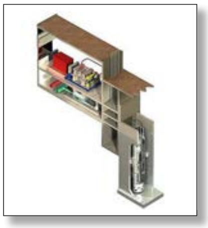
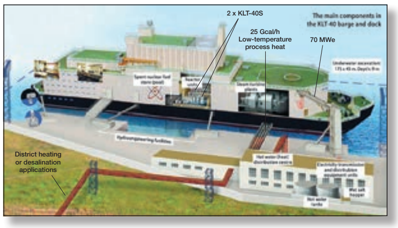
Nuclear Development
2016

Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment





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Nuclear Development

Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment

NEA No. 7213

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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Cover photos: System-integrated modular advanced reactor – SMART (Korea Atomic Energy Research Institute); NuScale module and turbine (Oregon State University); Floating nuclear power plant layout (OKBM Afrikantov).

Foreword

Over the past few years, small modular reactor (SMR) projects have been making substantial progress, with two reactors currently under construction: the CAREM-25 (a prototype) in Argentina and the KLT-40S in the Russian Federation. Interest in SMRs is being driven by a desire to reduce the total capital costs of nuclear power plants and to provide power to small grid systems, leading to more designs reaching advanced stages of development. To attempt to quantify the size of the market that SMRs could represent in the short to medium term, a project was launched at the Nuclear Energy Agency (NEA) to collect and analyse economic and market data on SMRs, including factory production cost estimates. The data for this study – gathered through questionnaires and interviews with SMR vendors and potential customers – were used to assess the potential for SMR commercial deployment around the world. Only short- to medium-term projections (2020-2035) and mature technologies (i.e. SMRs based on light water reactor technologies) were considered in the study, and factors influencing the SMR market throughout the world were examined. This report was drafted by NEA staff and overseen by the NEA Working Party on Nuclear Energy Economics (WPNE) and the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC).

Acknowledgements

The report was written by Dr Alexey Lokhov and Mr Vladislav Sozoniuk, Nuclear Energy Analysts, and updated for publication by Dr Geoffrey Rothwell, Principal Economist in the Division of Nuclear Development at the Nuclear Energy Agency. The authors are responsible for the overall content and the co-ordination of the project.

The report has benefitted greatly from the substantial contributions provided by colleagues at the NEA, outside experts and representatives from NEA member countries. Dr Marco Cometto (NEA) developed the methodology used to assess the optimal share of SMRs in the energy mix. Mr Matt Crozat (while at the US Department of Energy, Office of Nuclear Energy), Mr Paul Genoa and Mr Tae Joon Kim (Nuclear Energy Institute) organised a series of meetings with leading SMR vendors and utilities in the United States and also provided extensive comments on the draft report. Mr Mike McGough (NuScale), Mr Robin Rickman (Westinghouse), Mr Dan Stout (Tennessee Valley Authority), Mr Greg Halnon (FirstEnergy), Dr Jacques Chenais (French Alternative Energies and Atomic Energy Commission – CEA), Mr François-Xavier Briffod and Mr Sylvain Perrier (Direction des Constructions Navales Services – DCNS) and Dr Farshid Shahrokhi (AREVA) provided valuable information on SMR designs, economics and market assessments. Mr Barry Kaufer and Dr Andrew Wasylyk (World Nuclear Association) organised a review of the report within the Cooperation in Reactor Design Evaluation and Licensing (CORDEL) Working Group.

Dr Dan Ingersoll (NuScale), Dr Henri Paillère (NEA), Mr David Shropshire (International Atomic Energy Agency), Dr Song Danrong (Nuclear Power Institute of China) and Mr Richard Swinburn (Rolls-Royce) provided additional comments on the draft report.

