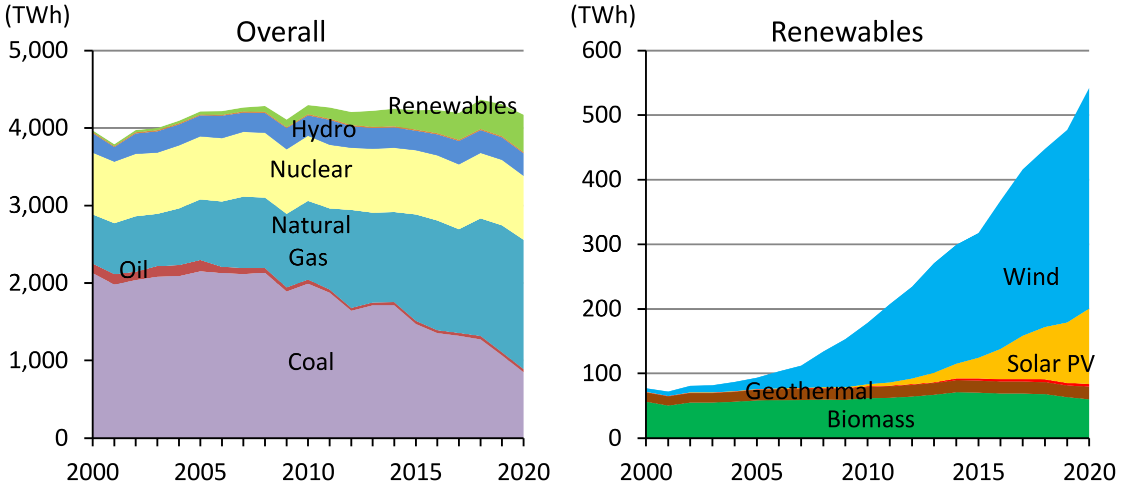
This chapter discusses nuclear energy policy and the status of small modular reactor (SMR) development in the leading countries and several emerging economies. The leading countries mentioned in this chapter are selected because of the efforts carried out by their governments and vendors to develop and deploy SMR technology, and some of them have already begun the construction of SMR plants. 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 2.1. Electricity Generation by Source in the United States



PV = photovoltaic, TWh = terawatt hour.

Source: IEA (2021).

In the United States (US), nuclear energy provided about 20% of total electricity generation in 2020, which was the largest share amongst clean energy sources (Figure 2.1). 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 photovoltaic (PV) and wind). For this reason, some nuclear power plants (NPPs) were closed before the expiration of their operating licences. However, the DOE has not changed its fundamental view that nuclear energy is important as a reliable low-carbon energy. This view is has been maintained even after the change from the Trump administration to the Biden administration.

The Federal Government is trying to reinforce the competitiveness of the nuclear energy sector 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 gigawatt (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$/megawatt (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 recover their investment.

In February 2022, the DOE (2022) released 'America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition'. This report is the first comprehensive plan to build the US energy sector industrial base (ESIB) needed to support a rapidly accelerating clean energy transition. As a future policy strategy specific to nuclear energy, the DOE intends to support the development of advanced nuclear reactors in a timely manner in coordination with the Nuclear Regulatory Commission (NRC).

(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 regulations 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.

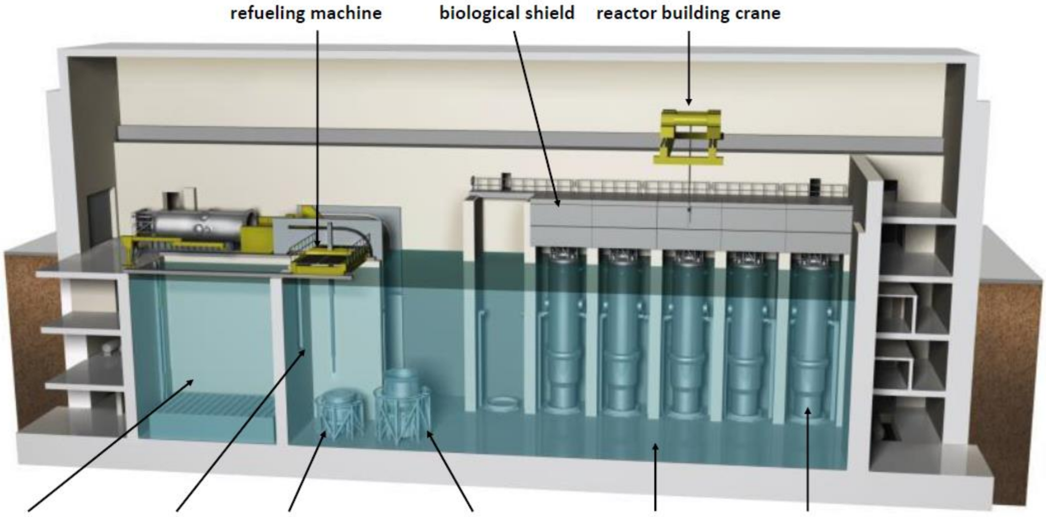
The DOE has already announced that the Natrium reactor (a sodium-cooled fast reactor) developed by TerraPower and GE-Hitachi, and Xe-100 (a high-temperature gas-cooled reactor), developed by X-energy, were awarded US$80 million each under the ARDP scheme.

The DOE also promotes research and development (R&D) for 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, which was already shut down in 1994, its amount is limited. On the other hand, in November 2019, the DOE signed a 3-year contract to deploy a cascade of centrifuges to demonstrate the production of HALEU fuel with Centrus Energy, a nuclear fuel and services supplier. 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 2.2) consists of 60 MW or 77 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 2.2. 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). This SMR plant consists of multiple reactor modules of 77 MW. Operation of the first module is planned to start by 2029. 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 considerable funding support for NuScale. In 2013, through the LTS programme, the DOE awarded US$226 million to their 5-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. In August 2020, the NRC completed the Phase 6 review of NuScale's DCA with the issuance of the Final Safety Evaluation Report. 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 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 2.1. Advanced Nuclear Energy Legislation in the United States

Title	Status	Main Objectives
Nuclear Energy Innovation Capabilities Act	Enacted in September 2018	• Provide Department of Energy (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	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 Leadership Act	Introduced in Senate in March 2019 Introduced in House in June 2019	• At least two demonstration projects led by the DOE of advanced reactors by 2025 • Additional 2–5 projects by 2035 • Establish high-assay low-enriched uranium transportation programme
[Bill] Integrated Energy Systems Act	Introduced in Senate in October 2019 Introduced in Senate in June	• Establishment of DOE-led research and development programme that focuses on the integration of nuclear energy with other energy sources

	2020	
[Bill] American Nuclear Infrastructure Act	Introduced in Senate in November 2020	• Prize for advanced nuclear reactor licensing • Credit allocation to certified reactors

Note: The Nuclear Energy Leadership Act has not been passed in Congress but was partially adopted in the Consolidated Appropriations Act, 2021.

Source: Authors.

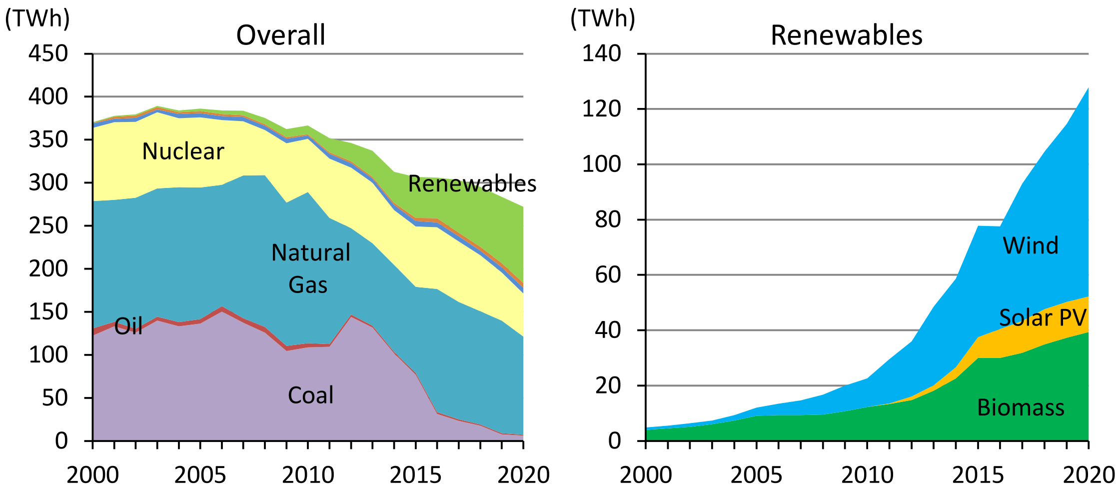
The attitude of the regulatory authority is also important for deploying advanced nuclear technology. In the US, the activities of the regulatory authority, the NRC, are supervised by Congress. As shown in Table , the NRC requires reforms so that it can cope with licensing new technologies. Therefore, the NRC has adopted a flexible and staged review process in which the NRC and applicants can intensively discuss and identify issues. It 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.

Moreover, in April 2021, the US Department of State announced a new programme called Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology, in which the US government will support capacity-building activities in partner countries.

1.2. United Kingdom

(1) Nuclear energy policy

2.3. Electricity Generation by Source in the United Kingdom



PV = photovoltaic, TWh = terawatt hour.

Source: IEA (2021).

In the United Kingdom (UK), nuclear provided 16% of total electricity generation in 2020 (Figure 2.3). 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 constructing. The BEIS (2020) said that the RAB model, with high-level design principles, remains a credible model for large-scale nuclear projects. In October 2021, the BEIS announced the introduction of the RAB model (BEIS, 2021a).

