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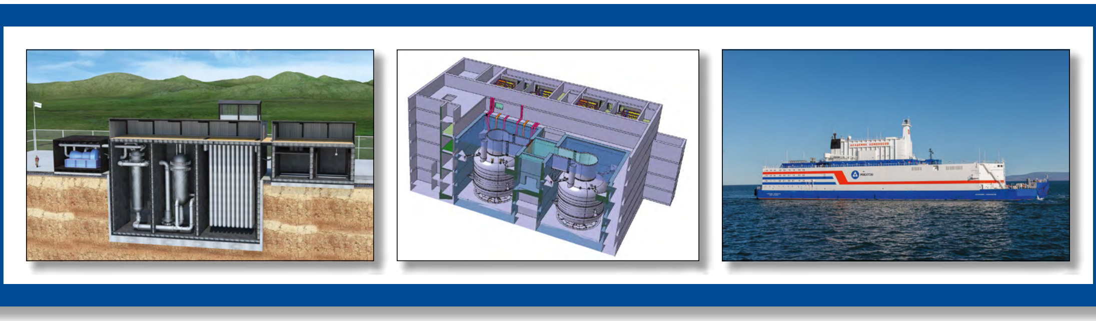
Small Modular Reactors: Challenges and Opportunities



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Nuclear Technology Development and Economics

Small Modular Reactors: Challenges and Opportunities

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- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;
- to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

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Foreword

Policymakers, nuclear power companies and energy analysts around the world have been demonstrating a growing interest in the potential of small modular reactors (SMRs) as a competitive, low-carbon technology component of future integrated energy systems. SMRs harbour the promise of inherent safety features, of simplification and standardisation that could make nuclear capacity far easier and more economic to deploy, and of significant advancements in terms of the overall flexibility of nuclear energy in meeting future energy needs. Developers are making significant progress towards deployment of demonstration plants, but important questions remain to be answered regarding the commercial viability of SMRs.

In 2011, the OECD Nuclear Energy Agency (NEA) published *Current Status, Technical Feasibility and Economics of Small Nuclear Reactors* (NEA, 2011), which mainly focuses on factors influencing the economic performance of SMRs. This report was followed by the publication of *Small Modular Reactors: Nuclear Energy Market Potential for Near-Term Deployment* (NEA, 2016). This latter study provided a first estimation of the size of the global SMR market by 2035 and concluded that future prospects could strongly vary depending on factors such as successful licensing and supply chain maturity. Energy markets have continued to evolve in parallel – underpinned by more ambitious decarbonisation policies – which has led to the emergence of new opportunities for all low-carbon technologies, including SMRs. In addition, the difficulties encountered by recent nuclear projects in OECD countries, which are based on traditional large Generation III+ nuclear designs, have further enhanced the desire for nuclear technologies that are more affordable and easier to construct.

In June 2017, the NEA Nuclear Law Committee (NLC) held a topical session on the legal aspects of SMRs. This session highlighted some issues that would need further discussion with regard to the application of the nuclear liability regimes to floating/transportable SMRs (such as the need to clearly incorporate them in the definition of “nuclear installation” and the concept of “operator”). The Committee also welcomed further assessment of the legal aspects of regulatory issues under the NLC Working Party on the Legal Aspects of Nuclear Safety (WPLANS). Similarly, at the NEA Committee on Nuclear Regulatory Activities (CNRA) topical session held in June 2019, the decision was made to consider initiatives related to SMRs within the context of the overall strategic review of the CNRA activities.

The present report is the most recent NEA contribution within this context, providing a comprehensive overview of the SMR technologies in order to assess the opportunities, and more importantly, the main challenges that these technologies have to overcome to achieve large-scale deployment and economic competiveness. It provides an overview of technical, economic and market aspects of previous publications, and it explores licensing, regulatory, legal and supply chain issues. The next steps in SMR development, will require more extensive international collaboration and governmental support in all these interconnected dimensions to build a global and robust SMR market.

Acknowledgements

Small Modular Reactors: Challenges and Opportunities is based on a background note that was prepared for the "Policy Briefing on Small Modular Reactors" held at the 139th Session of the Nuclear Energy Agency Steering Committee of Nuclear Power on 25 October 2019. Antonio Vaya Soler and Michel Berthélemy, from the NEA Division of Nuclear Technology Development and Economics (NTE), prepared the current report on this basis. Vladislav Sozoniuk, from the Office of the Director General (ODG), Aditi Verma (NTE), Andrew White, from the NEA Division of Nuclear Safety Technology and Regulation (SAF), and Kimberly Sexton Nick, from the NEA Office of Legal Counsel (OLC), also participated in the drafting. Management oversight and additional input was provided by the Heads of Division, Sama Bilbao y León and Gloria Kwong (NTE), Ximena Vásquez-Maignan (OLC) and Véronique Rouyer (SAF). They are all gratefully acknowledged.

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List of abbreviations and acronyms

CNL	Canadian National Laboratories
CNSC	Canadian Nuclear Safety Commission
CORDEL	Cooperation in Reactor Design Evaluation and Licensing (WNA working group)
COTS (components)	commercial, off-the-shelf
FOAK	first of a kind
Gen IV	Generation IV
GIF	Generation IV International Forum
GWe	Gigawatt electric
DOE	United States Department of Energy
EPZ	emergency planning zone
HALEU	high-assay low-enriched uranium
HEU	high enriched uranium
HTGR	High-Temperature Gas-Cooled Reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
INL	Idaho National Laboratory (United States)
kWh	kilowatt hour
LCOE	levelised cost of electricity
LOCA	loss-of-coolant accident
LRL	licensing readiness level
LWR	light water reactor
MDEP	Multinational Design Evaluation Programme
MMR	micro modular reactor
MOX	mixed oxide fuel
MWe	megawatt electric
NEA	Nuclear Energy Agency
NNL	National Nuclear Laboratory (United Kingdom)

NSSS	nuclear steam supply system
NLC	Nuclear Law Committee (NEA)
NRC	Nuclear Regulatory Commission (United States)
PHWR	pressurised heavy water reactor
SDS	Sustainable Development Scenario
SMR	small modular reactor
TRL	technology readiness level
VRE	variable renewable energy
WNA	World Nuclear Association

Executive summary

A large number of small modular reactor concepts at different maturity levels

Small modular reactors (SMRs) are generally defined as nuclear reactors with power outputs between 10 megawatt electric (MWe) and 300 MWe. SMRs present several technical features that enhance construction predictability and lead to potential reductions in construction costs and delivery times. Those designs with power outputs smaller than 10 MWe – often for semi-autonomous operation – have been referred to as micro modular reactors (MMRs).

According the International Atomic Energy Agency (IAEA), approximately 70 SMR concepts are currently under development, which represents a 40% increase from 2018. While the term "SMR" has been adopted around the world to refer to all small reactor designs, significant differences remain across the major types of SMRs under development. These SMR designs use a variety of coolants and fuel forms, for example, and have different technology readiness levels (TRLs) and licensing readiness levels (LRLs). SMR deployment can also adopt different configurations ranging from single-unit installations and multi-module plants to mobile powersets such as floating (i.e. barge mounted) units. The degree of modularisation also varies across designs.

The most mature SMR concepts being proposed by vendors are evolutionary variants of light water Generation II and Generation III/III+ reactors (LWR-SMRs) operating worldwide, and these benefit from many decades of operating and regulatory experience. They represent approximatively 50% of the SMR designs under development. The other 50% of SMR designs corresponds to Generation IV reactors (Gen IV SMR) that incorporate alternative coolants (i.e. liquid metal, gas or molten salts), advanced fuel and innovative system configurations. While Generation IV-based designs do not have the same levels of operating and regulatory experience as that of LWRs, and additional research is still needed is some areas, they nevertheless benefit from an extensive history of past research and development upon which developers and regulators may draw.

A new delivery model and value proposition at the centre of SMR competitiveness

The smaller size of SMRs would imply that they will not benefit from economies of scale. In order to overcome this economic challenge, "series construction" will become an imperative. SMR designs should thus display accelerated learning curves through higher degrees of modularisation, simplification and standardisation compared to those of larger nuclear reactors. Factory fabrication also provides an environment of enhanced quality control that can reduce construction risks, foster learning and enable the introduction of new manufacturing techniques. Some of these benefits have already been demonstrated in other industries but still need to be proven for SMRs.

At the same time, the smaller size and the prediction of shorter delivery times could reduce upfront investment needs for SMRs compared to larger reactors. The result is a lower financial risk for potential customers and investors, which could make SMRs a more affordable option. Other features that enhance the attractiveness of the SMR value proposition are related to SMR flexibility capabilities (both enhanced load-following and non-electric applications) that could bring system-cost benefits and new market opportunities, thus facilitating access to nuclear energy in regions and sectors where the use of large nuclear power plants is more limited.

Need to review the regulatory and legal framework

As these new technologies were not envisaged when the currently applicable international nuclear conventions were drafted, such conventions would need to be reviewed in order to adapt them, if necessary, to the innovative SMR concepts that are currently being assessed or undertaken.

For example, current licensing frameworks typically rely on the extensive experience base of large single-unit LWRs that use uranium oxide fuel with enrichment below 5%. The LWR-based SMRs being proposed have similar operating conditions and fuel arrangements, which are expected to facilitate their licensing process. However, the main difficulty with novel designs is the more limited experience base, making it challenging to demonstrate and approve their safety case based on more efficient passive safety features, fewer and less severe failure modes and reduced off-site emergency planning zones (EPZs). In addition, changes to the fuel and/or coolant will translate into greater deviations from previous regulatory paradigms and may require more flexible licensing approaches, as well as the development of a considerable amount of new expertise within nuclear safety regulatory organisations.

If the international nuclear liability conventions cover in principle SMRs, further attention will be required to address their application to floating/transportable nuclear power plants.

NEA countries gaining experience in SMR development

A number of NEA member countries are now supporting SMR development through different approaches by facilitating the development of a domestic programme and/or construction of demonstration and/or first-of-a-kind (FOAK) units. The United States Department of Energy (DOE), for example, is providing cost-sharing support to selected SMR companies via public-private partnerships and granting these companies access to experimental facilities housed at national laboratories. The United Kingdom also provide financial support to SMRs as part of the technology portfolio necessary to reach its 2050 carbon neutrality objective.

Countries, such as Canada or Finland, are also currently focusing on the development of policy frameworks, including licensing regimes, which can better support the deployment of new technologies.

Challenges ahead for large-scale SMR deployment

When assessing the economic rationale of SMRs, market issues become central. On the one hand, if SMRs are manufactured in a mass production fashion similar to commercial aircrafts, the economic benefits could be significant. This would require, however, that the market for a single design be relatively large, which thus highlights the need for a global market and also suggests that only a small subset of the many designs under development may ultimately be able to establish such a global market.

Higher levels of regulatory harmonisation will need to be observed in order to support a global market, as well as a reduction in the number of designs proposed by vendors. SMRs have furthermore introduced a series of untested innovations that may also lead to additional technology risks. However, as SMRs gain in maturity with the first demonstrators coming online, some of these risks should be mitigated, thus increasing interest from potential customers. The supply chain should also be ready to support the emergence of a market for SMRs, ensuring the timely availability of factory-fabrication capabilities, high-assay low-enriched uranium (HALEU) and other innovative fuel production capacities, along with the necessary skills and research and development (R&D) infrastructure.

Lastly, since several of these SMRs attempt to minimise evacuation zones and place the reactors closer to large population centres, additional challenges may arise in terms of public engagement.