Table of contents

List of figures

List of tables

List of abbreviations and acronyms

ALWR	Advanced light-water reactor (larger than 1 000 MWe)
CORDEL	Cooperation in Reactor Design Evaluation and Licensing (World Nuclear Association working group)
FNPP	Floating nuclear power plant
FOAK	First-of-a-kind
FPU	Floating (nuclear) power unit
FTS	Federal Tariff Service (Russia)
IAEA	International Atomic Energy Agency
LCOE	Levelised cost of electricity
NEA	Nuclear Energy Agency
NDC	NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle
NEI	Nuclear Energy Institute
NOAK	Nth-of-a-kind
NPP	Nuclear power plant
O&M	Operation and maintenance
SMR	Small modular reactor (integrated pressurised water reactor)
TVA	Tennessee Valley Authority
US	United States
US EIA	US Energy Information Administration
US EPA	US Environmental Protection Agency
US NRC	US Nuclear Regulatory Commission
VaRen	Variable renewables

Executive summary

The recent interest in small modular reactors (SMRs) is driven by a desire to reduce the total capital costs of nuclear power plants and to provide power to small grid systems. Over the past few years, many SMR projects have been making substantial progress. Two reactors currently under construction are CAREM-25 (a prototype) in Argentina and KLT-40S in the Russian Federation. More designs have reached advanced stages of development. To attempt to quantify the size of the market that SMRs could capture in the short- to medium-term, a project was launched at the Nuclear Energy Agency (NEA) to collect and analyse economic and market data on SMRs, including factory production cost estimates. These data – gathered through questionnaires and interviews with SMR vendors and potential customers – have been used to assess the potential for SMR commercial deployment in the world. Only short- to medium-term projections (2020-2035) and mature technologies (i.e. SMRs based on light water reactor technologies) were considered. Different factors influencing the SMR market around the world are also discussed.

Small modular reactor (SMR) economics and markets

The primary differences in SMRs compared to larger NPPs (e.g. advanced light-water reactors, ALWRs) are their small power output (typically below 300 MWe per unit) and modularity – in many SMR designs, the modules (which are intended to be produced in factory conditions) could be complete reactor units. (Other equipment such as the turbine-generator, condenser, the cooling system, etc., could also be produced as modules.) These stand-alone modules could be transported to the construction site (which could also involve factory-produced structures) and installed. Most SMR designs benefit from a reduced number of structures, systems and components.

The economics of SMRs (capital costs, operation and maintenance [O&M] costs and fuel costs) are not yet known. SMR vendors present the following advantages of small modular reactors:

- SMR designers stress that their concepts offer enhanced nuclear safety and allow for the implementation of unique passive features.
- Many SMR designs benefit from a reduced number of structures, systems and components, and from simplified power conversion systems.
- Because of the smaller upfront investment required for one unit, plants with SMRs are expected to be easier to finance.
- Plants with multiple SMR units offer better flexibility for utilities operating in the markets with large shares of variable renewable generating resources, or operating in small grids. Most of the SMR designs have high potential for operation in load-following regimes. In France and Germany, some nuclear power plants also operate in the load-following mode (NEA, 2011: 55).
- The transmission infrastructure requirements could be smaller for SMRs than for ALWRs (because of lower electricity output). This makes them suitable for deployment in a larger number of locations.

- In terms of human resource management of teams involved in operation and outage management, there are benefits in having several identical SMR units instead of one large unit. In addition, multi-unit configuration helps to avoid a long outage period (if compared with ALWRs) through unit-by-unit maintenance and refuelling.
- The energy output of SMRs is well suited to existing heat and water distribution networks and thus SMRs could offer higher potential for cogeneration, such as water desalination and district heating.
- Modularity of construction and small-sized units allow easier decommissioning.

According to the estimates available today, if the competitive advantages of SMRs are realised, SMRs are expected to have lower absolute and per kWe total construction costs than ALWRs. This would be possible if SMRs were produced in large numbers, through optimised supply chains and with smaller financing costs. According to vendors' estimates, most SMR designs require the construction of five to seven plants to get the most out of supply chain establishment and learning. The size of the SMR market (determining the possibility of factory production) is thus particularly important for achieving the desired level of competitiveness.