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 in 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 BEIS (2018) 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.

In April 2022, the UK government published the British Energy Security Strategy (HM Government, 2022), which consists of many measures to reinforce energy independence. As for nuclear energy, this strategy says that they will deploy up to 24 GW of generating capacity by 2050, and the share of nuclear should be up to 25% of the projected electricity demand.

(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 GW–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 Project. The 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.

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 a 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.

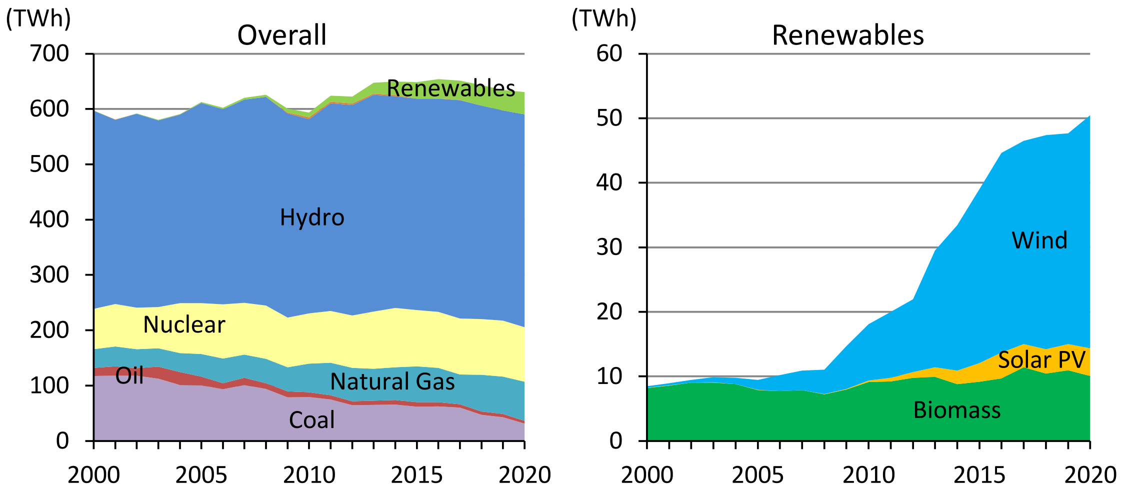
It can be said that one of the most famous UK-based SMR vendors is the consortium led by Rolls-Royce. They are developing a Pressurised Water Reactor (PWR)-based design. Rolls-Royce has told the BBC that they plan to install and operate their first reactor by 2029 (BBC News, 2020). In November 2021, the BEIS announced that the UK government would fund £210 million to develop Rolls-Royce SMR (BEIS, 2021b). Following the announcement of securing funding from the government, it submitted to the ONR its SMR design for the entry to GDA regulatory process. In April 2022, the application from Rolls-Royce was accepted, and the ONR announced that it had started the first step of GDA for Rolls-Royce SMR (ONR, 2022).

In April 2022, on the day following the publication of the British Energy Security Strategy mentioned in the previous section, the UK government unveiled investment plans for energy technologies of the future. These included £2.5 million of funding to develop next-generation nuclear technology. And it was also announced that the ONR and EA have been provided with £830,000 to help the deployment of AMR (BEIS, 2022).

1.3. Canada

(1) Nuclear energy policy

Figure 2.4. Electricity Generation by Source in Canada



PV = photovoltaic, TWh = terawatt hour.

Source: IEA (2021).

In Canada, nuclear energy provided about 15% of total electricity generation in 2020, which was the second-largest amongst all electricity generation sources following hydro power (Figure 2.4). 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 form of 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, 2020a)

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. The 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 the AECL's nuclear power reactors, the heavy water-cooled and moderated pressurised-water reactors known as the Canadian Deuterium Uranium 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, nine from the US, and nine 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. By 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 (Canadian Small Modular Reactor Roadmap Steering Committee, 2018) 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 that 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 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 (Government of Canada, 2020b).

Canada's Ontario Power Generation (OPG) company announced in December 2022 that it had selected GE Hitachi Nuclear Energy's BWRX-300 from three candidate designs as the SMR to be built at the existing site of Darlington Nuclear Power Plant. The company plans to complete the first commercial SMR in Canada as early as 2028.

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 International Atomic Energy Agency (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

This 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 2022, 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), ARC Nuclear Canada (ARC-100), Moltex Energy (Molten Salt Reactor), NuScale Power (NuScale PWR), GE-Hitachi (BWRX-300), and X-energy (Xe-100).

c. Benefit for vendors

Vendors 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.

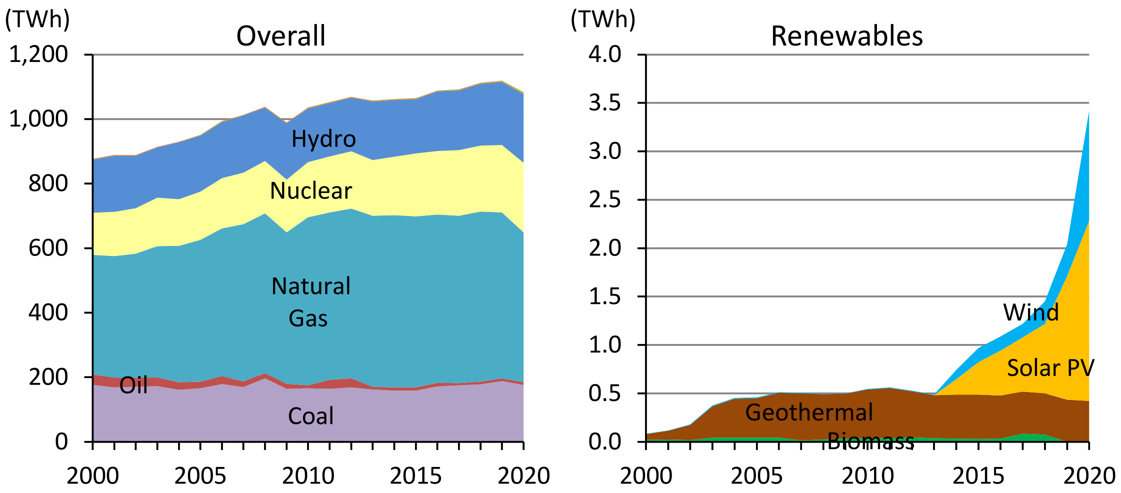
d. Benefit for people in Canada

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

1.4. Russia

(1) Nuclear energy policy

Figure 2.5. Electricity Generation by Source in Russia



PV = photovoltaic, TWh = terawatt hour.

Source: IEA (2021).

Russia is moving steadily forward with plans for an expanded role of nuclear energy, including the development of new reactor technology. As of 2020, 20% of total electricity generation comes from nuclear energy (Figure 2.5). The country is committed to closing the fuel cycle, and it sees fast reactors as a key technology to this policy.

Russia's first nuclear power plant was a 5-megawatt electrical (Mwe) Obninsk-type reactor, which began generating electricity for the first time in the world in 1954. Rosenergoatom is the only power company in Russia that operates nuclear power plants. It was founded in 1992 and restructured as a utility in 2001 as a division of Rosatom.

In the late 1990s, reactor exports to Iran, China, and India were negotiated, and Russia's stalled domestic construction programme was revived as funds allowed. This was a great boost to the morale of the Russian nuclear industry. However, in early 2017, the government decided to end state support for the construction of new nuclear power plants in 2020, and a shift is underway for Rosatom to focus primarily on commercial nuclear power projects in international markets.

Rosatom's long-term strategy for the period up to 2050 is to transition to intrinsically safe nuclear power plants with a closed fuel cycle using fast reactors, especially under the 'Prolyov (Breakthrough)' project. At that time, nuclear power is expected to account for 45%–50% of electricity, rising to 70%–80% by the end of this century. The overarching goal of the closed fuel cycle is to eliminate the generation of radioactive waste associated with power generation.

In addition to the construction of new nuclear power plants, the capacity factor of existing nuclear power plants has increased remarkably since 2000: in the 1990s, the capacity factor averaged around 60%, but it has steadily increased since then, reaching over 81% in 2010, 2011, and 2014. The Balakovo nuclear power plant remained at a high level of 92.5% in 2011 and 85.1% in 2014. In addition, most reactors have been licensed for extended lifetimes; half of the country's nuclear power in 2015 was upgraded for long-term operation, operating beyond its original design life of about 30 years.

Next is the development of new nuclear technologies: it is assumed that fast reactors will play a larger role in Russia in 2020–2025, with significant fuel recycling. The main plan for innovative nuclear power generation in Russia, based on the new technology platform, envisages full fuel recycling, balancing thermal and fast reactors so that only about 100 tonnes per year of input is needed with a total capacity of 100 gigawatt electrical (GWe), and enriched tail, natural uranium, thorium, and minor actinides will be burned.

As part of its international cooperation, Russia has been the lead country in the IAEA's Innovative Nuclear Reactor and Fuel Cycle Project since 2001. In 2006, Russia participated in the Generation IV International Forum, for which the Nuclear Energy Agency/Organisation for Economic Co-operation and Development (OECD/NEA) serves as the secretariat. Russia is also a member of the NEA's Multilateral Design Evaluation Program, which is becoming increasingly important in the rationalisation of reactor design standards (OECD/NEA, 2022).

Rosatom and the Russian government are actively expanding the construction and operation of new nuclear reactors abroad. Since the collapse of the Soviet Union, nuclear power plants have been built and operated for Ukraine, Iran, China, India, and Belarus. In addition to these countries, nuclear power plants are being built in Turkey, Bangladesh, and other countries. Rosatom's total foreign nuclear orders in 2015 were US$300 billion. However, given that Russia is invading Ukraine and has attacked nuclear power plants, it is not clear whether other countries will want to continue importing nuclear power plants from Russia.