Government support and international collaboration: Key enablers for SMR deployment

Countries supporting the SMR option may see value in setting a path forward that focuses on four main areas of action where government support and international collaboration will play a key role:

- **Public engagement**: Future projects can benefit from international collaboration, exchanging information on lessons learnt, and difficulties and best practices identified by early adopters through public engagement with local communities.
- **Construction of FOAK SMR demonstration units and learning**: Governments can support FOAK demonstration projects in many forms, ranging from specific long-term power purchase agreements to cost-sharing mechanisms that can minimise construction risks so as to attract more investors. Supporting regulators' efforts to develop the necessary licensing regimes and capabilities is also essential. In parallel, efforts should continue to translate research into effective deployment by hosting first experimental units and funding the necessary research infrastructure.
- **Harmonisation of licensing regimes**: Advancements can be made in harmonisation by leveraging existing collaborative frameworks for large reactors, as well as in other highly regulated sectors. While complete harmonisation may be unrealistic (and in some respects, undesirable), efforts should continue in areas where meaningful common regulatory positions could be achieved. NEA explorations of multilateral licensing co-ordination, bi-lateral collaborations and joint safety evaluations, such as were conducted under Multinational Design Evaluation Programme (MDEP), should be considered. Significant opportunities for harmonisation at pre-licensing level also exist, which could foster the down-selection process of SMR designs.
- **Development of manufacturing capabilities**: By committing to a national nuclear programme of several SMR units, governments can scale up manufacturing capabilities. Countries already engaged with large nuclear projects could take advantage of the synergies within existing capabilities and delivery processes. Key partnerships and industrial collaboration could also be explored among countries so as to share the potential risks. Fuel cycle issues need to be anticipated in order to properly support market prospects. And finally, efforts should be undertaken to harmonise codes and standards that could bring additional market benefits.

1. Introduction: SMRs in future energy systems

If countries are to meet Paris Agreement objectives to reduce greenhouse gas emissions, nuclear power will need to make a significant and indispensable contribution to the overall energy mix. According to the International Energy Agency (IEA) Sustainable Development Scenario (SDS), new nuclear capacity and ambitious lifetime extension programmes for existing nuclear power plants will be needed to meet such objectives. The Intergovernmental Panel on Climate Change (IPCC) has also confirmed the need for a growing role on the part of nuclear power to meet decarbonisation objectives (IPCC, 2018).

Nuclear power, however, is not on track to reach its required share in global electricity generation. In fact, the current rate of an additional 5 gigawatt (GW) annual capacity would need to at least double between 2020 and 2040 to meet the SDS. Life-time extensions beyond initial design lifetimes of 30 to 40 years would also be required in order to alleviate the pressure in the nuclear construction supply chain[1] and to contain overall decarbonisation costs (IEA, 2019, 2020).

Numerous reasons can be evoked for the shortfall of capacity additions in nuclear new build compared to the SDS scenario. Factors having the most impact are related to the high cost of new nuclear projects, particularly in countries that have not built nuclear plants in recent decades. These first-of-a-kind (FOAK) Generation III projects have been affected by construction delays and cost escalations, particularly in OECD countries, which has contributed to undermining stakeholder and public confidence in the ability of the nuclear industry to build new projects. In addition, the perception that new nuclear plants carry high project risks has dissuaded investors and further reduced the ability of countries to attract financing for future projects (NEA, 2020).

In parallel, small modular reactors (SMRs) have been capturing the attention of policymakers as an example of a technology option that can address part of the challenges observed in recent nuclear projects. The SMR technology would also offer opportunities to expand the role of nuclear energy as a means of decarbonising the overall energy mix. This is especially the case in non-electrical applications of hard-to-abate sectors where low-carbon technology options are more limited. While significant progress has been made in the validation of designs concepts, many challenges nonetheless remain.

The objectives of the present report are to:

- present SMR concepts and their current status of development;
- summarise the potential benefits of SMRs and their key economic features;
- identify the main challenges for the commercial development of SMRs and identify potential strategies that could help address them;
- propose a potential path forward for the development and deployment of SMRs.

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[1] To meet SDS capacity addition targets, around 20 GW of new capacity per year from 2021 would be required without the lifetime extensions of existing nuclear power plants beyond 40 years.

2. An overview of SMR technology

2.1. History and definition

Although they are today widely considered a revolutionary nuclear energy technology, nuclear reactors of small size are not a recent development in the global nuclear industry. In fact, the first commercial reactors developed and deployed during the late 1950s and 1960s – based on light water reactor (LWR) technology – were to a large extent scaled-up versions of small naval propulsion reactors. During that same period, a large variety of small reactors were constructed by governments for a range of security and military purposes. What makes current small reactors a potential game-changer is not simply their size but the fact that their design deliberately takes advantage of the smaller size to bring about transformative safety features, delivery models and business cases.

SMRs are defined today as nuclear reactors with a power output between 10 megawatt electric (MWe) and 300 MWe. They integrate by design higher modularisation, standardisation and factory-based construction in order to maximise economies of series (or the "series effect").[1] The different modules can then be transported and assembled on-site, leading to predictability and savings in construction times.

2.2. Reactor types and projects under development

SMR designs can be classified in a number of ways (NEA, 2011). SMR designs under development use a variety of coolants and fuel forms with different technology readiness levels (TRLs) and licensing readiness levels (LRL) (NEA, 2018). Most SMR concepts can be grouped into five broad categories.[2] These are:

- **Single-unit LWR-SMRs** – use of well-established LWR technology and fuels to provide stand-alone units that may replace small fossil-fuel units or be deployed as distributed generation.
- **Multi-module LWR-SMRs** – also use LWR technology, and may be either operated as a replacement for mid-size baseload capacity or in a distributed generation framework, depending upon generating capacity.
- **Mobile/transportable SMRs** – currently apply LWR technology and are intended to be easily moved from location to location. Floating reactors are included in this category.

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[1] As highlighted in this paper on several occasions, the series effect – among other conditions – plays a central role in the economic competitiveness of SMRs. The series effect has two components: i) the benefits of serial production of equipment, reducing the unit costs with an increased number of units; and ii) increased efficiency and cost-effectiveness through learning curves and feedback of experience. In the case of SMRs with smaller modules, the prospect of in-factory construction of reactor units is an important benefit.

[2] Note that more than one category may apply to a particular SMR design.

- **Generation IV (Gen IV) SMRs** – apply advanced, non-LWR technologies and include many of the concepts that have been investigated by the Generation IV International Forum (GIF) in past years.
- **Micro modular reactors (MMRs)** – represent designs of less than 10 MWe of capacity, often capable of semi-autonomous operation and with improved transportability relative to the larger SMRs. These technologies are typically not LWR-based and apply a wide range of technological approaches, including Gen IV technologies. MMRs are principally intended for off-grid operation in remote locations where they are expected to be competitive with prevalent sources of electricity.

While each individual design brings its own technological and licensing challenges, as well as potential benefits, it is more practical to consider SMRs within these five categories in future analyses, particularly as regulators engage in processes to approve the use of such technologies.

In general, the LWR-based SMR concepts are the most mature with the highest TRLs and LRLs, and they are likely to be the earliest available for commercial deployment. Several concepts are under construction (e.g. CAREM in Argentina, ACPR50S in China) or in commercial operation (e.g. KLT-40S in Russia[3]). Other designs are making significant licensing progress and may be constructed as initial prototypes by 2030. These technologies are small and evolutionary variants of the Gen II and Gen III/III+ reactors operating worldwide, and benefit from many decades of operating and regulatory experience. Similar conclusions can be drawn for pressurised heavy water reactor (PHWR) technologies.

Gen IV technologies use alternative coolants (i.e. liquid metal, molten salt or gas) and different system configurations compared to LWRs. While Gen IV-based designs do not have the same levels of operating and regulatory experience as those of LWRs, and additional research is still needed in some areas,[4] these designs nevertheless benefit from an extensive history of past research and development upon which developers and regulators may draw. The most mature Gen IV designs are metal-cooled and gas-cooled systems with some units currently in operation or under construction.[5] These designs may also provide specific opportunities to consider non-electric applications thanks to their higher outlet temperatures (see Figure 1) as well as advanced nuclear fuel cycles.

At present, at least 72 SMR concepts are under various stages of development (IAEA, 2020), a 40% increase from 2018 (IAEA, 2018). Table 1 provides a representative sample of SMRs under development at the international level, with about half of the design concepts listed based on LWR technology and the other half on Gen IV concepts. While the term "SMR" has been adopted around the world to refer to all small reactor designs, significant differences remain across the major types of SMRs, especially in the degree of design modularisation.

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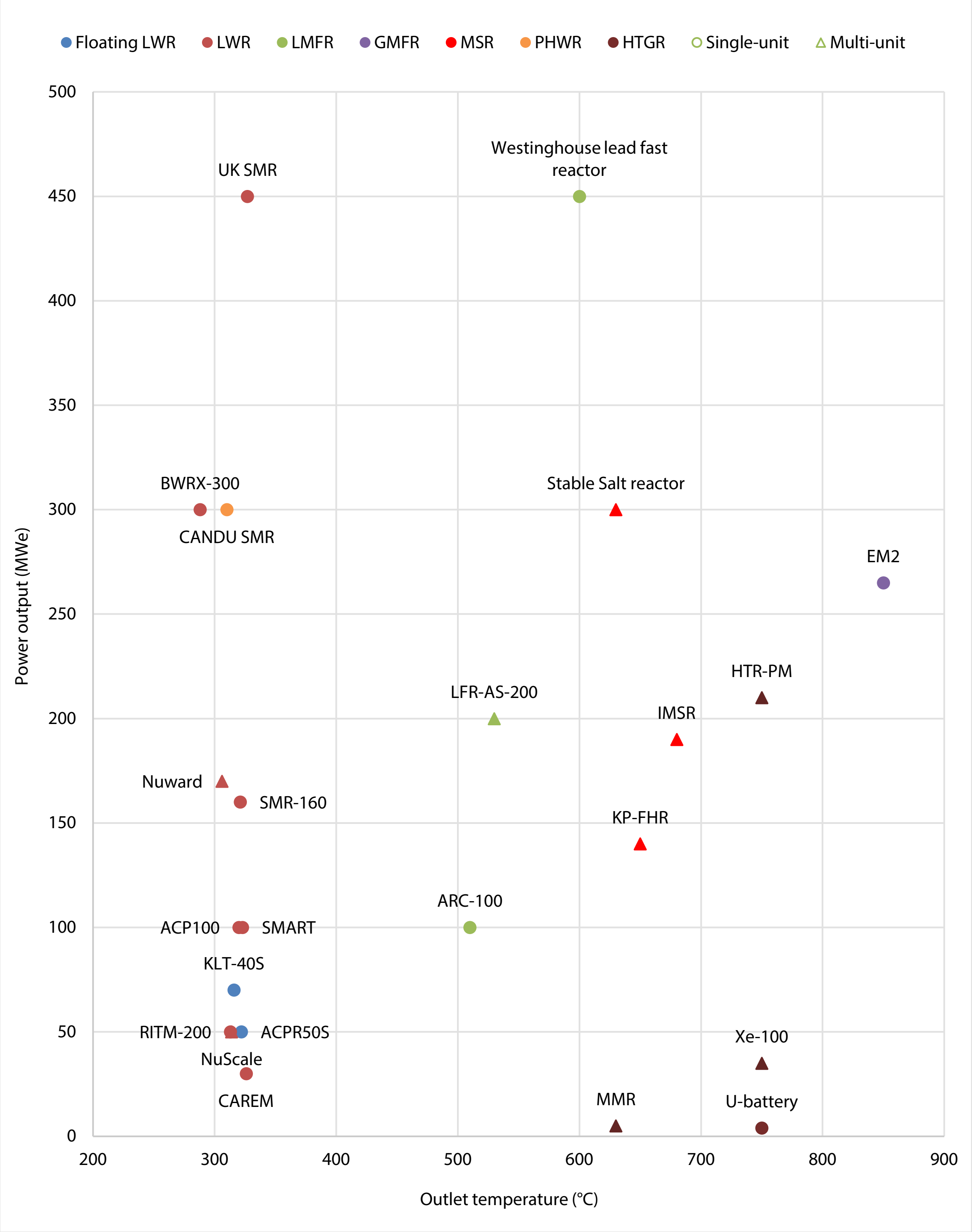
[3] This first-of-a-kind (FOAK) floating nuclear power plant "Akademik Lomonosov", with two KLT-40S reactors, was connected to the grid on 19 December 2019 in Pevek, Chukotka Peninsula (Rosatom, 2019). It started full commercial operation on 22 May 2020, generating electricity for households and local industries in Russia's east Arctic region (Rosatom, 2020).