Variable costs (O&M and fuel costs) for SMRs most likely will be higher than for ALWRs. Fuel costs are expected to be higher because of smaller core sizes and a less efficient use of the fuel. O&M costs will depend on the capability of the SMR designer to prove to the nuclear regulators that security and operation requirements could be achieved with fewer personnel than for ALWRs. However, for multi-unit plants with several SMR units, O&M costs per MWh are likely to decrease, although this will depend on regulatory requirements.

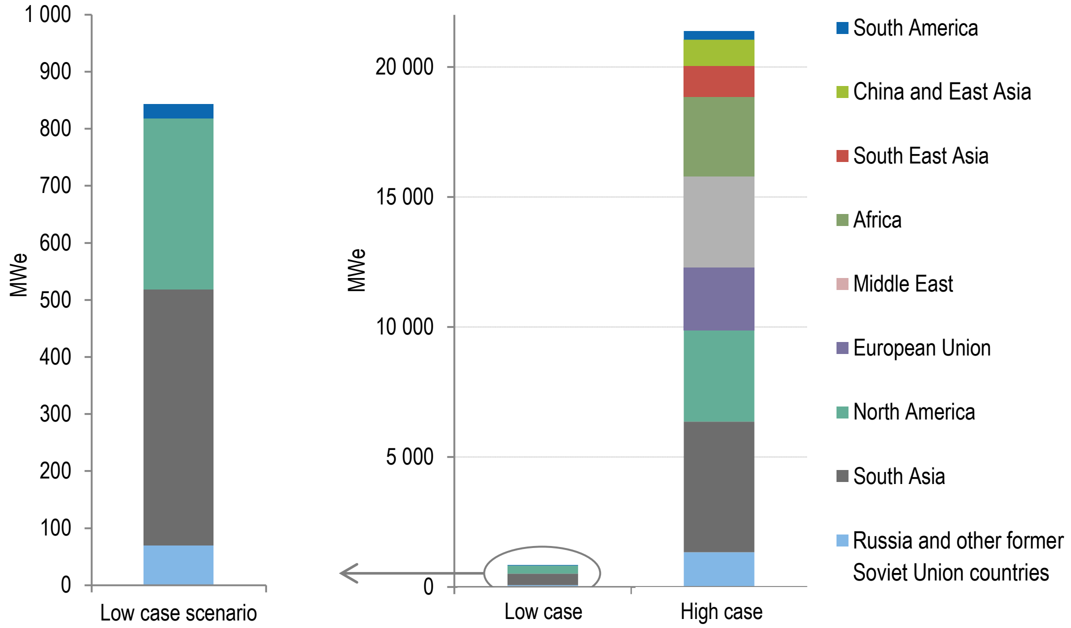
Consequently, if SMRs are produced in series in factory conditions, they are likely to be cheaper to build than ALWRs in terms of both absolute and per kWe total construction costs, although they will have higher variable costs. In economics terms, SMR costs are therefore situated between those of coal and large nuclear plants.

There is a market for SMRs in national energy mixes with large shares of renewables. This can be seen from the analysis of the residual load curve (with generation of electricity by variable renewables subtracted), which would allow for an energy mix to be obtained that minimises the total cost of electricity generation. This approach demonstrates that the optimal share of SMRs in the total nuclear capacity increases when large shares of variable renewables are introduced (leading to reductions of capacity factors of traditional baseload sources, such as nuclear and coal). Although these values are not universal and greatly depend on the energy system under consideration, and the actual economic characteristics of the SMR, this example indicates that there is a potential market for SMRs with a strong development of variable renewables.

The share of SMRs in nuclear new build in 2020-2035 could be estimated by using the arguments summarised above and applying them to different countries. Two scenarios are considered: an optimistic high-case scenario (that assumes successful licensing of SMRs and establishment of their factory production and associated supply chain), and a conservative low-case scenario in which the SMRs are expensive to build and to operate, and thus only a limited number of projects are completed, including prototypes and plants in remote/isolated areas.

In the high-case scenario (based on updated data for NEA/IAEA, 2014), up to 21 GWe of SMRs could be deployed in 2035, representing ~3% of the total installed nuclear capacity in the world (see Figure ES.1). Thus about 9% of the total nuclear new build in 2020-2035 could be SMRs.