(2) SMR development

Small nuclear power plants (SNPPs) are one of the promising areas of Rosatom's activities. Rusatom Overseas, one of the group enterprises of Rosatom, is in charge of their development as the system integrator.

Russian SNPPs, like SMRs in other countries, have been developed for use in remote regions with undeveloped power grid infrastructure where it is not feasible to build conventional large-scale reactors. SNPPs have a wide range of evident advantages connected directly with the energy constituent, ensuring energy independence of hard-to-reach territories as well as environment-friendly energy generation. The flexible use of SNPPs gives advantages for the development of small local businesses and could ensure a synergetic effect for the development of hard-to-reach territories. Also, SNPPs are capable of producing heat, which is important for regions with cold climates, such as the Arctic Coast area.

Today, in 2022, Rosatom operates the world's only floating nuclear power plant based on a floating power unit, Akademik Lomonosov, with two 70 MW reactors. Akademik Lomonosov was built on the farm of one of the Rosatom Group enterprises in Saint-Petersburg and was moored in Pevek in September 2019. In December 2019, the floating nuclear power plant supplied its first electricity to the city of Pevek and started commercial operation in May 2020.

Rosatom is also implementing a construction project for the world's first on-ground SNPP in the Ust-Yansk Region of Yakutia. It is very difficult to bring fuel to the north of Yakutia because of the severe Arctic conditions. Therefore, the industry development and prospects of mining mineral deposits in the region require a stable and clean energy source.

Rusatom Overseas, the licensee of the SMR in Russia, received a licence from Russian nuclear regulator Rostekhnadzor to build SMRs in Yakutia. It is on track to start operation in 2028.

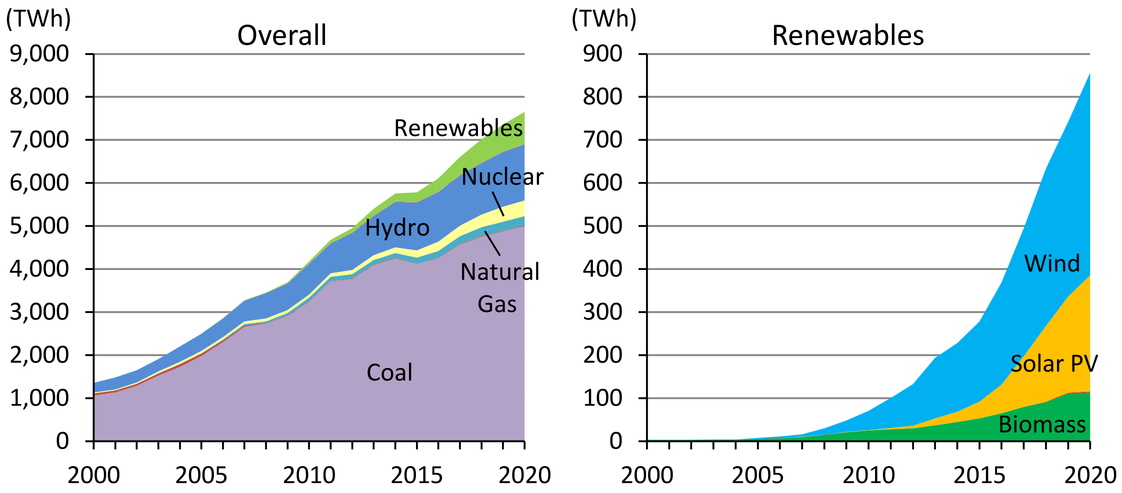
Seligdar, one of the Russian tin and gold miners, is also interested in developing SMRs to secure stable power, and its chairman, Sergey Ryzhov, signed an agreement with Rusatom Overseas on the supply and consumption of energy generated by the Yakutia SMR to develop the Kyuchus gold deposit in Ust-Yansk and Verkhoyansk districts in Yakutia (S&P Global, 2022).

Rosatom thinks that the Russian SNPPs (SMRs) could be adaptable to overseas markets. In January 2022, Kyrgyzstan's Energy and Industry Minister Doskul Bekmurzaev and Rosatom Director General Alexey Likhachev signed a memorandum of understanding, expressing their interest in developing cooperation to construct a Russian-designed SMR in Kyrgyzstan. Additionally, the memorandum of cooperation envisages assistance in the development of nuclear infrastructure in Kyrgyzstan and joint work to improve the qualification of R&D and technical support personnel in various areas where there is peaceful use of nuclear energy (New Europe, 2022).

1.5. China

(1) Nuclear energy policy

Figure 2.6. Electricity Generation by Source in China



PV = photovoltaic, TWh = terawatt hour.

Source: IEA (2021).

The movement to build nuclear power in China began in 1970, and the reform of state-owned enterprises in 1998 led to the division of major enterprises, accelerating market competition and opening up monopolies. The subsequent 11th Five-Year Plan (2005) led to the rapid development of the nuclear industry. In addition, the amount of nuclear power generation and power generation facilities have been steadily expanding, boosted by the high economic growth in the 2000s. Nuclear energy generated 366 TWh of electricity, which accounts for 5% of total power generation (Figure 2.6).

Nuclear technology was introduced from France, Canada, and Russia, and local development was mainly based on French technology. Recent technology acquisitions have come from the US (via Westinghouse, owned by Japan's Toshiba Corporation until 2018) and France. The State Nuclear Power Technology Corporation (SNPTC) is responsible for the development of CAP1000 and CAP1400, using Westinghouse's AP1000 as the main basis for technology development for the time being.

Through the development of CAP1400, intellectual property rights have been granted to China, leading to the acquisition of full fuel cycle capability. Against this backdrop, the central government has made a policy of exporting nuclear technology; in 2015, the Hualong One reactor became the main export product. This policy is being pursued with a high degree of political involvement, leveraging China's growing economic and diplomatic clout as one of 16 key national science and technology projects.

As for China's domestic nuclear policy, in July 2013, the National Development and Reform Commission (NDRC) set a wholesale power price of CNY 0.43 per kWh for all new nuclear power projects to promote the healthy development of nuclear power and guide investment in the sector. This policy has strengthened the price competitiveness of nuclear power, and the wholesale price to the grid is lower than that of coal-fired power plants equipped with flue-gas desulphurisation (the cost of basic coal-fired power is 0.3 CNY/kWh). In March 2015, new electricity market reforms were launched that prioritise clean power generation and changes to the system that allow nuclear companies to negotiate prices with customers.

Furthermore, regarding the future outlook for nuclear power generation, as of 2022, construction of 15 new nuclear power units (15.9 GW) is underway, with improved Generation III reactors being the mainstay. The 14th Five-Year Plan for a Modern Energy System sets a target of 70 GWe of installed nuclear capacity (NDRC, 2022). And the NDRC's

Energy Research Institute has pointed out that nuclear power generation needs to increase to 554 GWe by 2050 to meet the recent global trend of a net-zero strategy and to keep the global average temperature rise below 1.5 degrees Celsius (World Nuclear Association, 2022).

(2) SMR development

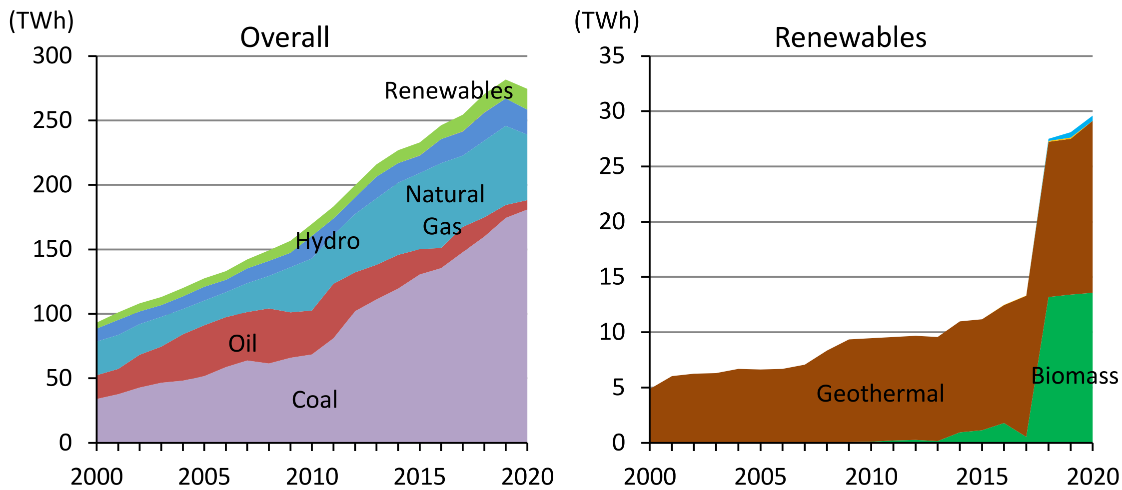
Construction of the ACP100 small modular reactor at Changjiang started in July 2021. Construction time is expected to be 58 months. This reactor is designed for electricity production, heating, steam production, or seawater desalination. The major components of its primary coolant circuit are installed within the reactor pressure vessel (World Nuclear News, 2022a).

2. SMR Potential in Developing and Emerging Economies

2.1. Indonesia

(1) Nuclear energy policy

Figure 2.7. Electricity Generation by Source in Indonesia



TWh = terawatt hour.
Source: IEA (2021).

Indonesia currently has no commercial nuclear reactors and most of their electricity supply depends on fossil fuels (Figure 2.7). 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 (EBTKE) (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.

The Indonesian government has made a road map to Net Zero Emissions by 2060. According to the road map, starting from 2049, nuclear power plants will enter the generation system (Ministry of Energy and Mineral Resources, 2022).