[4] Fuel and structural materials performance and qualification, modelling, etc.

[5] Russia currently operates the BN-600 and BN-800 SFRs, and China is building the CFR-600. China also runs HTGRs such as the HTR-10, and it is currently building an upgraded version: the 210 MWe HTR-PM.

Figure 1: Selected reactor designs as a function of power output, core outlet temperature and deployment configuration



Notes: LMFR = Liquid metal fast reactor; GMFR = Gas modular fast reactor; HTGR = High temperature gas reactor.

Source: IAEA (2020).

Table 1: Representative sample of SMR designs under development globally

Design	Net output per module (MWe)	Number of modules (if applicable)	Type	Designer	Country	Status
Single unit LWR-SMRs						
CAREM	30	1	PWR	CNEA	Argentina	Under construction
SMART	100	1	PWR	KAERI	Korea	Certified design
ACP100	125	1	PWR	CNNC	China	Construction began in 2019
SMR-160	160	1	PWR	Holtec International	United States	Conceptual design
BWRX-300	300	1	BWR	GE Hitachi	United States-Japan	First topical reports submitted to the US NRC and to the CNSC as part of the licensing process
CANDU SMR	300	1	PHWR	SNC-Lavalin	Canada	Conceptual design
UK SMR	450	1	PWR	Rolls Royce	United Kingdom	Conceptual design
Multi-module LWR-SMRs						
NuScale	50	12	PWR	NuScale Power	United States	Certified design. US NRC design approval received in August 2020
RITM-200	50	2	PWR	OKBM Afrikantov	Russia	Land-based nuclear power plant – conceptual design
Nuward	170	2 to 4	PWR	CEA/EDF/Naval Group/ TechnicAtome	France	Conceptual design
Mobile SMRs						
ACPR50S	60	1	Floating PWR	CGN	China	Under construction
KLT-40S	35	2	Floating PWR	OKBM Afrikantov	Russia	Commercial operation
Gen IV SMRs						
Xe-100	80	1 to 4	HTGR	X-energy LLC	United States	Conceptual design
ARC-100	100	1	LMFR	Advanced Reactor Concepts LLC	Canada	Conceptual design
KP-FHR	140	1	MSR	Kairos Power	United States	Pre-conceptual design
IMSR	190	1	MSR	Terrestrial Energy	Canada	Basic design
HTR-PM	210	2	HTGR	China Huaneng/CNEC/ Tsinghua University	China	Under construction
EM2	265	1	GMFR	General Atomics	United States	Conceptual design
Stable Salt Reactor	300	1	MSR	Moltex Energy	United Kingdom	Pre-conceptual design
Natrium	345	1	SFR	Terrapower/GE Hitachi	United States	Conceptual design
Westing-house Lead Fast Reactor	450	1	LMFR	Westinghouse	United States	Conceptual design
MMRs						
eVinci	0.2-5	1	Heat pipe reactor	Westinghouse	United States	Basic design
Aurora	2	1	LMFR	Oklo	United States	Licence application submitted to the US NRC
U-Battery	4	1	HTGR	Urenco and partners	United Kingdom	Basic design
MMR	5-10	1	HTGR	USNC	United States	Basic design

Source: NEA, IAEA (2020).

Note: BWR = boiling water reactor; CEA = Alternative Energies and Atomic Energy Commission; CGN = China General Nuclear; CNEA = Comisión Nacional de Energía Atómica; CNEC = China Nuclear Engineering Corporation; CNNC = China National Nuclear Corporation; KAERI = Korea Atomic Energy Research Institute; PWR = pressurised water reactor. If not specified, all of the reactors are land-based. RITM-200 units have already been constructed for “Arktika”, “Sibir” and “Ural”, all of which are nuclear-powered icebreakers.

3. Techno-economic characteristics of SMRs

3.1. Key design features of SMRs

Despite the loss of thermal efficiency for some light water-small modular reactor (LWR-SMR) designs (see Table 2), the reduced size of the SMR technology relative to traditional large nuclear reactors brings several advantageous features that are shared by most of the designs listed in Table 1:

- **Integral designs**: Smaller cores enable the use of integral designs. An integral system incorporates all of the components of the nuclear steam supply system (NSSS) into a single vessel. This configuration, in which the total primary coolant inventory contained within the primary vessel is significantly larger than for a traditional external loop configuration, substantially increases the heat capacity and thermal inertia of the system. Such a configuration thus results in a robust inherent safety case and simpler systems, operation and maintenance.
- **Inherent safety**: A lower power output, and the higher surface-to-volume ratio offered by smaller cores will increase the efficiency of passive safety systems both for normal and off-normal operating conditions. For example, many LWR-based designs have very large water inventories for passively cooling the reactor systems even under extreme circumstances (e.g. loss of offsite power). A higher reliance on passive cooling systems allows for more simplified designs and streamlined operation and maintenance.
- **Lower core inventories**: A smaller core inventory has both an on-site and off-site benefit. On-site, less shielding is required and radiation exposure doses for workers are thus reduced. Off-site, the smaller inventory, the reduced probability of an accident occurring, and less energy driving potential radioactive releases can reduce the need for emergency planning zones (EPZs). Such benefits could mean that some SMRs may be located closer to where energy is needed.
- **Improved modularisation and manufacturability:** Weight and size directly dictate how easily the various components can be manufactured, transported, lifted and installed. The smaller size of SMR designs enables the adoption of more ambitious modularisation schemes, as well as new manufacturing techniques (NEA, 2020).
- **Enhanced flexibility**: by leveraging the manoeuvrability capabilities of existing Gen II reactors (NEA, 2012), SMRs could achieve enhanced load following modes resulting from inherent design features, as well as through the optimisation of multi-module unit operation (Ingersoll et al., 2015). More generally, the flexibility of SMRs also covers deployment capabilities (e.g. lower siting constraints) and diversity of products (combined heat and electricity production).

These key design features can have important implications on the safety approach for SMRs (see Chapter 4), while at the same time supporting several key economic drivers that will ultimately govern the overall competitiveness of this technology.

3.2. Fuel cycle considerations

SMRs under development will need to be integrated with a nuclear fuel cycle, which means building either on existing infrastructures, or in some cases, on dedicated investments in new industrial capabilities. The range of SMR concepts under consideration, and their overall level of technological maturity, has led to the consideration of a number of fuel cycle options. Few SMR developers have thus far fully developed or communicated their strategies in this field, in particular in relation to the back end of the fuel cycle (IAEA, 2020).

Fuel cycle strategies for LWR-SMRs

LWR-SMRs are expected to develop front-end fuel cycles compatible with existing industrial capabilities, in particular in terms of the enrichment level (below 5%) or fuel type and assembly. The range of burnup and fuel technologies also mean that in a first approach the fuel from these reactors should be compatible with reprocessing solutions for countries that have established strategies to close their fuel cycle. An exception concerns the floating SMR developed in Russia, which is considering an enrichment level close to 20%. Most developers have not ruled out the possibility of SMRs using mixed oxide (MOX) fuel, but it is rarely discussed as a priority for these reactors (IAEA, 2020).

The lower thermal efficiency observed in LWR-SMR designs means that the uranium requirements per kilowatt hour (kWh) of energy produced will be higher and will directly impact the fuel cycle costs. It should also be noted that the refuelling cycle is expected to be longer than that of existing LWRs.[1]

Fuel cycle strategies for Gen IV SMRs and micro reactors

While most Gen IV SMRs and micro reactors are considering uranium-based fuel, the development of new fuel cycle facilities will nonetheless be required. A key feature shared by several of these reactor concepts is that they will offer much longer refuelling cycles. Heat-pipe micro reactors are a primary example, with these reactors having refuelling periods of up to 20 years. Gen IV SMRs operating with tristructural-isotropic (TRISO) fuel or with molten salt fuel can take advantage of online refuelling approaches.

Several designs are considering use of high-assay low-enriched uranium (HALEU) fuel. HALEU fuel has enrichment levels between 5 and 19.75%. Its applications are today limited to the production of small batches for research reactors and medical radioisotope production. HALEU fuel is not currently produced at a commercial scale in NEA member countries, as the existing commercial nuclear fuel cycle does not exceed 6% enrichment. Current HALEU material is therefore downblended from American or Russian high-enriched uranium (HEU) stocks (Euratom Supply Agency, 2019). However, as already reported by the United States Department of Energy (DOE), HEU stocks could be completely exhausted by 2030-2040.

Without the development of HALEU production capabilities, the development of advanced SMR technologies could be severely limited. Although some accident tolerant fuel (ATF) concepts for LWRs may also require HALEU, this issue should have less of an impact on LWR-SMRs.

A secure, future supply of HALEU fuel requires upgrades in the current nuclear fuel cycle infrastructure to comply with potential criticality safety limits, in particular the development of enrichment, de-conversion and fabrication facilities. In addition, new packaging and transport solutions will be needed, especially for the transport of the larger quantities of HALEU that may be needed for the global deployment of advanced SMRs. The design and certification of new transport containers is a complex and costly process that

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[1] Progress with the deployment of advanced fuels may however bridge that gap over the next few years, in particular in the United States.

requires compliance with International Organization for Standardization/American National Standards Institute (ISO/ANSI) standards and approval from the competent transport authorities.

The impact of HALEU fuel on the back end of the fuel cycle may need to be further assessed. Long-term management of used nuclear fuel and the high-level radioactive waste generated by HALEU fuel may require adjustments in terms of current approaches, including upgrades in reprocessing facilities and new container designs for interim storage of used fuel.

Conversely, few of the fast neutron reactor Gen IV SMRs are currently considering plutonium-based fuel. A notable exception is the Stable Salt Reactor from Moltex, which is developing its reactor concept in part to offer a solution for countries that are facing specific issues with the management of plutonium.

Table 2: Fuel cycle features of selected SMR designs

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

Source: NEA, IAEA (2020)

Note: if not specified, all of the reactors are land-based.

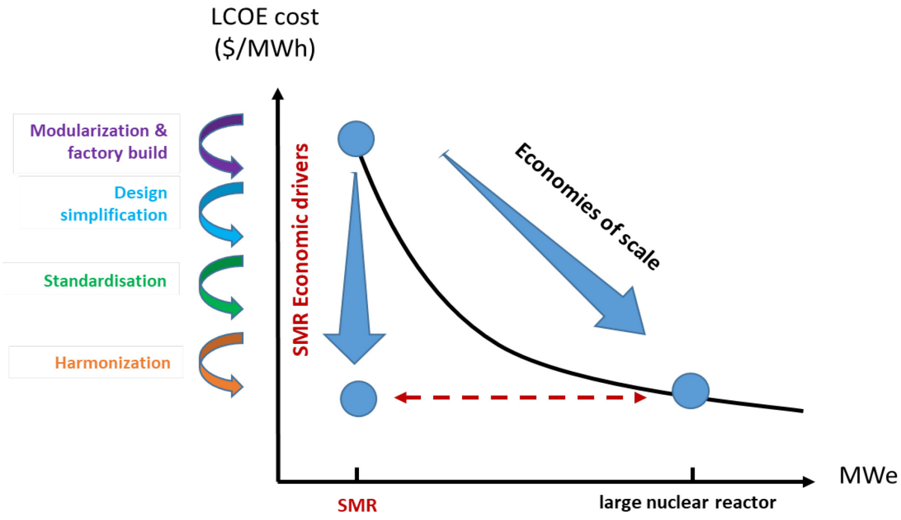
3.3. Key economic drivers

Reactor designers have traditionally scaled reactors up to larger sizes in order to take advantage of economies of scale (NEA, 2011). To counterbalance diseconomies of scale and improve competitiveness, the business case of SMRs is supported by economies of series production, which rely on four key costs drivers: design simplification, standardisation and modularisation, while maximising factory fabrication and minimising on-site construction.

The benefits of serial construction have been well-documented in other industries, including the shipbuilding and aircraft industries, in which serial manufacturing has resulted in learning rates between 10 and 20% (NNL, 2014). For the first SMR units, serial production may also lead to amortisation of non-recurrent costs, such as research, development and design certification costs.