Figure ES.1: Estimated SMR capacity in 2035 by region



Source: NEA calculations based on analysis in the text.

These projections do not take into account the potential for further development of SMR technologies and regulatory frameworks that might lead to major changes in the NPP market. Other projections (e.g. UxC, 2013) provide similar estimates at 22 GW in the mid-case in 2040 and less conservative estimates for a low-case scenario of 9 GWe. There are even more optimistic assessments, e.g. the report co-ordinated by the United Kingdom National Nuclear Laboratory (NNL, 2014) projects the size of the potential SMR market in 2035 at 65-85 GW, e.g. 15 GW in both China and the United States (if this technology is made cost-competitive with ALWRs).

Challenges of SMR development

One of the key elements for SMR competitiveness is factory production. It is obvious that an assembly plant that does not operate at a sufficient level of volume will fail to achieve economic competitiveness. The intended assembly mode for SMRs represents a drastic change from the existing nuclear supply chain and might require flexibility and scalability of the assembly process. Since the initial production rate for SMRs will be low, the supply chain should be designed in a way that allows it to build up to a higher rate as the product matures and market confidence grows.

An example of such a supply and assembly strategy can be seen in the production of nuclear engines for ships. There are many prerequisites for the successful implementation of this scheme in the case of SMRs. The product should be highly standardised, which implies that the vendor must find an appropriate balance between standardisation and customisation demands. In addition, any rework should be avoided because it disturbs the assembly process. Finally, all components/parts/kits required for ongoing work should be available at due time because any delays will affect the production of the entire plant and not only one unit.

An important challenge for the factory assembly of SMRs is nuclear regulation. While all of the safety features of SMRs could be addressed generally within the existing regulatory framework, there are issues that must be resolved. In particular, current regulatory practices might not be fully compatible with a factory assembly mode, especially if the assembly process is automated. Regulators must adapt their methods of work to test the units to the greatest extent possible at the assembly stage and reduce the potential for rework.

Other important regulatory issues include validation of enhanced passive safety systems and multi-modular deployment, size of the emergency planning zone and the staffing requirements for operation and security. This validation could be obtained with existing procedures, using a risk-informed approach similar to larger nuclear plants. However, SMRs must demonstrate that they can meet safety requirements. Regulators and technical support organisations will need time and resources to form opinions on these options and innovations, and this process could lead to delays in SMR licensing.

Ideally, for the successful deployment of SMRs, a new approach to licensing should be developed to allow factory-based manufacturing and serial deployment. It might require strong co-ordination not only between regulators but also between manufacturers. Regulators in several countries must work closely with SMR vendors to examine various approaches and possibilities. Among the proposed schemes, the example of certification for airplanes and engines is often cited. However, an application of aviation-type schemes to nuclear installations is not straightforward. In particular, effective full factory assembly of SMRs does not give regulators the possibility to inspect all assembly steps. With respect to SMR deployment, an innovative licensing scheme could separate the general approval or licensing of SMR units, the selection of the site, and licensing of the "master facility" (i.e. the facility in which individual SMR units will be integrated).

Case study: United States

There is strong interest in the United States to redevelop the nuclear industry, and particular attention has been focused in recent years on the development of SMRs that could potentially replace coal-fired power plants that must shut down because of new, strict regulations on air pollution from the US Environmental Protection Agency (US EPA). The United States has had an active SMR programme over the last few years. There are several SMR designs with near-term deployment potential including mPower, NuScale, Westinghouse and Holtec designs under development. The US Department of Energy (US DOE) has made available USD 452 million in matching grants to the mPower and NuScale SMR designs to support their design development and licensing programmes. Recently, however, the outlook for the deployment of SMRs has been revised with some leading SMR design companies reducing development efforts.

Small reactors could be an interesting alternative for new electricity generation capacity in the United States, in particular to replace some of the retiring coal plants. About 60 GWe of coal plants in the United States were constructed before 1975 and have a capacity of between 50 and 300 MWe. However, although there is a large variation in electricity prices across the United States, the generation component of the electricity price is about 60%. It is likely to remain at this level for the next decade.