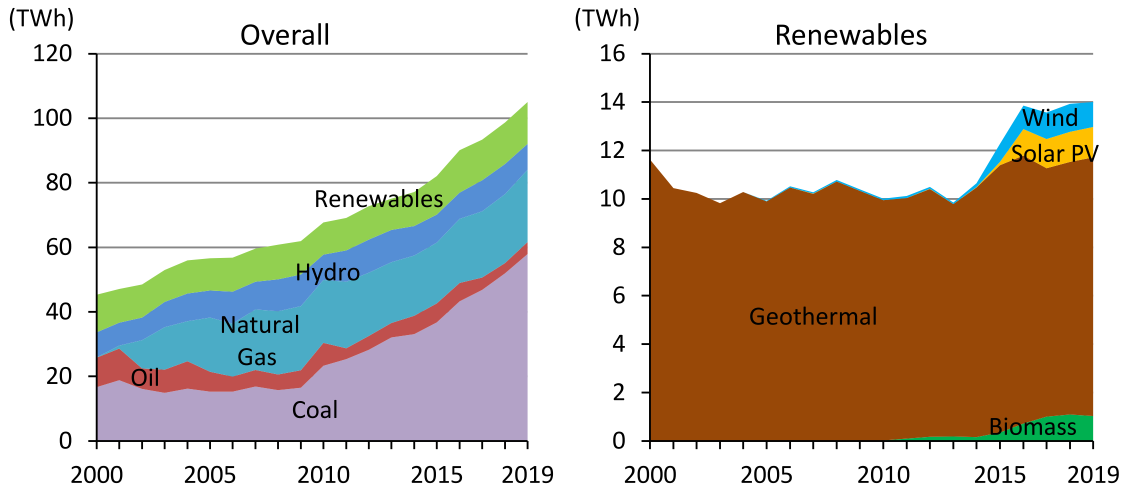
(2) Discussion on SMR development

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 megawatts thermal of 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 2.8. Electricity Generation by Source in the Philippines



PV = photovoltaic, TWh = terawatt hour.

Source: IEA (2021).

The Philippines currently uses no nuclear power (Figure 2.8). However, in response to the 1973 oil crisis, they decided to build the two-unit Bataan Nuclear Power Plant. 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 submitted a study result that said it would take US$1 billion to rehabilitate the Bataan Nuclear Power Plant (ABS-CBN, 2010).

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.

President Rodrigo Duterte signed an executive order in February 2022 that outlines the government's position for the inclusion of nuclear energy in the Philippines' energy mix, taking into account economic, political, social, and environmental objectives (World Nuclear News, 2022b).

(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 the 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.

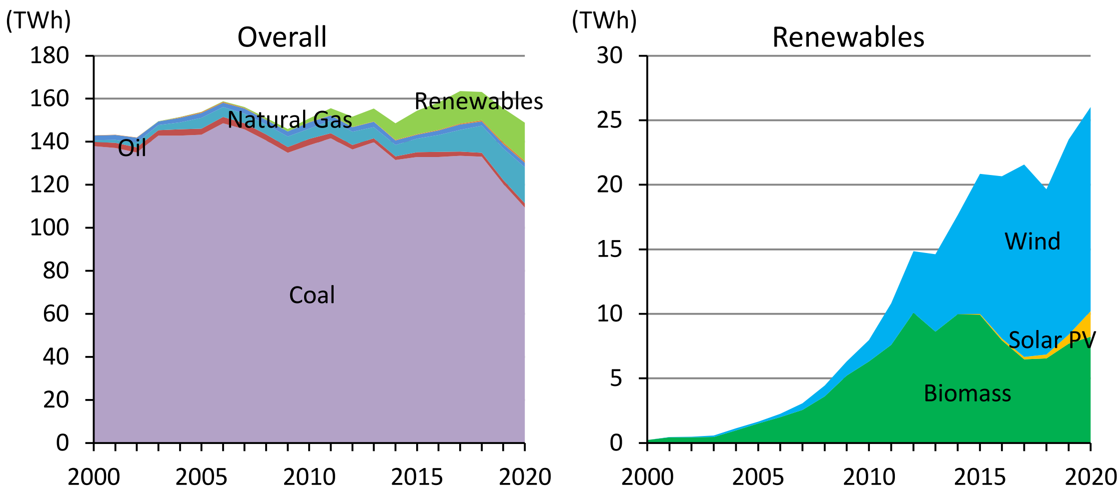
In addition to Korea, Russia also cooperates with the Philippines in the field of nuclear technology. The DOE signed an agreement with Rosatom in October 2019 to assess the feasibility of a small NPP, floating or on land, and probably using RITM-200 reactors.

In February 2022, DOE Undersecretary Gerardo Erguiza noted that the Philippines is in talks with Russia, Korea, and the US on the use of SMR technology (World Nuclear News, 2022b).

2.3. Poland

(1) Nuclear energy policy

Figure 2.9. Electricity Generation by Source in Poland



PV = photovoltaic, TWh = terawatt hour.

Source: IEA (2021).

Poland currently has no commercial NPPs (Figure 2.9), but according to the Energy Policy of Poland until 2040 (PEP2040) (Ministry of Climate and Environment, 2021) approved by the cabinet in 2021, the Polish government has a plan to deploy the first one by 2033. It is planned to have a capacity of 1.0 GW–1.6 GW, with the next NPPs 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).

The work for selecting sites for nuclear power plants is making steady progress. Polskie Elektrownie Jadrowe (PEJ), the government company that is progressing its policy to deploy up to six reactors at multiple sites by 2040, announced in December 2021 that Lubiatowo and

Kopalino in Choczewo municipality would be the preferred locations for Poland’s first large nuclear power plant. The company also said that detailed environmental and location studies have been conducted on the area since 2017, and as a result, they concluded that the selected locations would be the best option for the environment and safety (World Nuclear News, 2021a).

Germany, a neighbouring country of Poland, expressed concerns about the construction of the nuclear power plants in Poland and about the impact of its development of the Oder River that runs along the border between the two countries. Steffi Lemke, the Federal Minister for the Environment and Consumer Protection (Germany), stated that nuclear power plants in Poland might be a threat to a neighbouring country and said, ‘If reactors are to be built in Poland, we will work with the appropriate legal instruments…at the European level.’ (Notes from Poland, 2022)

Certainly, Poland decided to use nuclear energy and began preparation for it, but it should be kept in mind that the plan for introducing nuclear power plants in Poland is in its early stage, and nothing has been decided.

(2) Discussion on SMR development

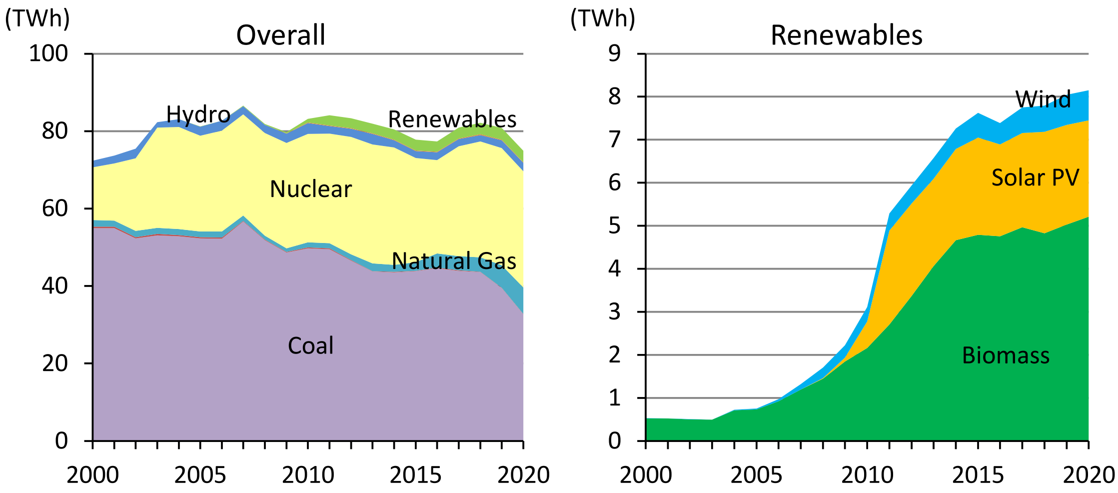
In October 2019, GE Hitachi Nuclear Energy and Synthos SA, a chemical industry company based in Poland, agreed to collaborate on potential deployment applications for GE Hitachi’s BWRX-300 SMR in Poland. Also, in November 2020, Synthos Green Energy, an affiliated company of Synthos SA, signed a cooperation 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. In August 2021, Synthos and ZE PAK, Polish energy companies, signed an agreement to launch a joint project to build four to six BWRX-300 SMRs, replacing the Pątnów coal-fired power plant owned by ZE PAK (World Nuclear News, 2021b).

Similarly, in February 2022, NuScale signed a definitive agreement with KGHM Polska Miedź SA, to initiate work towards deploying NuScale SMRs. They intend to introduce NuScale SMRs in Poland as early as 2029 (World Nuclear News, 2022c).

2.4. Czech Republic

(1) Nuclear energy policy

Figure 2.10. Electricity Generation by Source in the Czech Republic



PV = photovoltaic, TWh = terawatt hour.

Source: IEA (2021).

Nuclear energy has a large share today in the generation mix of the Czech Republic (Figure 2.10), 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.

In September 2021, the Chamber of Deputies of Czech Republic approved a new law to allow a state-owned electric company, ČEZ, to purchase electricity from new nuclear power plants at a fixed rate for at least 30 years with the possibility of extension. The power will be resold on the wholesale market and any profit or loss translated into an adjustment to power bills, although the government said it will set an upper limit on any extra cost. The law is known as Lex Dukovany, after the power plant site where the new build is planned (World Nuclear News, 2021c).