In order to achieve serial factory fabrication, the market for a single design must be sufficiently large, highlighting the potential benefits of developing such a global market while at the same time suggesting that only a small subset of the many designs under development may be able to establish such a market. Co-operation among nuclear safety regulators to increase the harmonisation of licensing regimes can be expected to play a central role in enabling the emergence of this global market (see Section 4.3). The economic drivers governing SMR competitiveness are summarised in Figure 2 below.

Figure 2: SMR key economic drivers to compensate for diseconomies of scale



Source: NEA (2020).

Note: KW$_e$ = kilowatt electric.

Design simplification

The unique physical features of smaller cores in terms of enhanced passive mechanisms and higher design integration offer new opportunities for the simplification of SMR systems. Some active components, for example reactor cooling pumps and their associated auxiliary systems, may no longer be necessary in novel SMR designs,[2] which represents an important advantage compared to current large LWR designs.

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[2] NuScale and BWRX-300 SMRs, for instance, are designed to operate with natural circulation.

The heat generated in the core of larger LWRs is generally removed by active cooling systems that require power. The need to ensure safe cooling under a range of conditions has led to a complex layering of redundant safety and auxiliary systems, contributing, along with other factors, to cost increases observed in large LWR designs (Ingersoll, 2009). The simplification of safety systems in the design of SMRs, can make a positive contribution towards reducing plant complexity, and in turn, the overall capital costs.

Other simplification opportunities for SMRs may arise at the level of overall plant architecture, ranging from reactor components to regular civil structure, constructability and the use of commercial, off-the-shelf (COTS) components. Some multi-unit SMR developers are also considering additional simplifications through the development of shared plant infrastructure, such as shared turbine buildings and control rooms.

These different simplification approaches could translate into lower construction costs for SMRs, both directly through a reduction in the number and size of components and systems, and indirectly through benefits at the project management level. Design simplification, for instance, could lead to a reduction in the risks associated with rework, as well as a reduction in the delays during construction, which have had a significant impact on recent Gen III first-of-a-kind (FOAK) projects (NEA, 2020).

Standardisation

SMR designs provide higher levels of standardisation. Standardisation of design, and its subsequent replication, has proven to be an effective way to drive costs down for large reactors as it fosters learning by doing and contributes to the mobilisation of the supply chain through long-term new build programmes (Lovering et al., 2016). These benefits are not limited to reactor design since they can be extended to the associated delivery processes.

In practice, as highlighted by the World Nuclear Association (WNA) through its Cooperation in Reactor Design Evaluation and Licensing (CORDEL) Working Group, *"The concept of standardized reactor designs does not require units to be completely identical. Rather all units that use the standardized design technology should at least share the same global architecture and the same specifications for the nuclear steam supply system design and components, and associated safety systems"* (WNA, 2015).

For integral SMR designs, the reactor modules and primary safety systems are envisaged to meet this definition. Additional features could foster the standardisation of reactor architectures. For instance, the possibility of building SMRs underground and the use of seismic isolation systems would reduce the need to adapt designs to local seismic conditions. Greater standardisation levels could furthermore be achieved by maximising the use of COTS components in SMR designs.

As SMRs move to the demonstration and deployment stages, early involvement of the nuclear supply chain will play a central role in supporting the design standardisation process.

Modularisation and factory-based construction

Modularisation is a way of simplifying construction by splitting the plant up into packages (modules) that can be factory-built, transported and then assembled on-site. Although modular construction has been used for large nuclear power plants,[3] SMRs can even further capitalise on the benefits of modular construction approaches. In particular, cost reductions from modularisation can be expected from construction and/or pre-assembly of modules away from the construction site in a dedicated factory, where labour productivity and quality control can be expected to be higher and project management risks lower. The degree of modularity may vary across designs. Designs in earlier stages of development may, for example, have the potential to incorporate greater modularity.

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[3] More recent examples include the AP1000, APR-1400 and ABWR Gen III designs (NEA, 2020).

In parallel, size also plays a central role in determining the transportability of a large technological system. In some industries, despite high levels of modularisation, transport challenges persist. Several SMR developers have announced that the entire nuclear steam supply system (NSSS) module will be directly transported using conventional trucks, ships or rail.

The benefits of modular construction have been well-documented in other industries, such as shipbuilding and aircraft construction, where modularisation of construction in factories has resulted in cost reductions. General observations of modularisation in the power sector indicate lead-time reductions of 40% and 20% in terms of lower costs (Lloyd, 2019). For the construction of nuclear reactors, modularisation and factory fabrication is already applicable to about 30% of the construction and could increase to up to 60-80% with the adoption of the more ambitious strategies enabled by the reduced size of the components (NEA, 2020). Increases in labour productivity are likely attributable to the repeatability of tasks and an ability to better capture tacit knowledge, which, on construction sites having a high turn-over of workers, is often lost.

Factory fabrication can also present additional benefits, in particular in terms of application of advanced manufacturing techniques, which would otherwise be difficult to deploy on-site. Advanced manufacturing techniques, such as laser welding or additive manufacturing, lower costs and shorten delivery times through the reduction of the number of welds and the elimination of costly in-service inspections. The opportunities offered through the digitalisation and the higher connectivity of manufacturing chains – the so-called "Industry 4.0" – could also lead to additional cost and time savings.

Finally, modular construction can also yield indirect benefits to the extent that it would result in shorter and more predictable construction durations, ultimately reducing risk premiums expected by some investors. It would also mean a faster time to market, which could positively influence SMR market outlook (see Section 3.5).

Modular construction may nevertheless have some drawbacks. Additional upfront engineering efforts are required to identify and properly design the different modules in order to reduce construction risks during their assembly. The different modules' components and materials also have to be procured before construction begins, increasing upfront investment needs and thus off setting, to some extent, some of the financial benefits (see Section 3.4).

3.4. The value proposition for SMRs

SMR designs can change the business case of nuclear power through their value proposition.

Financing benefits

From a financial perspective, SMRs could present an attractive investment option compared with large LWRs, especially in liberalised electricity markets:

- **Affordability**: The lower, overall capital outlay implies that private investors will face lower capital at risk, which could make SMRs a more affordable option. In turn, this lower capital risk could attract new sources of financing (e.g. private equity, pension funds), lower the cost of capital and ultimately the levelised cost of electricity (LCOE) generated by SMRs.
- **Shorter payback**: The shorter construction duration promoted by SMR developers would further reduce the cost of financing.
- **Scalability**: For multi-unit SMRs, the ability to add modules and start generating electricity incrementally reduces both upfront investment and capital risk, which translates into lower financial costs.

- **Portfolio strategy**: For multi-unit SMRs, the ability to add modules incrementally could also allow investors to adjust to changes in electricity demand and cash flow/financing availability, thus improving the management of financial risks.

Delivery model and time to market

The serial construction of standardised SMR modules represents not only benefits in terms of levelised costs but also a shift in the delivery model. When the market has reached a sufficient level of maturity, it could lead to a reduction in the time to market (i.e. the time needed between the development of the project and the commissioning of the reactor).

Such a benefit could be particularly valuable when comparing the time to market of SMRs with other dispatchable generation alternatives, especially in emerging newcomer countries that have to meet a rapidly increasing electricity demand.

System cost benefits

The flexibility capabilities of SMRs (both enhanced load-following and non-electric applications), as well as their ability to provide ancillary services to the grid (frequency, inertia, reactive capacity, etc.) could also present some benefits from the perspective of system cost[4] optimisation. These benefits would appear at the system level to the extent that SMR capabilities would reduce the need for alternative and potentially more expensive (e.g. batteries, demand side management) and carbon intensive (e.g. coal, oil and gas-fired plants) sources of flexibility and ancillary services. The extent to which these benefits will be of interest from a private investor perspective will depend on the value (and therefore price) that future electricity markets place on these attributes.

3.5. Market opportunities for SMRs

In terms of the market outlook for SMRs, significant uncertainties remain at this stage of both technology development and licensing readiness (see Box 2). The cost competitiveness of SMRs is intrinsically linked to the robustness and size of the global market, and also to the level of regulatory and policy support needed to serve this emerging market.

SMRs are being developed in part to expand the market of nuclear power applications beyond traditional baseload electricity provision in a centralised electricity system. At a strategic level, this translates into three overlapping market opportunities (see Figure 4):

- decarbonising energy systems;
- complementing the deployment of variable renewable energy (VRE);
- facilitating the access of nuclear energy into new sectors and/or regions.

Decarbonising energy systems

Growth of SMRs may be supported by decarbonisation policies. In the electricity sector, for instance, SMRs could be considered as a suitable fit in terms of reactor size to replace a subset of retiring coal power plants. About 60 gigawatt electric (GWe) of coal generation built in the United States before 1976 have unit sizes between 50 and 300 megawatt electric (MWe), which closely matches the sizes proposed for SMRs (NEA, 2016).

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[4] System costs are defined as the total costs accrued beyond the perimeter of a power plant to supply electricity at a given load and at a given level of security of supply. System effects measure the impact that the integration of a specific power generation source has on the whole electricity system (NEA, 2019b).

SMRs could also support the decarbonisation of other energy sectors, such as district heating applications, which require output temperatures between 80 and 200°C and can be easily met with LWR-SMRs. In Finland, for example, the use of SMRs for district heating has recently been proposed as a viable option to site SMRs closer to demand, and to fully decarbonise the heat sector (Partanen, 2019). Similarly, the UK Energies Technology Institute (Energy Technologies Institute, 2015) suggests that SMRs operated in cogeneration mode could play an important role in the 2030 UK energy system, providing low-carbon heat for housing while improving the economics of SMRs.

The higher temperatures provided by some Gen IV SMRs (i.e. 450-850°C) may offer new opportunities to decarbonise hard-to-abate industrial sectors with the production of low-carbon, high-quality process heat. Potential applications include petroleum refining, steam reforming of natural gas and thermo-chemical hydrogen production.

Saudi Arabia has also been reporting over the last few years its interest in SMRs to meet its desalination needs. In March 2015, the Korea Atomic Energy Research Institute (KAERI) signed a memorandum of understanding (MOU) with the King Abdullah City for Atomic and Renewable Energy (KA-CARE) to assess the potential for building two SMART reactors in Saudi Arabia.

Complementing the deployment of variable renewable energy (VRE)

SMRs have inherent load-following characteristics that make them capable of operating flexibly in electricity systems with variable residual loads, such as in regions pursuing the large penetration of VREs (wind, solar photovoltaic [PV]). Support to VRE deployment could also be considered through the lens of integrated "hybrid" energy systems, which means coupling SMRs with non-electric applications (hydrogen, synthetic fuels and desalination) as a means of supporting the integration of wind and solar PV (Garcia et al., 2016; Chen et al., 2016). These types of integrated systems can improve the overall reliability and resilience of the energy system, making them an economically attractive option.

Box 1: Recent estimates on the potential market for SMRs

In 2016, the NEA investigated the near-term (2035) market potential for SMRs (NEA, 2016) and developed two scenarios that reflected uncertainty in terms of market development:

An optimistic high-deployment scenario that assumed successful licensing of SMRs and the establishment of the factory production and associated supply chain that would lead to cost competitiveness;

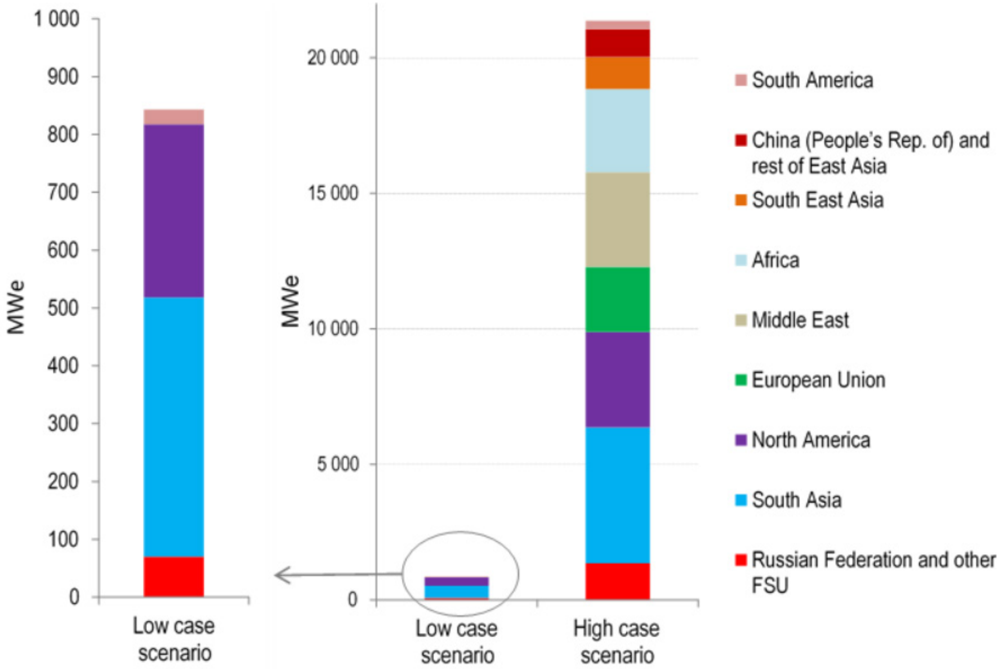
A conservative low-deployment scenario in which SMRs would be considered expensive to build and operate, and thus only a limited number of projects would be completed, including prototypes and plants in remote/isolated areas.