Despite the low level of electricity prices, about 3.5 GWe of SMRs could be deployed in the United States. In the high-case scenario (based on updated data for NEA/IAEA, 2014) up to 21 GWe of SMRs could be deployed in 2035. This will correspond to ~3.5% of the total nuclear capacity projected in the United States in 2035-2040. The low-case scenario corresponds to a pessimistic case in which only prototypes are constructed.

Licensing SMRs remains an important issue for their development. The current approach to SMR licensing is similar to the one established for ALWRs. In the near term, the advanced features of SMRs are addressed through exemption requests and by developing Design Specific Review Standards. Based on feedback from licensing experience for the first SMRs, rulemaking dedicated to specific SMR issues could be envisaged in the longer term. Today, SMR vendors should prove that their designs are compliant with the US Nuclear Regulatory Commission (US NRC) regulations, in particular, equipment fabrication, security and operational requirements. This will be the major factor determining the economics of SMRs and thus the role that they will play in the future US energy mix.

Case study: Russia

SMRs could target not only traditional markets (i.e. on-grid deployment, in which case they must compete with other energy sources), but also niche applications, for example in remote or isolated areas or islands that require small-sized units and in which electricity produced with non-nuclear sources of power has high costs.

The Russian barge-mounted KLT-40S, currently under construction (scheduled to be completed in 2017), is intended to be deployed by 2019 in the Chukotka region (in north-east Russia). This project is based on the well-established technology of icebreaker-type nuclear reactors. According to the latest estimates, the cost of electricity produced by this first-of-a-kind (FOAK) plant is expected to be about USD 200/MWh. Such high values are a result of large staffing requirements (in total about 250 employees) motivated by the application of today's regulations in Russia. In addition, the fuel cost for such units is high, and maintenance of the barge and the coastal infrastructure requires a high level of resources.

Despite this high cost of electricity generation, the floating NPP is believed to be an adequate solution for bringing power to remote regions in Russia because the cost of alternatives, including a power grid extension, is also high. Given the typical power demand of 50 to 100 MWe, estimates show that a 500 to 1 000 km grid extension is more expensive than deploying an SMR locally. In the future, up to seven floating NPPs (not necessarily of the same design) could be constructed in Russia, but the decision will be taken based on the feedback from experience with this first unit.

Conclusions and recommendations

Although the economics of SMRs are not fully known, there is a large potential for these technologies that can represent an alternative way forward for nuclear power development. In the high-case scenario, up to 21 GWe of SMRs could be added globally by 2035. The actual SMR market development will strongly depend on successful deployment of prototypes and FOAK plants. To achieve the ambitious goals of SMR development, recommendations are being made.

Governments and industry should work together to accelerate the construction of SMR prototypes that could demonstrate the benefits of this technology. Governments willing to develop nuclear power should consider supporting international collaboration and common R&D on SMRs, and work on national and international licensing frameworks for small nuclear power plants.

SMR vendors and potential customers should work closely with nuclear regulators to allow early resolution of various issues related to SMR development (including validation of innovative safety features and solutions) and factory assembly. In the case of overseas deployment of SMRs, both nuclear and non-nuclear regulatory authorities, for instance export control agencies, should be associated with this process.

SMR vendors and customers should work together to estimate the economics of small nuclear power plants taking into account the role that the SMRs could play in new energy mixes, in particular when large shares of variable renewables are present. Detailed SMR market assessments should be performed taking into account realistic estimates of SMR economics and the capabilities of the supply chain. These results must be carefully drafted for policymakers and the public.

Chapter 1. Small nuclear reactors

1.1. Definition of SMRs and overview of selected designs

Small modular reactors (SMRs) are reactors with an electric output below 300 MWe that strongly rely on serial, factory-based production of reactor modules (see Table 1.1). The characteristics of SMRs make them a natural solution for niche markets (application in remote or isolated areas, islands, etc.) where any power generation option is technically difficult to implement and costly. However, these niche markets, as in the case of islands, are very specific and might ultimately contradict the standardisation requirements of the products.