After six months of this decision, in March 2022, ČEZ launched a tender process to select a builder for a new nuclear unit at Dukovany. Construction of the new unit should begin in 2029 and be completed by 2036. Industry Minister Jozef Síkela said it would be the biggest investment in the modern history of the Czech Republic. The project could cost around €6 billion. As of April 2022, three companies are in the running for the contract, having passed a security appraisal: France's EDF, Korea's KHNP and the US firm Westinghouse (EURACTIV, 2022).

(2) Discussion on SMR development

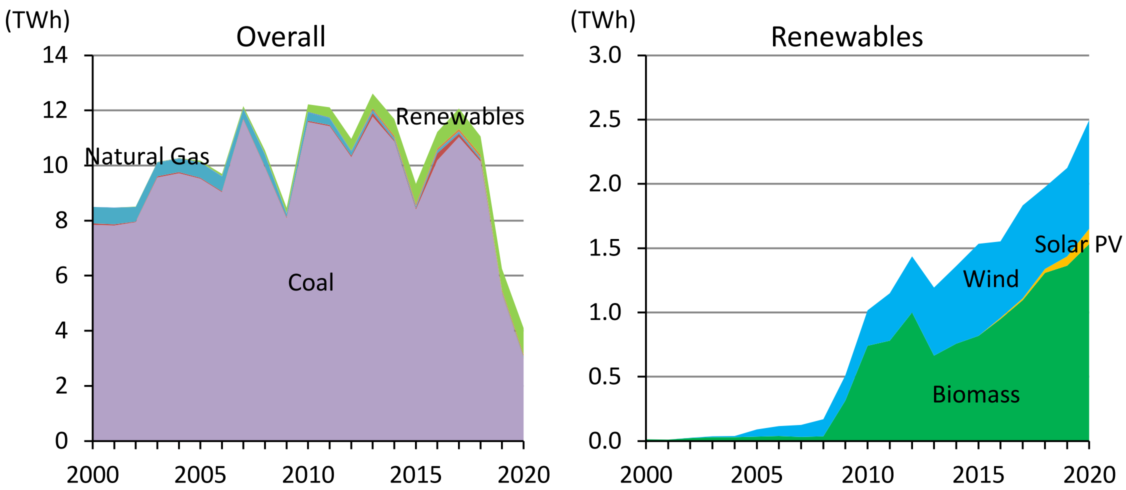
In September 2019, NuScale Power signed an MoU with ČEZ to explore applications for its SMR in the Czech Republic. In February 2020, GE Hitachi Nuclear Energy and Czech utility ČEZ signed an MoU on examining the economic and technical feasibility of potentially constructing a BWRX-300 in the Czech Republic (World Nuclear News, 2020a). In addition to these activities, ČEZ has signed an MoU to explore the potential for SMRs in Czech Republic also with the British engineering company, Rolls-Royce (World Nuclear News, 2020b).

On 31 March 2022, ČEZ released a decision that it has set aside a special space at the Temelin Nuclear Power Plant site where the country's first SMR could be built in the future. Upon the decision, ČEZ informed representatives of the South Bohemian Region and another US SMR developer, Holtec International. 'This decision (to build SMRs) does not interfere in any way with our plan to build two standard units at the Temelín site. Options for them are also part of the tender for the construction of a new nuclear unit at Dukovany, which we launched in March,' explained Daniel Beneš, Chairman of the Board of Directors and CEO of ČEZ (ČEZ, 2022).

2.5. Estonia

(1) Nuclear energy policy

Figure 2.11. Electricity Generation by Source in Estonia



PV = photovoltaic, TWh = terawatt hour.

Source: IEA (2021).

Estonia has no experience of operating nuclear power generation, and most of its electricity supply depends on coal (Figure 2.11). However, recently, it has begun considering the option of SMRs, as stated in the next section. In April 2021, the Estonian government formally approved the formation of a nuclear energy working group (NEPIO), which includes representatives of various Ministries and is tasked with analysing the possibility of introducing nuclear energy in Estonia. NEPIO will analyse technologies and actual projects under development in other countries and assess whether the development of a nuclear power plant should be carried out by the state or the private sector and what the possibilities for private-public cooperation could be (World Nuclear News, 2021d). However, all matters are yet to be decided.

(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.

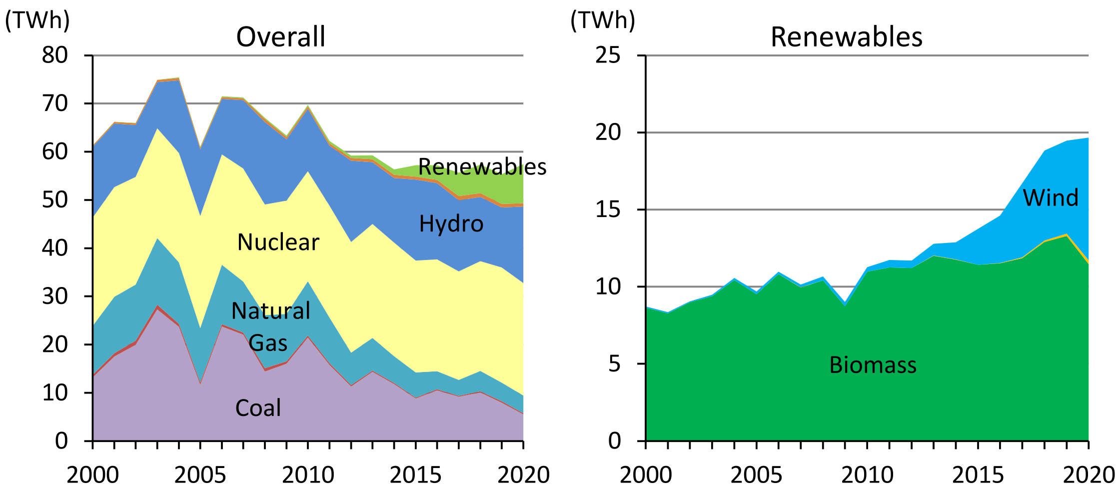
Fermi Energia held an online conference on 8 February 2022 supported by the Ministry of Environment of Estonia and some international organisations. At the conference, speakers including Kalev Kallemets, the CEO of Fermi Energia, and Meelis Münt, Secretary General of the Ministry of the Environment, agreed that Estonia needs to put in place the necessary legislation and competencies if an SMR is to be in operation by 2035 (World Nuclear News, 2021e).

The technology choice is, however, yet to be further considered before a decision is made. The high-temperature gas-cooled reactor would also be an option as well as other Generation-IV reactors. Licensing and the regulatory scheme would be the next challenges to be solved.

2.6. Finland

(1) Nuclear energy policy

Figure 2.12. Electricity Generation by Source in Finland



PV = photovoltaic, TWh = terawatt hour.

Source: IEA (2021).

Nuclear energy covers 34% of total electricity generation of Finland in 2020 (Figure 2.12). Additionally, construction of Olkiluoto-3, a large-scale European pressurised water reactor (EPR) was completed after long delay, and it was connected to the Finnish grid in January 2022. Another NPP was being planned in Hanhikivi, which was to adopt the Russian design VVER. However, the Russian invasion in Ukraine may affect the project. Fennovoima, a Finnish nuclear energy company that owns the Hanhikivi-1 project, said that detailed impacts of the decided sanctions against Russia on the project cannot be assessed for the time being and that it would keep carefully assessing the impact (Fennovoima, 2022).

(2) Discussion on SMR development

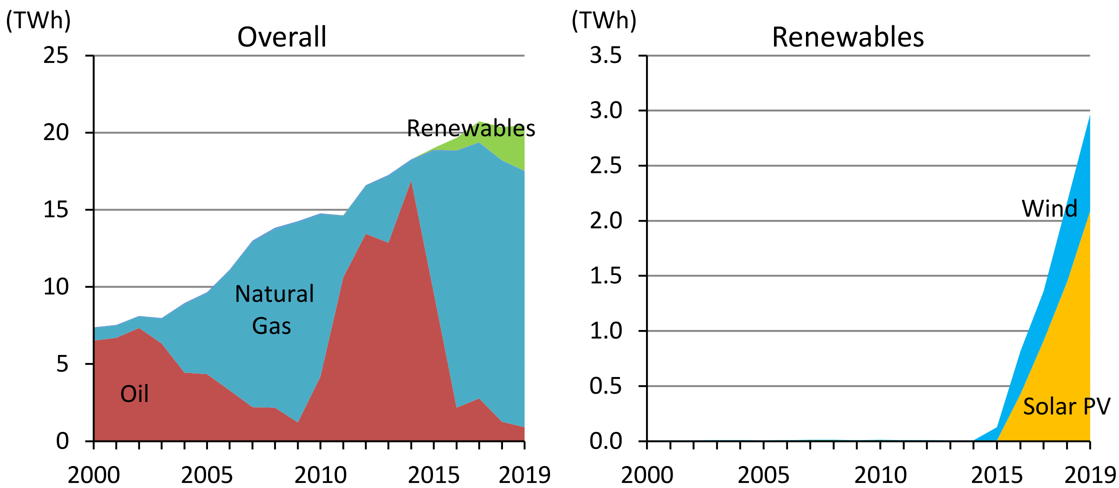
The Finnish Radiation and Nuclear Safety Authority (STUK, 2020) has published a report discussing issues related to licensing SMRs, which says: 'The current licensing procedure and safety requirements are mainly created for large, electricity generating, water-cooled reactors', and 'the needs for regulatory 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 2.13. Electricity Generation by Source in Jordan



PV = photovoltaic, TWh = terawatt hour.