These two scenarios take into account a number of market drivers, such as grid development, expected penetration of intermittent generation, development of new nuclear build in International Energy Agency (IEA) scenarios, and national nuclear policies.

In the high-deployment scenario, up to 21 GWe of SMRs would be deployed by 2035 in several regions of the world, representing about 3% of the total installed nuclear capacity in the world (see Figure 3). Thus, about 9% of the total nuclear new build in 2020-2035 could be SMRs. Conversely, the low-deployment scenario sees a limited deployment of less than 1 GWe, essentially with prototypes in countries with ongoing national SMR programmes.

It could be expected that after 2035 the SMR market will further develop, in line with decarbonisation objectives that will foster the need for low-carbon dispatchable electricity. Understanding the different market opportunities of SMRs is thus important in estimating their long-term market potential.

Figure 3: Estimated SMR capacity by region in 2035



Source: NEA (2016)

Note: This market outlook is in line with estimates from UxC (2013), which also foresee up to 20 GWe of installed capacity globally by 2035. The National Nuclear Laboratory (NNL, 2014) in the United Kingdom anticipates a larger market potential, with up to 65 GWe of installed capacity by 2035.

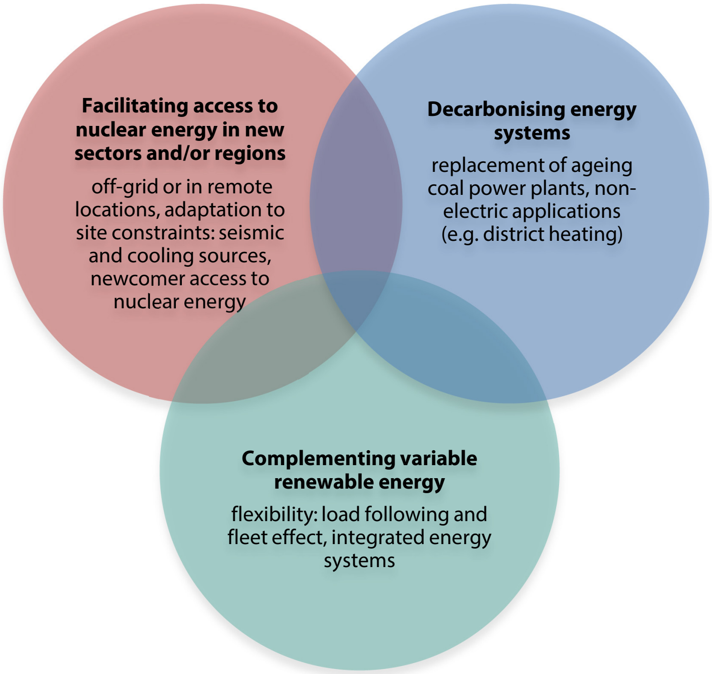
Facilitating access to nuclear energy in new sectors and/or regions

Today, large nuclear power plants contribute to baseload power production primarily within centralised and interconnected power systems. The development of low-carbon nuclear energy is more limited, however, in regions where economic, geographical and/or grid-related constraints make it more difficult to construct large nuclear power plants.

SMRs are able to be deployed in remote areas that are not connected to the grid, in regions with small electricity grids or in regions with limited suitable sites for large nuclear power plants. In the 2018 Canadian SMR Roadmap (Government of Canada, 2018), for example, a number of off-grid remote communities and mining operations were identified in which SMRs – and in particular MMRs – could be cost-competitive as a means of replacing diesel generators. The modularity, flexibility and low-grid requirements of SMRs contribute to their attractiveness. However, such niche markets are rarely found within countries with a well-developed nuclear programme (Canada, Russia and the United States are notable exceptions).

An extension of the nuclear market could thus more generally include newcomer countries that do not currently use nuclear energy. SMRs could present specific benefits in terms of affordability and time to market for those countries in particular that already have well-established nuclear infrastructures from nuclear research-related activities.

Figure 4: Applicability of SMRs



4. Licensing and regulatory aspects

4.1. Safety considerations

The design features of small reactor cores described in Section 3.1 also result in inherent safety features that improve the overall safety case of small modular reactors (SMRs):

- **Efficiency of passive safety features:** The higher reliance on passive safety mechanisms reduces the need for active systems, potentially simplifying safety evaluations and reducing failure modes. In addition, the higher surface-to-volume ratio of small reactor cores is conducive to enhanced decay heat removal modes, such as via natural circulation that results in longer coping times.[1]
- **Fewer and less severe failure modes**: The combination of higher levels of design simplification and integration results in fewer failure modes. For example, the smaller number of reactor vessel penetrations reduces possible leakage points, and the design is therefore more resistant to a loss-of-coolant accident (LOCA). The integration of control rods into the vessel also supresses the risk of control-rod ejection accidents. Moreover, the higher thermal inertia and lower power density of the integral designs leads to a slower response in case of temperature transients, thus increasing safety margins.
- **Reduced off-site emergency planning zone (EPZ)**: The benefits of smaller inventories combined with very high passive safety characteristics may lead to reduced shielding requirements and reduced offsite emergency planning zones (EPZ). With several SMR designs reaching maturity, opportunities to further reduce EPZs may arise.

SMR features also make below-grade siting possible, which provides more protection from natural (e.g. seismic or high-wind events depending on the location) or human-made (e.g. aircraft impact) hazards.

All the above safety features are applicable to both light water reactor (LWR) and Generation IV (Gen IV) SMR designs. The latter designs may, however, introduce additional enhancements in terms of safety.

4.2. The opportunity to enhance licensing regimes

Current licensing frameworks typically rely on an extensive experience base with large single-unit LWRs that use uranium oxide fuel with enrichment below 5%. The LWR-based SMRs under development have similar operating conditions and fuel arrangements, which are expected to facilitate their licensing process. The simpler design and engineering required for these concepts is expected to reduce the number of failure modes that need to be considered, as well as the complexity in determining the consequences. However, the limited experience base of these novel designs poses challenges in terms of demonstrating and approving their safety cases. A number of regulatory considerations must be taken

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[1] The coping time is the time between the start of an accident and the point at which operator intervention is required to prevent serious consequences.

into account for the effective deployment of SMRs; for example, the introduction of inherent safety features and multi-module deployment configurations all result in specific failure modes and consequences that are relatively new for regulators, and these should be carefully investigated.

In addition, changes to the fuel and/or coolant will translate into greater deviations from previous regulatory paradigms and may require more flexible licensing approaches, as well the development of a considerable amount of new expertise within nuclear safety regulatory organisations. At the same time, it remains a challenge for designers to prove that all of the possible failure modes have been appropriately considered and mitigated. A performance-based regulatory approach would appear to be more favourable to SMR development because it has proven to be more flexible when considering new reactor designs (Sainati et al, 2015). The attractiveness of Canada for SMR vendors can be partly explained by the adoption of a regulatory philosophy that is flexible and allows a designer to propose how their concept will meet each performance requirement. If the inherent safety of SMR concepts is to be considered reasonably achievable, designers should be able to demonstrate that reduced EPZs and/or a reduced number of on-site certified staff would still meet safety targets and would result in high levels of public confidence.

Some SMR features may face challenges in meeting general safety requirements. The use of modularisation and factory fabrication for large portions of a reactor (including for the reactor core) can for example pose challenges for the current national and international framework for the transport of nuclear materials. The degree of regulatory involvement in the manufacturing process, alongside the question of multinational licensing of modules and individual components, are also emerging issues. Multi-module SMR designs may require specific considerations for nuclear safety owing to the use of shared systems and to the shifting of manufacturing and construction from on-site to factories. These changes may impact how and where initial plant tests are conducted in comparison to conventional nuclear power plants. These changes may affect the potential stages of SMR licensing and pose challenges to the traditional view of the licensing approach (IAEA, 2019).

International co-operation could help to resolve these challenges for national and international regulatory frameworks, for example through the establishment of an international forum co-ordinating – for countries actively considering SMRs – the development of specific approaches to licensing classes of SMRs.

4.3. Streamlining licensing and regulation

Regulatory regimes may vary significantly among different countries in terms of the level of prescription of regulatory guidance. Each country ensures that safety requirements are aligned with national interests and current regulatory practice, while preserving public confidence in the decisions of the regulatory body. It is nevertheless possible for regulatory organisations around the world to co-operate on the licensing of a given design. A good example is the degree of multinational convergence that has been achieved in a number of areas through the Multinational Design Evaluation Programme (MDEP) framework.

Some opportunities exist to achieve a higher degree of harmonisation, notably in the three levels of regulatory harmonisation (NEA, 2020):

- **legal framework** (governments);
- **licensing and regulatory guides** (nuclear regulators);
- **codes and standards of practice** (industry).

Several challenges will appear at each level, and even if complete harmonisation is unlikely (especially at the government level), it is often possible to identify specific areas where streamlining may be achievable. For that, international collaboration is necessary.

In practical terms, a possible next step would be for an interested group of like-minded countries to consider areas for harmonisation in relation to a particular SMR design or family of designs. As one example, the International Atomic Energy Agency (IAEA) SMR Regulators Forum has concluded that the defence-in-depth (DiD) concept is valid for SMRs and should be a fundamental basis for design and safety demonstration of SMRs. In addition, existing IAEA Safety Standards already address EPZ as well as DiD and are applicable to new reactor designs (including SMRs). Nevertheless, the group also concluded that the deployment of SMRs might require a flexible regulatory framework to address specific safety challenges related to the novel aspects of proposed designs, such as the use of passive systems; multi-module, multi-unit or design extension conditions; and the practical elimination of situations that may induce large radioactive releases (IAEA, 2020).

Harmonisation in licensing requirements and licensing processes for LWR-SMRs could facilitate the deployment of these SMR designs in different countries without significant adaptations to meet national regulations. Design changes will rather be driven by site-specific characteristics. The procurement of different components in local markets would also be facilitated, which will in turn enable the creation of global markets and global supply chains. As such, harmonisation will play a central role in supporting the economies of series, indispensable for the competiveness and commercial viability of this technology.

5. Legal framework

There are a number of legal questions associated with the deployment of small modular reactor (SMR) technology, although none of these issues pose an insurmountable obstacle. Such issues relate more specifically to the type of SMR technology selected, particularly in the case of micro modular reactors (MMRs) since the nature of an MMR is different from that of a multi-module SMR power plant. Only a general outline of these issues is thus presented below.