SMRs could also be deployed in traditional markets (i.e. on-grid) where conventional plants and large-scale nuclear power plants (NPPs) are serious competitors. In this market segment, SMRs are expected to benefit from a reduced number of structures, systems and components (compared to large-scale NPPs), simplified power conversion systems, enhanced flexibility and easier financing, but this last advantage has yet to be demonstrated.

Table 1.1: Status of pressurised light water SMR projects in the world

SMR	Electric output		Plant configuration	Licensing status
	Unit(s)	MWe(net)		
CAREM-25 (a prototype) Argentina	1	27	Single module	Licensed Under construction
KLT-40S (w/desal) Russia	2	2 x 35	Twin-unit barge-mounted	Licensed Under construction, completion in 2019
SMART (w/desal) Korea	1	90	Single module	Licensed
mPower United States	2	2 x 180	Multi-module	Pre-application review
NuScale United States	12	12 x 45	Multi-module	Pre-application review
Holtec HI-SMUR United States	1	160	Single module	Pre-application review
Westinghouse SMR United Kingdom	1	225	Single module	Pre-application review

Source: IAEA, 2014.

Before discussing the differences between small and large reactors, a distinction should be made between first-of-a-kind (FOAK) and Nth-of-a-kind (NOAK) cost estimates. Generation IV International Forum's Economic Modelling Working Group (EMWG) suggests that cost estimators prepare both FOAK and NOAK cost estimates, because of uncertainties in regulation and in the supply chain, cost estimators generally ignore many FOAK costs and are implicitly estimating NOAK costs, assuming that "all goes well" (EMWG, 2007: 135–137). Instead, most cost estimates should be treated as NOAK estimates and the learning rates discussed should then be used to increase the cost estimate from the implicit NOAK estimate to the explicit FOAK estimate, so that potential investors understand what they are getting into. Promoters will instead state that they have estimated a FOAK cost and will decrease the cost estimate to arrive at the NOAK estimate. Further, the first plant will usually not be built in a dedicated factory, to distinguish between the first plant and later plants with factory-built modules, the earliest version of a technology will be designated as a "prototype." On how to estimate FOAK costs from NOAK costs, see Rothwell (2016: 96-100), an update of *The Economic Future of Nuclear Power* (University of Chicago, 2004).

1.2. Differences between SMRs and large reactors

The primary difference of SMRs, when compared to advanced light-water reactors (ALWRs), is their modularity. Although modern ALWRs also rely on modular construction (i.e. some of the tasks that were performed in sequence are done in parallel with factory-built modules), for SMRs in some cases the module is the entire reactor system including all components of the primary circuit. These stand-alone modules could be transported to the construction site (that could also involve factory-produced structures) and installed.

The types of equipment shared by SMR units vary depending on design. Most SMR vendors intend to install their factory-built modules in individual containments, similar to those of ALWRs. Some designs, for example the barge-mounted KLT-40, share only a few categories of equipment (except the vessel of the barge).

SMR vendors indicate that their concepts offer enhanced nuclear safety and allow the use of unique passive features (that are available because of the small-sized cores). In most advanced designs there are no rotating parts inside the reactor pressure vessel; all coolant flows through the core because of natural circulation. However, some ALWRs (e.g. economic simplified boiling water reactor – ESBWR) also rely on natural convection.

According to SMR designers' estimates, full factory assembly of units will allow large savings in the costs of manufacturing. Most of SMR designs require the construction of five to seven plants to get the most out of supply chain establishment and learning. Thus, SMRs strongly rely on the effects of serial production in factory conditions that could compensate for diseconomies of scale. Theoretically, for a large production series, the overnight investment cost per kWe of SMRs could be smaller than for ALWRs. In addition, in absolute terms a single small modular reactor is much cheaper than an ALWR, i.e. it is expected to be easier to finance, in particular for incremental deployment, and thus SMRs are more affordable for many utilities.

Plants with several SMR units offer better flexibility for utilities sharing the grid with variable renewables or operating in small grids. The transmission infrastructure requirements could be smaller for SMRs than for ALWRs (because of lower electric output). This makes them suitable for deployment in a larger number of locations.