Source: IEA (2021).

Jordan currently has no commercial NPPs, and the country seriously depends on fossil fuels (Figure 2.13). It imports around 95% of its energy consumption, and energy independence is an important issue. In 2007, the Jordan 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 (World Nuclear News, 2017a).

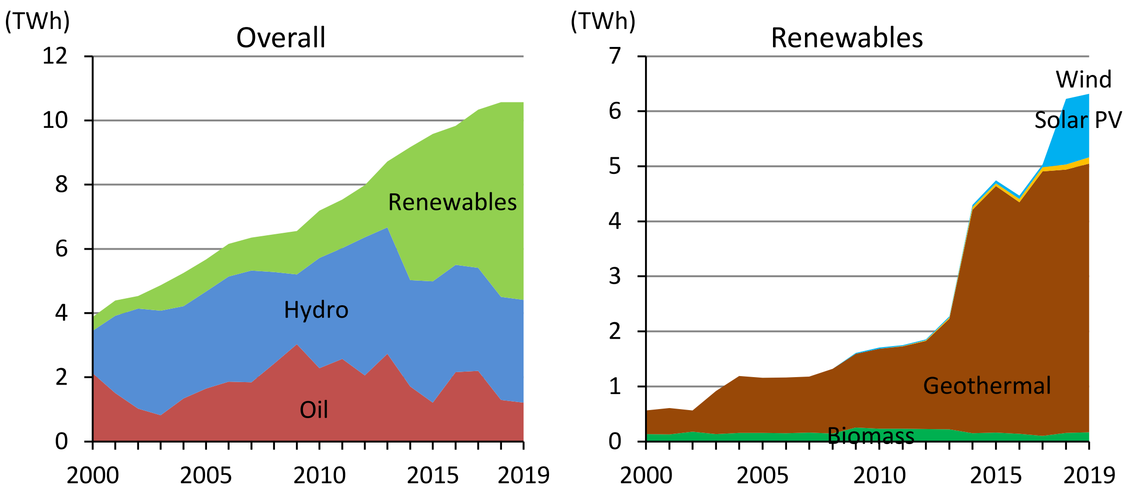
In November 2017, Rolls-Royce signed an MoU with the state-owned JAEC to conduct a technical feasibility study for the construction of Rolls-Royce SMRs in the Middle Eastern country (World Nuclear News, 2017b). In the same month, the JAEC signed an MoU with X-energy to assess the US company's SMR. They will look at the potential deployment of X-energy's Xe-100 high-temperature gas-cooled pebble bed modular reactor in Jordan (World Nuclear News, 2017c).

In addition, in January 2019, JAEC and NuScale Power signed an MoU that will launch a joint feasibility study on the deployment of NuScale's SMR in Jordan (World Nuclear News, 2019).

2.8. Kenya

(1) Nuclear energy policy

Figure 2.14. Electricity Generation by Source in Kenya



PV = photovoltaic, TWh = terawatt hour.

Source: IEA (2021).

Kenya currently has no NPPs, and the country deploys a lot of hydro and geothermal power generation (Figure 2.14). It 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, which was subsequently transformed into the Kenya Nuclear Electricity Board in 2012. In 2015, IAEA's Integrated Nuclear Infrastructure Review (INIR) was done, which made some recommendations and suggestions. And 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 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, the country planned to complete the first construction by 2027. However, it seems that the plan faces some challenges now. These challenges include the long compliance procedures before setting up, higher costs compared to renewable energy, and the problem of radioactive waste disposal.

In 2021, a follow-up mission of the Integrated Nuclear Infrastructure Review that was done in 2015 assessed Kenya's progress. Kenya had completed 10 of the recommendations and four of the suggestions from the 2015 review. Progress was as follows: (1) development of the National Nuclear Policy and the National Policy and Strategy for Safety to enable the government to make an informed decision on whether to introduce nuclear power; (2) enactment of a national nuclear law and establishment of a regulatory body with clear responsibilities for safety, security, and safeguards; (3) completion of an assessment of the national legal framework and identification of other laws needing review; (4) enhanced coordination amongst key stakeholders in the development of a nuclear power programme (World Nuclear News, 2021f).

(2) Discussion on SMR development

Ruwah (2019), who worked for NuPEA, reported an initial case study of Kenya's SMR reactor technology assessment. The study concluded that most SMRs are 'first-of-a-kind' technology and are still in the early stages of development (conceptual and design stages). It also referred to the insufficiency of data and noted that 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 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 models, the adoption of SMR 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. In the leading countries, such as 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. At first, the Western countries were in the lead for SMR development. However, China and Russia also boosted their efforts and have started construction of their first SMRs. As for the emerging countries mentioned in this chapter, they are considering the deployment of SMRs for their future energy mix and have begun discussions with SMR vendors.

Chapter 3

Small Modular Reactor Advantages and Opportunities

As interest in SMRs grows in the world, more and more people and organisations are having discussions or publishing reports to evaluate their benefits and feasibility. Some countries have already begun the pre-licensing phase of safety regulation. It is interesting that not all of them have favourable conclusions regarding SMRs. Such discussions would be meaningful for Asian countries that are considering deploying nuclear energy. Therefore, this chapter summarise such international discussions, reports, and a letter related to SMRs conducted or written in recent years.

1. NEA-IFNEC Webinar: The Financing of SMRs

On 18 May 2021, International Framework for Nuclear Energy Cooperation (IFNEC), an international framework for promotion of civilian nuclear energy cooperation, and OECD/NEA held an online webinar focusing on issues related to the financing of SMR projects. Below is a summary of the webinar.

1.1. Session 1 – Presentation of the NEA SMR Report

- SMRs are smaller in physical size and electrical output than conventional reactors. SMRs can be mass-produced at factories and transported to the construction site, which can improve economic efficiency. Relatively large-scale SMRs are suitable for replacing coal-fired power plants, and micro-reactors are applicable to off-grid areas.
- Load-following SMRs can coexist with variable renewable energy. They can also be used to desalinate seawater and produce hydrogen.
- Nevertheless, SMRs are facing many challenges. Significant progress has been made in terms of technology, but public trust and regulatory readiness remain problems.
- Decreasing the size of a project would reduce the risks and make it more attractive to financial institutions.

- To make SMR projects more feasible, we need to harmonise the international regulatory framework. Cooperation in global value chains would also be needed.

1.2. Session 2 – SMR Financing – Customers' perspective

- Coal-fired power plants have been shut down one after another in Europe, and some countries are closing nuclear power plants. Such countries are importing electricity, and electricity prices are supported by subsidies from the government.
- The carbon price is expected to keep rising in Europe. Therefore, the deployment of SMRs is an essential step. SMRs are important to meet the decarbonisation targets of each country.
- Funding should be secured step-by-step in parallel with the procurement process. It would also be important to have the government actively involved in communicating with local communities to help their decision-making.
- Kenya has published a roadmap to introduce nuclear power within 50 years. It seems that the economic competitiveness of SMRs is not so high today, but the Kenyan government sees SMRs as an important option given the potential for shorter construction time, lower maintenance costs, and utilisation other than electricity production. It is also paying attention to the combination of SMRs and renewable energy.

1.3. Session 3 – SMR Financing – Vendors' perspective

- X-energy's Xe-100 is a true game-changer. It can contribute to desalination, the petrochemical industry, district heating, and hydrogen production. It can also help renewable power generation through its load-following operation. Three major initiatives are underway: a programme led by the US Department of Defense, that led by Ontario Power Generation (OPG), and the Advanced Reactor Demonstration Program (ARDP) led by the US DOE. X-energy is a candidate for these programmes.
- There are emerging markets, including desalination and hydrogen production, as well as a distributed power market. These markets usually separate ownership, management, and operations to reduce the risk, so financing is likely to be complex.

State support of low-carbon power sources and a carbon tax would be meaningful.

- SMRs would be a game changer from a financial perspective because of their shorter construction period and small project size. It is important to expand the markets and secure policy support for SMRs. As financial policies, there are science and technology funds developed by national and local governments, as well as policy guidance for the early stages of R&D. We need to guarantee both the safety and the interests of our investors. Therefore, a flexible regulatory scheme is needed.

1.4. Session 4 – Panel discussion

- It was very difficult for X-energy to build a relationship of trust with investors under the COVID-19 pandemic. It was also difficult to quantify the risk related to regulatory requirements in each country.
- In China, the government funds almost all investment for R&D and it also provides tax credit. It will probably offer power purchase agreements at a fixed price. Despite this, it cannot be said that SMR projects will be successfully carried out without fail.
- One of the important issues in financing SMRs is government guarantees. There are also some social problems, such as the case with thermal power plants, which have already faced opposition from local communities. In some countries, the construction of thermal power plants has been stopped by lawsuits even though the projects had entered their final phase.

2. OECD/NEA Expert Group on Advanced Reactor Systems and Future Energy Market Needs

In December 2021, the OECD/NEA Expert Group on Advanced Reactor Systems and Future Energy Market Needs (ARFEM), which investigates the changing needs of energy markets and the potential role of advanced nuclear reactors, published a report of their study results. Below is a summary of the report.

2.1. Introduction

The needs of energy markets are continuously changing. Low-carbon energy sources can help to unlock hard-to-abate sectors, and various efforts are underway to develop these alternative energy sources.

Currently, various advanced nuclear reactor systems are under development and are capable of offering more flexible options with respect to energy supply. In order to analyse how and to what extent these technologies will be able to address future energy market needs and conditions, and the possible constraints that might arise, the OECD/NEA established ARFEM. ARFEM investigated the current situation and future prospects of energy market needs, as well as the characteristics and prospects for the development of advanced reactor systems. It also identified key factors that would help maximise the potential benefits of advanced reactor systems in future energy markets.