5.1. Main international and regional legal instruments that apply to SMRs

Safety

Both the Convention on Nuclear Safety[1] (CNS) and the 2009 Euratom Safety Directive[2] as amended in 2014[3] apply to "nuclear installations". The CNS defines a "nuclear installation" as "any land-based civil nuclear power plant under its jurisdiction" [Article 2(i)]. In determining whether the CNS applies to SMRs, questions arise in relation to the interpretation of the terms "land-based" and "nuclear power plant". The first question is therefore which type of SMR technology is under discussion. Since the definition above only applies to "land-based" nuclear power plants, floating SMRs would presumably not be covered, but questions remain in terms of whether other types of mobile SMRs would be covered. While one might argue that micro SMRs would not be included[4] in the definition of a nuclear power plant under the CNS, the question remains regarding what does and does not qualify as a nuclear power plant. It should not be unduly burdensome if future are included SMRs within the scope of the CNS because the CNS framework has already been

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[1] Convention on Nuclear Safety (1994), IAEA Doc. INFCIRC/449, 1963 UNTS 293, entered into force 24 October 1996 (CNS). The CNS is an incentive convention with 89 parties (including EURATOM), which aims to, *inter alia*, achieve and maintain a high level of nuclear safety worldwide through the enhancement of national measures and international co-operation, including, where appropriate, safety-related technical co-operation.

[2] Council Directive 2009/71/Euratom of 25 June 2009 establishing a Community framework for the nuclear safety of nuclear installations, Official Journal of the European Union (OJ) L 172 (2 July 2009) (2009 Safety Directive). The 2009 Safety Directive is binding on European Union (EU) member states and aims to maintain and continuously improve nuclear safety and to ensure that EU member states provide for appropriate national arrangements for a high level of nuclear safety to protect workers and the general public against the dangers arising from ionising radiation from nuclear installations. Many of the provisions mirror the CNS, but it calls for, in addition, decennial peer reviews.

[3] Council Directive 2014/87/Euratom of 8 July 2014 amending Directive 2009/71/Euratom establishing a Community framework for the nuclear safety of nuclear installations, OJ L 219 (25 July 2014) (2014 Amended Safety Directive). The 2009 Safety Directive was amended in 2014 to take into account lessons learnt from the Fukushima Daiichi nuclear power plant accident, with additional requirements related to the powers and independence of national nuclear regulatory authorities, a more frequent peer review system on specific safety issues, increased transparency and the promotion of an effective nuclear safety culture.

[4] The CNS definition of nuclear installation does not cover research reactors. IAEA (2006), Code of Conduct on the Safety of Research Reactors, IAEA Doc. IAEA/CODEOC/RR/2006, p. 1.

established in nuclear power countries. There could, however, be challenges for newcomer countries to establish the legal, regulatory, organisational and technical foundations required under the CNS prior to SMR deployment. For example, some of these obligations are: to establish and maintain a legislative and regulatory framework to govern the safety of nuclear installations (Article 7); to establish a regulatory body and provide it "with adequate authority, competence and financial and human resources to fulfil its assigned responsibilities" (Article 8); and to ensure adequate financial resources [Article 11(1)] and sufficient qualified staff [Article 11(2)].

Within the EU, the same scoping question applies to the Safety Directive, which defines "nuclear installation" as, *inter alia,* "a nuclear power plant" [Article 3(1)(a)]. Although non-land-based nuclear power plants are not excluded, questions still remain in relation to what types of SMRs would be classified within this definition. The argument could be made that all SMRs would be covered under the Safety Directive as the definition of "nuclear installation" includes "research reactor facility", and one could reasonably conclude that an SMR falls in between a traditional large-scale nuclear power station and a research reactor, and therefore is included within this scope. Discussions have already taken place on one type of SMR, light water SMRs, being within the scope of the Safety Directive.[5] Depending on its coverage, European countries embarking for the first time on a nuclear power programme with SMRs would nonetheless need sufficient time to ensure compliance with the Safety Directive.

Environmental protection and public participation

As in the case of the CNS, additional legal procedures will be necessary in respect of the interpretation of the definition of activities within the scope of the Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention)[6] and the Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters (Aarhus Convention),[7] both of which largely concern European countries. In addition, as in the case of safety, additional considerations apply to EU member states under the EU Environmental Impact Assessment (EIA) Directive[8] and the various Aarhus Convention-related Directives[9] and regulations.

Among other measures, the Espoo Convention requires parties to carry out an environmental impact assessment (EIA) procedure, which includes the participation of members of the public from both the party of origin and those of affected parties[10] and the preparation of an EIA [Article 2(2)] for those proposed activities listed in the convention

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[5] See Euratom Work Programme 2018, "NFRP-2018-3: Research on the safety of Light Water Small Modular Reactors", p. 9.

[6] Convention on Environmental Impact Assessment in a Transboundary Context (1991), 1989 UNTS 310, entered into force 10 September 1997 (Espoo Convention).

[7] Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters (1998), 2161 UNTS 450, entered into force 30 October 2001 (Aarhus Convention).

[8] Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment, Official Journal of the European Union (OJ) L 124 (25 Apr. 2014).

[9] Directive 2003/4/EC of the European Parliament and of the Council of 28 January 2003 on public access to environmental information and repealing Council Directive 90/313/EEC, OJ L 41, pp. 26-32 (14 Feb. 2003); Directive 2003/35/EC of the European Parliament and of the Council of 26 May 2003 providing for public participation in respect of the drawing up of certain plans and programmes relating to the environment and amending with regard to public participation and access to justice Council Directives 85/337/EEC and 96/61/EC, OJ L 156, pp. 17-25 (26 June 2003).

[10] Article 1(iii) of the Espoo Convention defines "party of origin" as "the Contracting Party or Parties to [the] Convention under whose jurisdiction a proposed activity is envisaged to take place" and "affected party" as "the Contracting Party or Parties to [the] Convention likely to be affected by the transboundary impact of a proposed activity".

that are "likely to cause significant adverse transboundary impact". Under the original text of the Espoo Convention, Appendix I, paragraph 2, includes within the list of subject activities: "nuclear power stations and other nuclear reactors (except research installations for the production and conversion of fissionable and fertile materials, whose maximum power does not exceed 1 kilowatt continuous thermal load)." This definition broadened slightly under the Second Amendment to the Espoo Convention (but only for those who have ratified, approved or accepted the amendment) to also include "the dismantling or decommissioning of such power stations or reactors", with the caveat that "For the purposes of this Convention, nuclear power stations and other nuclear reactors cease to be such an installation when all nuclear fuel and other radioactively contaminated elements have been removed permanently from the installation site." The Espoo Convention definitions are slightly different from those of the CNS and the Safety Directive, as the Espoo Convention definitions cover "other nuclear reactors".

Even if SMRs are covered by Appendix I of the Espoo Convention, the second step of the screening process is to determine whether they are likely to cause a significant adverse transboundary impact. One could argue that the enhanced safety features of SMR designs provide assurance that there will not be significant adverse transboundary impacts, especially if situated far enough from the border. However, this determination would have to be made on a case-by-case basis. The uncertainty associated with this issue could lead to questions before the Espoo Implementation Committee, which reviews parties' compliance with their obligations under the convention, or an inquiry procedure before the Espoo Convention inquiry commission [Article 3(7) and Appendix IV].

The Aarhus Convention has three pillars: 1) access to information; 2) public participation in decision-making; and 3) access to justice. Each pillar provides certain rights and applies to different activities. It should be noted that interpretations of the "public" and the "public concerned" in the Aarhus Convention, to whom rights are provided, are very broad and as stated in Article 3(9), "Within the scope of the relevant provisions of this Convention, the public shall have access to information, have the possibility to participate in decision-making and have access to justice in environmental matters without discrimination as to citizenship, nationality or domicile and, in the case of a legal person, without discrimination as to where it has its registered seat or an effective centre of its activities."

The first pillar, requiring that environmental information be provided upon request and that environmental information be proactively collected and disseminated, applies regardless of the type of activity in question. For the second pillar, as with the Second Amendment to the Espoo Convention, Appendix I lists "Nuclear power stations and other nuclear reactors", with the same caveat, among the included activities. Here, however, there is no second screening regarding whether the activity is likely to cause significant adverse transboundary impact. Should all or some SMR technologies be covered by this definition, the public concerned must be provided with information about the proposed activity, and be allowed to provide comments. In addition, the outcomes of public participation must be taken into account in the final decision (Article 6). Should a member of the public believe that their rights under the first and second pillars were violated, the third pillar would then ensure access to justice, which provides procedures for the public to enforce their rights under the Aarhus Convention.

5.2. Nuclear third party liability and SMRs

The international conventions governing nuclear third party liability are:

- the Paris Convention on Third Party Liability in the Field of Nuclear Energy ("Paris Convention" or PC),[11] which will soon be amended by a 2004 Protocol yet to enter into force ("Revised Paris Convention" or RPC);[12]
- the Vienna Convention on Civil Liability for Nuclear Damage ("Vienna Convention" or VC);[13]
- the Vienna Convention as amended by the 1997 Protocol ("Revised Vienna Convention" or RVC);[14]
- the Convention on Supplementary Compensation for Nuclear Damage (CSC).[15]

SMRs are included in the definition of "nuclear installation" provided in the conventions, which covers "reactors other than those comprised in any means of transport".[16] Having regard to the nature of the nuclear installation involved and to the likely consequences of a nuclear incident originating therefrom, the conventions (except for the Vienna Convention) allow countries to establish a lower amount of liability for that installation, provided that in no event shall any amount so established be less than the amounts provided in the conventions for low-risk installations.[17] The aim of this option is to avoid burdening the nuclear operators concerned with unjustified insurance or financial security costs.[18] Therefore, SMRs may be considered as low-risk installations if the installation states' applicable convention(s) and national laws allow for such a case.

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[11] Convention on Third Party Liability in the Field of Nuclear Energy of 29 July 1960, as amended by the Additional Protocol of 28 January 1964 and by the Protocol of 16 November 1982 (1960), available at: www.oecd-nea.org/law/paris-convention.html.

[12] Protocol to Amend the Convention on Third Party Liability in the Field of Nuclear Energy of 29 July 1960, as amended by the Additional Protocol of 28 January 1964 and by the Protocol of 16 November 1982 (2004) (not yet in force), available at: www.oecd-nea.org/law/paris-convention-protocol.html.

[13] Vienna Convention on Civil Liability for Nuclear Damage (1963), IAEA Doc. INFCIRC/500, 1063 UNTS 266.

[14] Protocol to Amend the 1963 Vienna Convention on Civil Liability for Nuclear Damage (1997), IAEA Doc. INFCIRC/566, 2241 UNTS 302.

[15] Convention on Supplementary Compensation for Nuclear Damage (1997), IAEA Doc. INFCIRC/567, 36 ILM 1473.

[16] Extract of the definition of "nuclear installation" under the Paris Convention, which is similar to the one provided under other nuclear third party liability conventions. The Revised Explanatory Texts of the Vienna Convention and the CSC stated in the past that the Vienna Convention relates exclusively to land-based nuclear installations; however, this has been rectified in its 2020 version [IAEA International Law Series No. 3 (Rev. 2)].

[17] For more information on low-risk installations under the nuclear liability conventions, see paragraph 43 of the Exposé des Motifs of the Paris Convention, paragraphs 68 and 69 of the Exposé des Motifs of the revised Paris Convention [NEA/NLC/DOC(2020)1/FINAL] and pages 43 and 46 of the Explanatory Texts of the revised Vienna Convention and the CSC [IAEA International Law Series No. 3 (Rev. 2)].

[18] The NEA has made a table publicly available that aims to gather information on the amounts available to compensate potential victims of a nuclear incident in countries and economies having nuclear power plants and/or having ratified at least one of the international conventions on nuclear third party liability. The table is available at: www.oecd-nea.org/law/table-liability-coverage-limits.pdf; www.oecd-nea.org/upload/docs/application/pdf/2020-11/2020.10_operators_liability_amount_table_general_final_clean_v2_2020-11-10_09-01-46_808.pdf.

However, if the damage caused by the nuclear incident proves to be in excess of that "lower" amount, the Installation State must ensure that public funds shall be made available up to the minimum amount provided in the applicable convention for nuclear installations in general.

The conventions do not, however, cover reactors used as a source of power for a ship, whether the power is used for propulsion or any other purpose associated with the operation of a ship.[19] Most experts concur at the same time on the view that the conventions do cover SMRs located on ships that are anchored or otherwise fixed in a specific place and are used exclusively for generating power for external consumption, as long as these reactors are not intended to propel the platform but are to be operated once the ship is anchored at shore and immobilised. In such a case, the ship would be viewed as a floating platform on which the reactor is located and not as a nuclear ship that is excluded from the application of the conventions.