Most SMR designs offer high potential for operation in load-following regimes. (In France and Germany some NPPs also operate in the load-following mode; NEA, 2011.) Normally for a single large nuclear reactor load-following is inefficient because nuclear power generation is composed almost entirely of fixed costs. Therefore, lowering the power output does not greatly reduce generating costs and some plant components are thermo-mechanically stressed. A more efficient solution could be to maintain the primary circuit at full power and to use the excess power for cogeneration. Because of the intrinsic modularity of an SMR site it is possible to operate the primary circuits of the SMR plant at full capacity and switch the entire thermal power of some of the modules or use the electricity produced for the cogeneration of suitable by-products. Therefore, the load-following strategy can be realised at the site level, by diverting 100% of the electricity produced or 100% of the thermal power generated of some SMR units, to different cogeneration purposes and let the remaining units to produce electricity for the market.

In terms of operation and outage management there are benefits in having several SMR units instead of one large unit because the refuelling and maintenance team could be fully employed by the operator. In addition, multi-unit configuration helps to avoid long outage periods (when compared with ALWRs) through unit-by-unit maintenance and refuelling. Holtec claims that refuelling will require only one week every 42 months (Holtec, 2011). Finally, decommissioning should be easier and less costly with modules.

One of the only licensed SMRs is the Korean Atomic Energy Research Institute's (KAERI) SMART (System-Integrated Modular Advanced ReacTor) (Keung et al., 2014). SMART is a 330 MWth steam-generator-integrated pressurised water reactor with advanced safety features. The unit is designed for electricity generation (up to 100 MWe) and thermal applications, such as desalination (up to 40 000 m^3/day). The design has a 60-year life and three-year refuelling cycles. It received Standard Design Approval (SDA) from the Korean regulator, Nuclear Safety and Security Commission (NSSC) in July 2012. In March 2015 KAERI signed a Memorandum of Understanding with Saudi Arabia's King Abdullah City for Atomic and Renewable Energy (KA-CARE). Under the agreement, the two countries will conduct a three-year preliminary study to review the feasibility of constructing SMART reactors in Saudi Arabia. The agreement anticipates that the cost of building the first SMART unit in Saudi Arabia at USD 1 billion (World Nuclear News, 4 March 2015). The SMART supply chain and possible success can be compared to the supply chain and success of the four Korean Electric Power Company APR-1400s being built in the United Arab Emirates (UAE) on the Arabian Peninsula (NEA, 2015: 97-104).

Following the general methodology in NEA, 2011: Figure E.3, one can estimate the cost of SMART based on the cost estimates for the APR-1400 from NEA/IEA, 2015. The size of the APR-1400 is about 1 340 MWe (net) and its overnight cost (in 2013 USD) is approximately USD 2 000/kWe (NEA/IEA, 2015: 41). Following the cost breakdown in TVA (2005), approximately 40%, or USD 800/kWe, is the cost of the reactor. Applying the scaling function from NEA, 2011: 17, and assuming a 10% savings in factory production, the cost of the SMART integrated reactor could be about USD 100 million. Adding the other components, as well as contingency, the Nth-of-a-kind (NOAK) total overnight cost is about USD 525 million or USD 5 250/kWe. With financing costs (with a weighted cost of capital of 7.5%) this leads to a levelised capital cost of about USD 62/MWh. (Note that this cost is for a plant that can produce both electricity and desalinated water.) This levelised capital cost can be compared to the estimated levelised capital cost for twin 180 MWe SMRs in the United States of USD 58/MWh (Rothwell,2016: 172). This can be added to the estimates for fuel and O&M (Operation and Maintenance) costs in the next section. Of course, these are NOAK costs. Prototype (pre-factory assembly) and first-of-a-kind (FOAK with factory assembly) costs could be much higher. Therefore, the values estimated here should be considered as "target" NOAK costs.