2.2. Future market opportunities and requirements

The need for flexible power operation from power plants is growing as variable renewable sources are increasingly penetrating electricity grids. Future advanced reactor system concepts have different characteristics for flexible operation.

The role of nuclear power in the electricity system may be more diverse in future, depending on the regional characteristics of the system. The development of electric vehicles, demand-side management, and storage technologies could allow conventional plants to operate at high-capacity factors, even with significant variable renewable sources deployment. Advanced reactor systems are also capable of providing firm capacity to ensure manoeuvrability over a wide range of timescales.

The heat sector is another area where advanced reactor systems can make a significant contribution. Lower temperature heat systems can be provided by conventional nuclear reactor systems, and higher temperature heat, under which a large percentage of the current global demand falls, could be provided by generation IV concepts. Also, small modular reactor systems aim to achieve higher deployment flexibility, which allows the reactors to be located closer to regions of demand.

Hydrogen production by advanced nuclear reactor systems could significantly contribute to the reduction of CO_2 emissions in many sectors. All advanced reactor system concepts can produce hydrogen using the existing low-temperature electrolysis technology, and some concepts could supply high-temperature heat, producing hydrogen with even higher efficiency. The role of advanced reactor systems in hydrogen production should be underlined for the potentially significant contribution to the decarbonisation of hard-to-abate sectors. Some national R&D programmes are working on coupling nuclear reactors with hydrogen-producing facilities.

The potential benefits of closed fuel cycle and generation IV systems may prove to be another strong motivation for deploying such systems in the short-to-medium term. For those generation IV systems that can demonstrate high levels of safety, co-location on certain sites may also be a valuable option.

2.3. Policy recommendations

The characteristics and needs of energy markets are becoming more diverse, and the strategies to reach carbon neutrality vary depending on the conditions. However, advanced reactor systems could adapt to such needs. In order to maximise the potential, the NEA is proposing the following policy recommendations:

- The potential of advanced reactor systems as a low-carbon, cost-effective means to support country policies with respect to low-carbon emission targets and variable renewable energy deployment should be recognised.
- Non-electric applications involving advanced reactor systems should be included in policymaking considerations.
- Governments and industry should work together to demonstrate the current capabilities of advanced reactor systems in target markets.
- International collaboration should be promoted to improve the economic viability of advanced reactor system development.
- Public understanding for advanced reactor systems should be continuously fostered.

3. The Socio-Economic Impact of GE Hitachi SMRs

One of the Canadian electric power utilities, Ontario Power Generation (OPG) is seeking to deploy an SMR plant at its Darlington site. Amongst three candidate designs, OPG eventually selected BWRX-300 developed by GE Hitachi Nuclear Energy. Prior to the decision, international consulting firm PricewaterhouseCoopers (PwC) conducted a research project that evaluated the impact that would be brought by the deployment of the BWRX-300 in Ontario. Below is a summary of the report.

3.1. About GE's BWRX-300

The BWRX-300 is a 300 MWe boiling water reactor (BWR). This reactor technology builds on existing BWR technology with a proven track record, which means the BWRX-300 is advantageous in commercial readiness. At the same time, the reactor design is innovative, with dramatic simplification and the elimination of unnecessary systems. The regulatory process for the BWRX-300 has been progressed in North America. The Nuclear Regulatory Commission (NRC) in the US has issued a Final Safety Evaluation Report for three licensing topical reports. In addition, the vendor design review process with the Canadian Nuclear Safety Commission (CNSC) is underway. To date, feedback has been positive, and no barriers have been identified.

3.2. Economic footprint of the GE SMR

PwC assessed the direct, indirect, and induced economic footprint of development, manufacturing, and operations of GE's SMR with the OPG. According to their assumptions, CA$2.0 billion would be spent for GE's first-of-a-kind SMR over seven years in the manufacturing and construction phase. After that, operation of the SMR at the Darlington site would bring annual spending of CA$35.0 million over the project lifetime. This spending would increase GDP by CA$1.3 billion, labour income by CA$1.1 billion, and tax revenue by CA$460 million and would sustain 1,712 jobs per year over seven years of the construction phase. As for the operating phase, GDP would be increased by $1 billion, labour income would be increased by CA$768 million, and tax revenue would be increased by CA$303 million, and 197 jobs would be sustained per year over 60 years.

If another BWRX-300 plant is constructed in Ontario or in other provinces of Canada or is exported to other countries, it would bring further economic impact as shown in Table 3.1.

Table 3.1. Estimated Economic Impact of the BWRX-300

Scenario	Economic footprint (excluding operating impacts)
Future Ontario reactors: per-reactor benefits of subsequent SMRs that GE will install alongside partners in Ontario	CA$1.1 billion in GDP, CA$728 million in labour income, CA$312 million in tax revenue, and sustain 1,951 jobs per year over four years
Future Canadian reactors outside of Ontario: per-reactor benefits of subsequent SMRs that GE will install alongside partners elsewhere in Canada	CA$1.1 billion in GDP, CA$730 million in labour income, CA$313 million in tax revenue, and sustain 1,956 jobs per year over four years
Export activity: per-reactor benefits to Canada of GE's BWRX-300 SMRs installed internationally	CA$98 million in GDP, CA$110 million in labour income, CA$46 million in tax revenue, and sustain 217 jobs per year over four years

Source: PwC (2021).

3.3. Broader benefits

The benefits of deployment of the BWRX-300 go beyond the economic footprint above. There would also be various additional benefits. First, the deployment of the SMR would help Canada to fulfil its climate change commitments. GE, especially, is taking action to reach net zero emissions for its operations by 2030. Second, GE is committing to diversification and inclusion. It is trying to increase the representation of women and other marginalised groups in the nuclear sector. Third, GE emphasises engagement with indigenous communities as part of the SMR deployment, including creating opportunities for employment. Fourth, the deployment of the BWRX-300 would bring skill development for employees that will enhance safety and technical excellence and increase the technical skills of workers in Ontario and Canada. Finally, technical excellence will enhance the concentration of engineering talent and know-how in Ontario and Canada.

4. Nuclear Power and Small Modular Reactors in Indonesia

In 2017, the Nautilus Institute for Security and Sustainability, a public policy think tank studying various issues related to security, energy, and climate change, etc. published a report that evaluates the possibility of SMR deployment in Indonesia. The following is a summary of the report.

4.1. Indonesian Interest in SMRs

Since the late 1970s, the Indonesian Atomic Energy Agency (BATAN) has been trying to convince the government of the need to embark on a nuclear power programme. However, since state-owned companies are not in a position to make large-scale investments, it is not possible to build nuclear power plants in Indonesia for the time being. Therefore, a possible breakthrough for construction is the introduction of small reactors of Generation IV nuclear power, with the goals of low power generation costs that can compete with thermal power, high safety without major accidents, less waste, and nuclear proliferation prevention. On the other hand, the technological innovation of SMRs itself has not progressed as much as expected. Whilst SMRs that satisfy the three requirements of safety, non-proliferation, and reduction of nuclear waste are being developed, the lack of SMRs with price advantages has become a bottleneck in the construction of new nuclear power plants.

4.2. Public opinion and opposition to nuclear power

Since the 2010s, based on BATAN surveys of public attitudes, it has become clear that nearly 60% of the public generally supports nuclear power plants, whilst 40% do not. In particular, the 2011 survey confirmed that disapproval exceeded support, which is believed to be due to the Fukushima nuclear power plant accident. In response, BATAN actively undertook activities designed to increase public support for nuclear power.

Like many countries around the world, Indonesia is in the midst of a heated debate over the pros and cons of nuclear power. Civil society organisations have played an important role in this debate. The main organisations opposing nuclear are the Indonesian Anti-Nuclear Community (Masyarakat Anti Nuklir Indonesia, MANUSIA), the Indonesian Forum for Environment (Wahana Lingkungan Hidup Indonesia, WALHI), Greenpeace, and Nahdlatul Ulama (especially in the Central Java sector).

4.3. SMR proposals

In addition to a general interest in SMRs, the Indonesian nuclear establishment has studied some SMR possibilities in much greater detail.

- Gorontalo floating small NPP proposal

The oldest nuclear proposal directly relevant to SMR technology stems from the mid-2000s when the Russian nuclear supplier Rosatom proposed a small Russian floating nuclear power plant to supply electricity to Gorontalo Province, Sulawesi. Floating nuclear power plants are modelled after the reactors used to power a small fleet of nuclear-powered icebreakers operated by Russia for decades. The government, on the other hand, has expressed its opposition to the construction of floating nuclear power plants and believes that they should be built on land.

In May 2015, the provincial government of Sulawesi urged the central government of Indonesia to build a nuclear power plant, as the region was experiencing power shortages. However, such motivation for building a nuclear power plant disappeared because they decided to build a 100-MW (four 25 MW plants) gas-fired power plant in Pohuwatu in the same province.

- Madura desalination small NPP proposal

In October 2001, under the framework of the Interregional Technical Cooperation Project of the IAEA, BATAN signed an agreement with Korea Atomic Energy Research Institute to undertake a joint study, entitled 'A Preliminary Economic Feasibility Assessment of Nuclear Desalination in Madura Island'. The institute has been developing an SMR called the System-Integrated Modular Advanced Reactor since 1996. However, no progress can be seen since they conducted seismic and economic surveys.