It would be beneficial, in order to avoid different interpretations by national courts, for parties to the international liability conventions to nevertheless clarify the above understanding, as well as the concept of "operator". Under the conventions, the "operator" of a nuclear installation is "the person designated or recognised by the competent public authority as the operator of that installation". It is important to ensure a common understanding of what the "competent public authority" is with regard to a floating nuclear power plant.

If most experts agree that a floating nuclear power plant anchored at shore and immobilised should be considered as a nuclear installation covered by the international third party nuclear liability conventions, questions remain with regard to the application of such conventions when the floating nuclear power plant moves and potentially navigates through different maritime zones and the high seas. For the time being, the conventions only refer to the carriage of nuclear substances, i.e. nuclear fuel (other than natural uranium and other than depleted uranium) and radioactive products and waste. A discussion on the liability regime applicable during the carriage is necessary; especially to facilitate the insurance coverage of such installations and protect potential victims in case a nuclear incident occurs during the journey.

In summary, the commercialisation and deployment of SMRs requires the resolution of several legal issues concerning the interpretation and applicability of international and regional safety and liability conventions in relation to SMR designs. While none of these issues are insurmountable, they should nevertheless be resolved prior to setting in motion any significant programme of deployment. The resolution of these issues is becoming critical in light of the significant progress being made towards commercial deployment of new SMR technologies.

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[19] The Vienna Convention, the Revised Vienna Convention and the CSC specifically exclude from the definition of "nuclear installation" "any nuclear reactor … with which a means of sea or air transport is equipped for use as a source of power, whether for propulsion thereof or for any other purpose". The Paris Convention and Revised Paris Convention do so as well since they include "reactors other than those comprised in any means of transport". The 1962 Brussels Convention on the Liability of Operators of Nuclear Ships would cover nuclear-powered vessels, once it enters into force.

6. Policy aspects

6.1. Overview of key recent national and international initiatives

Canada

In 2018, Canada decided to facilitate the development of small modular reactors (SMRs) through a dedicated roadmap in order to actively engage with local, national and international stakeholders.

The roadmap aims to foster innovation and establish a long-term vision for the nuclear industry, as well as to assess the features of different SMR designs and their alignment with Canadian requirements and priorities. The goal of the roadmap is to frame a national conversation on the needs and priorities of the country that will lead to an understanding of the potential value of SMRs, identify some key issues around their use, as well as their potential risks and challenges, and identify some policies that could influence the feasibility of SMRs.

In addition, in 2016 the Canadian Nuclear Safety Commission (CNSC) launched a new, optional pre-licensing framework in order to foster engagement with innovative SMR developers, including those developing advanced reactor concepts. This new licensing framework has led to ten SMR vendors being currently engaged in the pre-licensing process, along with one advanced SMR vendor (Global First Power,[1] with its 5 megawatt electric [MWe] High-Temperature Gas-Cooled Micro-Modular Reactor [HTGR MMR] concept) in a licensing process to build, own and operate a first demonstration unit at the Canadian National Laboratories (CNL) site in Chalk River by 2026.

Moreover, in July 2019 the CNL launched the Canadian Nuclear Research Initiative (CNRI), a programme to support collaborative, SMR research projects with third-party proponents in Canada. The project is designed to accelerate SMR deployment by enabling research and development, and by connecting global vendors of SMR technology with facilities and expertise within Canada's national nuclear laboratories. California-based Kairos Power, Moltex Canada, Terrestrial Energy Inc. (with offices in Ontario, New York and the United Kingdom), as well as the Seattle and Washington-based USNC, were selected in November 2019 as the first companies to receive support from the CNRI programme. These companies are expected to match contributions from the CNL, either monetarily or in-kind.

The People's Republic of China

In parallel to its national programme for large nuclear power plants, China is diversifying its technology portfolio with a number of light water and advanced SMR designs under development. LWR-SMRs include the ACPR50S (60 MWe) of China General Nuclear (CGN) that targets maritime applications and the ACP100 (125 MWe) of China National Nuclear Corporation that focuses more on inland applications. Other LWR-SMR designs are also being developed with the objective to provide district heating applications in the north of China. Finally, since 2012 the CNNC has been overseeing the construction of the HTR-PM demonstrator, a 210 MWe HTGR with both power and industrial heat applications.

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[1] A joint venture formed by Ultra Safe Nuclear Corporation (USNC)-Power (the Canadian subsidiary of USNC) and the Ontario Power Group.

France

Since 2019, the French government has been supporting an industry consortium to develop the basic design the integrated SMR Nuward. This 300-400 MWe twin SMR design is intended for deployment primarily to meet market needs at the international level, while the construction of a demonstration/first-of-a-kind (FOAK) unit is being considered in France. The programme is also actively promoting international co-operation, including a partnership with Westinghouse. More recently, as part of its economic recovery plan (the "Plan de *Relance*"), the French government has granted EUR 100 million to support the development of the Nuward basic design.

The Russian Federation

Following the commercial operation of the first-of-a-kind floating nuclear power plant "Akademik Lomonosov", Rosatom is planning more floating SMRs at the Baltic Shipyard in St. Petersburg. In parallel, this state-owned company has been developing the next generation of SMRs, the RITM-200 reactor, for both floating and land-based deployment. Serial construction could start by 2030, with the first units to be installed at Russia's biggest mine sites.

United States

Since 2012, the United States Department of Energy (DOE) SMR Licensing Technical Support (LTS) has provided support to NuScale, with USD 217 million in government matching funding. In 2015, government support to NuScale was extended with USD 16.6 million for the preparation of a Construction and Operating License Application (COLA) in partnership with its first potential client: the Utah Associated Municipal Power System (UAMPS). The DOE is also facilitating the construction of the first NuScale demonstration unit that could be sited on a federal site at the Idaho National Laboratory (INL). In August 2020, the NuScale concept became the first SMR design to receive design approval by the United States Nuclear Regulatory Commission (NRC). As a result of continuing public support for NuScale, the DOE granted an additional cost-sharing award of USD 1.4 billion to support the construction of the first demonstration plant. The US International Development Finance Corporation (DFC) further announced on 16 October the signing of a letter of intent to help NuScale develop as an independent power producer (IPP) 2 500 MWe of nuclear energy in South Africa.

In parallel, the US DOE is providing support towards innovative SMR concepts being developed by private vendors, including start-up companies. In 2015, the DOE launched the Gateway for Accelerated Innovation in Nuclear (GAIN) initiative, which aims to facilitate access of SMR vendors to US national laboratories' R&D infrastructures. This grant programme is usually contingent on private financing to match DOE funds.

In 2019, the DOE announced the launch of the National Reactor Innovation Center (NRIC) at the INL, a new initiative to assist the private sector in the development of advanced nuclear energy technologies by providing technology developers support to test and demonstrate their reactor concepts and assess their performance. This initiative was followed in 2020 by the launch of the Advanced Reactor Demonstration Program (ARDP). This new initiative is open to both SMRs and large reactors, and it intends to support the demonstration of near-term advanced designs that are expected to be fully deployed within seven years of the award date, as well as earlier stage designs that are expected to be ready for full-scale deployment in 2030 and beyond. The total budgetary allocation for this programme is USD 230 million. The first designs that have been selected are Xe-100 and Natrium, both of which received USD 80 million in October 2020.

The DOE is also supporting more advanced SMR concepts through the Advanced Research Projects Agency-Energy (ARPA-E). This programme focuses especially on micro modular reactors (MMRs).

Further, the US government is supporting SMRs through a reform of the legislative framework. For instance, the 2018 Nuclear Energy Innovation and Modernization Act (NEIMA) fosters access to national R&D infrastructure and supports the role of the US NRC to adapt the certification process to the specificities of SMR designs.

In addition, the US NRC has released a draft white paper on its strategy for reviewing licensing applications for advanced non-light water reactor technologies (NRC, 2019). By mid-2019, the NRC had been notified by six reactor designers of their intention to seek design approval. These included three molten salt reactors (MSRs), one HTR, one sodium-cooled fast reactor (SFR) and the Westinghouse eVinci heat-pipe reactor. In December 2019, the Canadian Nuclear Safety Commission (CNSC) and the US NRC selected Terrestrial Energy's Integral Molten Salt Reactor (IMSR) for the first joint technical review of an advanced, non-light water nuclear reactor.

United Kingdom

In 2015, the United Kingdom launched the first steps of its national programme to support SMR and advanced reactor designs through an open competition, inviting vendors to submit proposals to meet the country's energy needs and industrial potential. One application promoted by the UK government concerns fuel cycle issues (i.e. the use of its separated plutonium stock as an energy resource). In July 2019, the UK government committed GBP 18 million as part of the Industrial Strategy Challenge Fund to support the development of the UK SMR proposed by a Rolls-Royce-led consortium. In its Ten Point Plan for a Green Industrial Revolution released in November 2020, the UK government announced additional GBP 215 million to be granted for the development of this domestic SMR design (S&P Global Platts, 2020).

The UK Department for Business, Energy & Industrial Strategy (BEIS) has also committed up to GBP 44 million under the Advanced Modular Reactor Feasibility and Development Project. Feasibility studies of eight Generation IV (Gen IV) SMRs have already been completed under Phase 1. Three designs have been down selected for Phase 2, and these will receive up to an additional GBP 10 million each. Another possible GBP 5 million was also made available to regulators to support this initiative. The recent National Infrastructure Strategy has allocated additional GBP 170 million to the budget of this initiative (S&P Global Platts, 2020).

6.2. Insights on policy making and international collaboration

Global policy trends presented in the previous sections show that current government support for SMR deployment encompasses four key areas:

- Provision of **long-term policy support** that facilitates discussions and mobilisation among the relevant stakeholders at the government, private and community levels.
- **Fostering of domestic programmes** at the design and development stages (from basic to detailed design). These programmes can include access to national R&D infrastructures and other mechanisms that support development efforts.
- **Review of licensing frameworks** to enable SMRs.
- **Financial support for the construction** of demonstration and/or FOAK units.

These initiatives can take place through existing or dedicated legislative frameworks in order to integrate SMR development efforts into national energy policy frameworks.

Beyond current national efforts, the international nature of the SMR market provides a rationale for co-ordinated approaches at the international level. The development and initial deployment of SMRs will require a concerted effort between governments and industry. In countries that have decided to deploy SMRs, the role of governments is expected to cover these two stages, and to include policy support both at the national level and as part of co-ordinated initiatives at the international level – in particular in terms of the development of international licensing frameworks for SMRs.

Examples of recent efforts that are already ongoing and can be noted at the regulatory and industrial levels are:

- **Bilateral level**: In August 2019, the United States and Canadian regulators (NRC and CNSC) announced plans for collaboration in order to increase regulatory effectiveness through work on the technical reviews of advanced reactor and small modular reactor technologies. In September 2019, the French utility EDF and the US-based vendor Westinghouse announced ongoing discussions for the joint development of SMR technology.
- **Multilateral level**: The NEA continues to explore the potential of design-specific licensing co-ordination as well as the potential for greater harmonisation of industrial codes and standards. Also, the IAEA continues its SMR Regulator Forum which provides discussions between countries and relevant stakeholders regarding common SMR regulatory issues.

7. Main challenges to enable large-scale deployment of SMRs

The economic competiveness of SMRs will rely heavily on the existence of a sufficiently large market to support the economies of series needed to counterbalance diseconomies of scale. This chapter outlines the challenges that need to be addressed in order to enable SMR deployment.

7.1. The problem of technology choice

The considerable variety of SMR designs currently under development (see Table 1 and Figure 1) across NEA member countries presents both opportunities and challenges. While there appears to be general consensus that only a few of these technologies will ultimately be commercialised, views differ on when, how and by whom decisions should be made about which technologies should be further developed or commercialised.