- West Kalimantan NPP proposal

Another region that has been identified by BATAN as a potential site for SMRs is West Kalimantan, in part because of the paucity of grid infrastructure in the area. This plan seemed to be supported by the provincial government. Based on this, the Nuclear Power Plant Development Coordination Team was formed. Considering the long-term electricity demand in the West Kalimantan region, they argued that if a nuclear plant were to be built at all, then it would necessarily have to be an SMR, which is not the same as asserting that a SMR should be built.

4.4. Electricity landscape and comparison of costs

Domestic forecasts of the future Indonesian energy mix by 2050 seek to increase the share of new and renewable energy. The fuel mix in the power sector is projected to be dominated by coal and gas-fired power plants. The total new and renewable energy target for Indonesia's energy is set at 31% by 2050. According to the same projections, nuclear power plants are 'estimated to enter the Java-Bali electricity system in 2030 with a capacity of 2 GW' and this is projected to 'increase up to 6 GW in 2050' (BPPT, 2015). Moreover, the National Development Planning Agency has incorporated plans for nuclear energy into the National Mid-Term Development Plan 2015-2019, and nuclear energy is also included in the most recent Government Work Plan. On the other hand, in the long-term scenario, there is currently no prospect that new SMR construction will be promoted.

The Nautilus Institute shows a study that compares the power generation costs of solar PV, a conventional large-scale NPP, and an SMR. As a result, PV has the lowest cost of power generation at US$73.25/MWh, followed by the large-scale NPP at US$183.63/MWh, and the SMR at US$222.15/MWh.

4.5. Conclusion

There are two bottlenecks to realising the construction of SMRs in Indonesia. First, it is difficult to improve the political environment for contributions to the expansion of the nuclear industries. Since the 1970s, attempts to establish a nuclear power plant have failed to convince government leaders, and no obvious progress has been made thus far. In addition to this, it has been pointed out that there is not enough public consensus on nuclear energy. Secondly, the cost of SMRs is high compared to conventional large-scale nuclear reactors and solar power generation, which has become more competitively priced in recent years. For these reasons, it is unlikely that the installation of SMRs in Indonesia will be large enough to contribute to the improvement of power generation.

5. NRC letter: Denial of the Aurora combined operating licence application

In the US, NuScale's SMR has successfully received the standard design approval from the US Nuclear Regulatory Commission (NRC). However, Oklo's micro-reactor, named Aurora, was refused in the pre-licensing process. Below is a summary of NRC's letter declaring the denial of the review of Aurora. It is important to learn from the NRC's letter why Oklo's proposal was refused and what the issues were in the regulatory discussions.

5.1. Overview

The custom combined licence application for the Aurora micro-reactor was denied by US NRC staff. The specific reasons for the denial are based on the following: (1) Oklo repeatedly failed to submit the information needed to complete the Step 1 review of its maximum credible accident (MCA) analysis and safety classification of its structures, systems, and components (SSCs); (2) Oklo's 30 October 2020 responses to NRC staff's requests for additional information (RAI) did not contain sufficient technical information; and (3) the topical reports Oklo submitted to address Step 1 of the review to support a predictable review schedule contained information that was conceptual in nature and did not adequately describe Oklo's methodologies for Aurora's MCA analysis or for the safety classification of the SSCs.

5.2. Two-step process

After providing limited information about its final design to the NRC staff in the pre-application engagement, Oklo submitted a custom combined licence application for one micro-reactor, designated as the Aurora, located at the Idaho National Laboratory, by letter dated 11 March 2020. However, a custom combined licence application must contain complete design information and all site-specific information necessary for the NRC staff to reach safety and environmental findings for licensing and establish a full review schedule. Instead, the NRC staff developed a novel two-step process for the review, and informed Oklo by letter dated 5 June 2020 that the application would be docketed and reviewed under this two-step process. Step 1 intended to obtain from Oklo additional information on key safety and design aspects of the Aurora licensing basis. In establishing the two-step review process, the NRC staff noted their commitment to completing the safety review of the Aurora application within the established generic 36-month NRC schedule for such reviews. To complete Step 1 of the review, the NRC staff engaged with Oklo in numerous public meetings, conducted regulatory audits, and issued RAIs on four key aspects of the application.

The NRC's letter dated 5 June 2020, communicated the need to address four foundational aspects of the Aurora licensing basis during Step 1 of the review: (1) MCA analysis, (2) safety classification of the SSCs, (3) scope of the quality assurance programme, and (4) applicability of regulations.

5.3. Oklo's failure

Of the four issues identified for resolution in Step 1 of the custom combined licence application review, Oklo's MCA analysis and safety classification of SSCs remain open. Oklo proposed a novel approach to determining the spectrum of potential accidents and the safety classification of the SSCs within its design. Oklo was required to explain its novel approaches and the NRC staff would evaluate their reasonableness. Although Oklo has been provided several opportunities to provide the necessary technical information, it has failed to do so.

By letter dated 2 July 2021, Oklo submitted two topical reports that contained insufficient technical information to address the open Step 1 issues for NRC staff review. The NRC staff performed completeness reviews of the topical reports and determined that neither topical report contained sufficient information to initiate detailed technical reviews. Each report contained conceptual information, rather than repeatable methodologies, and each left many issues unresolved and open for future potential applicants referencing the topical reports to address.

The NRC staff identified significant information gaps in the Aurora custom combined licence application in its 5 June 2020 docketing decision and has engaged with Oklo since August 2020 in sustained efforts to provide Oklo with options for providing the information needed on the topics of MCA and the safety classification of the SSCs. The NRC staff used public meetings, audits, RAIs, and conducted two completeness reviews of the topical reports to provide Oklo with clear descriptions of the information Oklo must provide. However, the NRC staff has been unable to obtain the necessary information from Oklo to support the completion of the Step 1 review.

Prior to submitting its custom combined license application for Aurora or its topical reports, Oklo chose to conduct limited pre-application discussions with the NRC staff regarding its

MCA methodology and safety classification of the SSCs. Additionally, the NRC staff reviewed and approved the Oklo Quality Assurance Program Description and the safeguard information protection and handling plan. Oklo covered a broad range of topics in its pre-application engagement with the staff, but the effectiveness and relevance of the pre-application engagement was limited because (1) NRC staff feedback from the pre-application engagement was not incorporated into the Aurora custom combined licence application and (2) Oklo made other changes to the Aurora design and/or design basis after these interactions that limited the applicability of prior discussions to the Aurora custom combined licence application.

5.4. Conclusion

Based on Oklo's failure to provide the NRC with the necessary information on its reactor, as described above, the NRC staff has insufficient information to establish a schedule or conduct a full review of the Aurora custom combined licence application and, therefore, denied the application for failure to supply information.

Chapter 4

Conclusion and Recommendations

1. Analysis

As this research has revealed, SMRs can be a new solution for world energy demand that cannot be satisfied by conventional large-scale nuclear reactors. The technical features of SMRs would be suitable for the general demand in the world today because (1) low-carbon energy is required, especially since 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 financial capacity. Therefore, many countries in the world recently have shown interest in investing in SMRs, as clarified in Chapters 2. In addition to those motivations, the Russian invasion in Ukraine, which began in February 2022, may highlight the value of nuclear energy, including SMRs, in energy security and independence. In fact, the UK published its Energy Security Strategy in April 2022 and has announced that it will boost construction of nuclear power plants and increase investment in SMR deployment.

Such interest in SMRs has encouraged discussions all over the world, as described in Chapter 3. Many experts have pointed out the advantages of SMRs at international conferences and in reports. Some organisations, such as PwC (2021) referenced in Chapter 3, have published concrete and quantitative studies on the benefits of SMR deployment. However, it is important to note that there are many problems to be solved and not all experts are favourable towards SMRs. The Nautilus Institute (2017) showed a critical view of SMR deployment in Indonesia. Government authorities and electric power utilities in countries that are considering deploying SMRs should promote further studies and make their decisions taking various viewpoints into account. Discussions with regulatory authorities are also important for vendors because they can identify safety issues in reactor designs. Through such discussions, vendors should submit the required information and explain how their reactors can satisfy the regulatory requirements, otherwise their applications for approval must be rejected. The letter from NRC to Oklo (2022) referenced in Chapter 3 clearly shows the importance of such interaction between vendors and regulatory bodies.

At the same time, SMR vendors should accelerate their efforts for technology development and deployment. You can see the concepts of SMRs referred to even in documents or articles published around 30 years ago (e.g. IAEA (1996)), which means SMRs have been researched and developed for a long period but have not been deployed for commercial use yet. Keeping in mind the fact that customers finally decide whether to purchase a product or not, it is crucial to make an attractive proposal for customers. To this end, the IEEJ makes the following policy proposals.

2. Policy Proposals

1) For the leading countries of SMR development:

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. 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.

There should also be international efforts to harmonise the regulatory requirements for SMRs around 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 SMR vendors:

As stated in Section 0, SMR technologies have long been developed by vendors and research institutes, but no commercial reactors have been deployed until present. Now that China and Russia have started construction of their SMRs, vendors in Western countries should follow them. At the same time, their products should be attractive for their customers (electric power utilities, in most cases).

Concurrently, it is crucial for vendors to pass the review process of the regulatory authorities and get design approval for the commercial deployment of SMRs. For a smooth and flexible review process, it is important to have intensive discussions with the regulatory body. If the regulator shows clear instructions to solve safety issues, the vendor should follow them and submit the required documents as soon as possible.

SMR vendors in the leading countries should also promote discussions in Asian or African countries that are considering the deployment of SMRs. To this end, it is important for vendors to clarify the technological features and specifications of their products to help potential customers in their decision-making processes.

3) For countries in Asia or Africa considering the deployment of SMRs 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, as this can 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. Besides these efforts, if they want to deploy 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. Cooperation with countries that have experience in operating nuclear power plants and with international organisations like the IAEA would be very helpful for this step. Finally, 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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