The policy discourse in some NEA member countries appears to suggest a preference for adopting several technologies at least in the early stages – i.e. pursuing their simultaneous development up to the design, construction and operation stages of demonstration units – until that time when one technology emerges as superior after having competed for a sustained period. However, national baseline research and development expenditures appear inconsistent with these goals. A significant volume of expenditures is sometimes directed towards the creation of additional technological options and not towards the generation of demonstration efforts that might ultimately facilitate a market-based technology selection decision. Moreover, nuclear safety regulators will not have the resources to evaluate a large number of designs; the lack of clarity as to which concepts will ultimately be selected could impact the prospects for all SMR designs.

Such technology selection decisions are important because large-scale and truly global markets are needed for investments in large scale factory fabrication facilities. So long as several competing SMR designs continue to exist, it is likely that no single design or vendor will be able to capture a large market share.

7.2. Revisiting and harmonising licensing frameworks, and other legal challenges

Harmonising different licensing approaches will likely be a fundamental determinant in the deployment of SMR technologies. As illustrated in Table 1, however, the advances introduced in the SMR technology may deviate from current licensing regimes. The limited experience base with novel designs within nuclear safety regulatory organisations poses a significant challenge in terms of reviewing and approving the safety case.

Moreover, from a legal perspective, determining the adequacy of current licensing frameworks to support SMR deployment will depend on whether these frameworks are flexible enough to adapt to SMRs without implementing major modifications in their design. Countries with a technology-neutral licensing framework, performance-based regulatory systems and a widely used graded approach will likely find such a system easier to adapt to SMRs than countries with a technology-specific licensing framework or a prescriptive regulatory system.

As highlighted by the Advisory Panel of the NEA *Nuclear Innovation 2050* (NI2050) initiative, considering the "licensability" and economic dimension in the early stages of the innovation process increases the chances of reaching higher technology readiness levels (TRLs) faster and more cost effectively. Such TRLs can also be achieved through various forms of co-operation at the international level. Collaboration on high TRLs is, however, difficult because of the potential intellectual property (IP) issues that may arise. Focusing collaborative efforts on the qualification of the technology may encounter fewer hurdles, especially for high TRLs. It could also lead to a higher degree of harmonisation and increased chances for successful commercial deployment (NEA, 2018).

In line with the conclusions of the NI2050 initiative, SMRs could be viewed as an opportunity for the early development of international collaboration approaches for harmonisation of licensing frameworks, as well as codes and standards. These topics have already been extensively discussed in the context of large reactors and the experience gained could be applied to SMRs. At the level of industrial codes and standards harmonisation, for instance, the Word Nuclear Association (WNA) Cooperation in Reactor Design Evaluation and Licensing (CORDEL) Working Group has made significant progress, inspired by the example of the aircraft industry.

At the international regulatory level, the Multinational Design Evaluation Programme (MDEP) has shown that it is possible to co-operate on the licensing of a design in different regulatory regimes while ensuring a sufficient level of regulatory sovereignty at the national level. It is possible to build upon the success of MDEP and move even further towards multi-national licensing approaches. One example is that of the dedicated licensing of SMR modules applicable to different sites, which are approved in different countries under reciprocal agreements. Such an approach would help capture the benefits of standardisation, both in terms of learning by doing from serial production as well as in terms of a reduction of the fixed (non-recurrent) costs associated with licensing.

7.3. The potential advantages of SMR FOAK demonstrators

Even with the right set of conditions to guarantee that only the best technologies reach the final stages in the development pipeline, some technical uncertainties may remain. As a result of their innovative nature, SMRs may introduce additional technology risks that do not necessarily exist with current large LWR designs. For instance, LWR-based SMRs incorporate non-traditional components such as helical coil steam generators, internal control rod drive mechanism (CRDM) or new in-vessel instrumentation, for which limited operational experience has been accumulated. Gen IV SMRs will include features that have never been tested before. Pilot facilities could help to demonstrate these features and help open new technologies to the market, as consistent with historical experience.

Building a demonstrator will also help attract more funding to scale up manufacturing capabilities. From an investor's perspective, engaging significant capital in the construction of a module manufacturing facility prior to providing proof of performance of the modules seems unlikely. According to the Energy Policy Institute at Chicago (Rosner, Goldberg, 2011), demonstration units are part of a strategic SMR business plan moving towards commercialisation, and these demonstrations units will precede the development of a SMR module manufacturing plant.

For a FOAK SMR, it will therefore be difficult to secure a procurement, manufacturing and delivery system optimised for on time and on budget production. Nevertheless, first demonstration units should provide the basis for the optimisation of the supply chain and yield, to some extent, the expected benefits of modularisation. For instance, a FOAK SMR may experience fewer delays than recent stick-built, large LWR constructions.

Finally, it is important to build on lessons learnt from recent nuclear new build projects. Future SMR projects should have a complete detailed design before construction begins, as well as early engagement with both regulators and the supply chain. It will also be important to use collaborative contracting practices so as to align stakeholders' interests (NEA, 2020).

7.4. Supply chain and fuel cycle issues

As in the case of large LWRs, the supply chain will remain a central component of SMR competiveness. The hiatus in nuclear construction in NEA countries during the 1980s and 1990s has led to an erosion of the capabilities of the nuclear industry. Even if recent new build projects have helped to rebuild global supply chains to some extent, further efforts are needed.

Strategic partnerships for key components will thus be essential in order to share the risks associated with the first SMR projects and accelerate their deployment.

After the delivery of several modules, the SMR supply chain may evolve towards more consolidation (i.e. fewer suppliers) in order to take advantage of the economies of scale, similar to the aircraft sector. These projections will, however, be conditional on the evolution of the market perspectives and harmonisation trends driving competition. Future supply chain management strategies may also seek efficiency gains through higher integration.

Collaboration to increase the harmonisation of codes and standards could increase localisation opportunities, as well as the pool of suppliers, and result in a more competitive supply chain, thus lowering costs. The introduction of commercial, off-the-shelf (COTS) solutions for SMR designs could bring similar benefits in the supply chain.

SMRs may also require adjustments or new developments for the fuel cycle. For instance, some SMR vendors have proposed the use of high-assay low-enriched uranium (HALEU) in their designs. HALEU has enrichment levels between 5% and 19%. The impact of using HALEU in the global nuclear fuel supply chain and in the entire fuel cycle may need to be further assessed. Similarly, for countries pursuing a closed nuclear fuel cycle, the ability to use mixed oxide (MOX) fuel may also be an important attribute for some SMR designs.

Collaboration in the field of R&D will also be essential. By establishing agreements with research organisations and universities, the SMR supply chain will ensure the availability of a skilled workforce and R&D infrastructure. This collaboration will also help accelerate the deployment of promising new technologies, such as advanced and additive manufacturing and other digital applications.

Finally, the regulatory considerations associated with SMR deployment discussed above will benefit from intensive international collaboration and consensus. It is also important that experience gained by some NEA member countries to date in this field be shared in order to accelerate SMR commercialisation.

7.5. Public perception and engagement

Historically, opposition to nuclear power has stemmed from the possible damages that can be caused by a nuclear accident, despite the low probability of such accidents. Some of the earliest studies of public perception of risk found that the public was likely to view involuntary activities as significantly more risky than voluntary ones. More recent studies describe this phenomenon, in which individuals emphasise consequence over probability as probability neglect (Sunstein, 2001). These studies propose two possible alternatives as a response to public perception of risk.

- to educate the public about the possible benefits of the risky activity;
- to respond to public fears and reduce the riskiness of the activity or technology (Starr, 1969).

The inherent safety features presented by SMR designers could be viewed as an opportunity for adopting such an approach – designing a technology as a response to public concerns.

Successful siting of SMR-based plants will require close attention to the preferences of host communities. Building opportunities for local and regional job creation such that SMRs are as attractive to local communities as large reactors will also be crucial.

Overall, it is likely that SMRs will face a somewhat different set of challenges related to public engagement than those faced by traditional, large LWRs. As a result, it is critical that countries considering the deployment of SMRs determine how public engagement efforts for SMRs might need to differ from those adopted for large reactors. To the extent that these efforts are launched early, they could be used as opportunities for a two-way dialogue in such a way that physical and institutional infrastructures for future SMRs are developed collaboratively with the public.

8. Conclusions and recommendations: Role of government support and international collaboration for SMR deployment

Small modular reactors (SMRs) are making progress to become a commercially viable nuclear product by the early 2030s. Their techno-economic features – some of them already proven in other industries – could not only help to overcome the delivery challenges encountered in recent large nuclear projects but also to enlarge the value proposition of nuclear technology so as to provide flexible and dispatchable low-carbon electricity and heat across several sectors.

When assessing the economic rationale of SMRs, the question of the market remains central. On the one hand, if SMRs are manufactured in a mass production fashion, similar to commercial aircrafts, the economic benefits could be significant. This would require, however, that the market for a single design be relatively large, which underlines the need for a global market while at the same suggesting that only a small subset of the many designs under development will ultimately be able to establish such a global market. Achieving a global market will in any case require higher levels of regulatory harmonisation and market consolidation.

On the other hand, most SMR designs have not reached an advanced stage of maturity and their attributes still need to be tested and proven. Light water (LW) SMRs are closer to commercial viability than Generation IV (Gen IV) systems, for which additional research and development efforts are needed. A certain degree of uncertainty therefore reigns, which directly affects risk perception and thus contributes to limiting the potential size of the market. As SMRs gain in maturity with the first demonstrators expected to be commissioned in the late 2020s, some of these risks should abate over time, thus increasing interest from potential customers. This increased interest will in turn support the establishment of a robust supply chain and sustainable construction know-how, which will result in more competitive capital costs.

The potential SMR market is hence not limited to economic considerations and will require a concerted effort between governments, regulators, vendors, suppliers and future owners to simultaneously address the different challenges outlined in Chapter 7. More specifically, those countries supporting the SMR option may see value in setting a path forward that focuses on four main areas of action where government support and international collaboration will play a key role:

- **Public engagement:** Future projects can benefit from international collaboration, exchanging information about lessons learnt, and difficulties and best practices identified by early adopters through public engagement with local communities.
- **Construction of SMR first-of-a-kind (FOAK) demonstration units and learning**: Governments can support FOAK demonstration projects in many forms, ranging from specific long-term power purchase agreements to cost-sharing mechanisms that can minimise construction risks so as to attract more investors. Supporting regulators efforts to develop the necessary licensing regimes and capabilities is also essential. In parallel, efforts should continue to translate research into effective deployment by hosting first experimental units and funding the necessary research infrastructure.

- **Harmonisation of licensing regimes**: Advancements can be made in harmonisation by leveraging existing collaborative frameworks for large reactors, as well as in other highly regulated sectors. While complete harmonisation may be unrealistic (and in some respects, undesirable), efforts should continue in areas where meaningful common regulatory positions could be achieved. NEA explorations of multilateral licensing co-ordination, bi-lateral collaborations and joint safety evaluations, such as were conducted under MDEP, should be considered. Significant opportunities for harmonisation at pre-licensing level also exist, which could foster the down-selection process of SMR designs.
- **Development of manufacturing capabilities**: By committing to a national nuclear programme of several SMR units, governments can scale up manufacturing capabilities. Countries already engaged in large nuclear projects could take advantage of the synergies within existing capabilities and delivery processes. Key partnerships and industrial collaboration could also be explored among countries so as to share the potential risks. Fuel cycle issues need to be anticipated in order to properly support market prospects. And finally, efforts should be undertaken to harmonise codes and standards that could bring additional market benefits.

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Small Modular Reactors: Challenges and Opportunities

Small Modular Reactors (SMRs) are gaining recognition among policymakers and industry players as a promising nuclear technology. SMRs can be defined as nuclear reactors with a power output between 10 MWe and 300 MWe that incorporate by design higher modularisation, standardisation and factory-based construction levels enabling more predictable delivery models based on the economies of series. Today, more than 50 concepts are under development covering a wide range of technology approaches and maturity levels. The value proposition of the SMR technology also includes potential financing and system integration benefits. These attractive features, however, rely on a business case that requires the development of a global SMR market to become economically viable. Large-scale deployment of SMRs faces several technical, economic, regulatory and supply chain challenges and will need considerable governmental efforts and efficient international collaborative frameworks to be realised in the next decade.

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