Chapter 2. Economics of small modular reactors

While the economics of small modular reactors (SMRs), capital costs, operation and maintenance (O&M) costs, as well as fuel costs are not yet known, SMR designers argue that per kWe overnight cost of SMRs could be lower than the overnight cost of advanced light-water reactors (ALWRs). This would be possible if SMRs were produced in large numbers, had optimised supply chains and had smaller financing costs. The number of SMR orders, which determines the economics of building production facilities, is thus particularly important for achieving SMR competitiveness. This section discusses key SMR economic variables.

2.1. Investment costs

As with ALWRs, SMR investment costs include the engineering, procurement and construction (EPC) costs and the owner's costs, primarily the costs of various licences. The total capital investment cost (TCIC, defined in EMWG, 2007: 27) is equal to the overnight cost plus contingency plus the cost of financing.

Although the economies of scale are unfavourable for SMRs, the factory assembly manufacturing of units and shorter construction times could reduce the per kWe construction cost. (Compare the economies of the AP600 with those of the AP1000.) Estimates (in particular, NEA, 2011: 15-16) suggest that the combination of these factors can lead to total overnight costs and overnight costs per kWe lower than ALWRs.

Financing is expected to be easier for SMRs than for ALWRs, because of their lower absolute cost, shorter period of construction and overall lower construction risk related to factory production (Rothwell and Ganda, 2014, and Rothwell, 2016: 123). In particular, even if the financing conditions (e.g. the cost of capital) are the same for the first unit, its successful construction and operation would ease the financing conditions for subsequent units. Such staged increase of capacity allows for better managing of the financial risk that is associated with long-lead-time, capital-intensive projects.

Another factor with potential for reducing the per kWe capital costs is related to the project structure and management. The increase in average capital costs per MWh for ALWRs in the last decade is mostly due, as identified by Rosner, Rothwell and Hezir, 2011a and Rosner et al., 2011b, to vendor/supplier agreements and risk management (increasing the cost by 70%), rising commodity prices (adding another 25%) and growing owners' costs (about 17.5%). Together, these factors more than doubled the costs of ALWRs between 2004 and 2011, according to Rosner et al., 2011b. The fragmented supply chain and "pancaking" of contingencies and margins led to a great escalation of costs. In comparison to ALWRs, SMRs are expected by vendors to rely on a more integrated supply chain and reduced number of layers of subcontractors within the "nuclear island." Such organisations have the potential for reducing the layering and multiplication of contingencies.

Current estimates suggest that the per kWe investment cost could become less for SMRs than for ALWRs because of potential savings related to optimised supply chains and smaller financing costs. Of course, this will strongly depend on the successful licensing and establishment of the factory for manufacturing the modules, size of the series and other factors that are further discussed in the next chapter.

2.2. Operation and maintenance, and fuel costs

O&M costs include all costs associated with operation, maintenance, administration, material supplies, licence fees and salaries of personnel. For ALWRs, the O&M component is typically in the range of USD 10-20/MWh (NEA/IEA, 2015).

The fixed component of O&M costs is independent of the size of plant. This component includes the cost of security, etc. If O&M costs for ALWRs are scaled down to power levels of SMRs, then the O&M cost per MWh could be higher for SMRs than for ALWRs. However, for multi-unit plants with several SMR units, O&M costs per MWh are expected to decrease with changes in regulatory requirements.

However, many SMRs propose innovative solutions for plant operation, e.g. a single control room for several reactors, replacement of reactors instead of refuelling on-site (e.g. for floating nuclear power plants, see Russian case study below) and if accepted by the regulators, could lead to lower O&M costs. Independent of such factors, operation of a multi-unit plant allows for reductions in O&M costs by optimising the number of personnel. For example, instead of hiring teams from outside once every 1-2 years to refuel and perform maintenance work for an ALWR, utilities operating a fleet of SMRs could optimise personnel and perform refuelling/maintenance work on individual SMR units one at a time, reducing replacement power costs.

The fuel component of the variable cost depends on the price of fresh fuel, including costs of uranium, conversion and enrichment services, fuel fabrication and the cost of the back-end of the fuel cycle (NEA, 2013). For ALWRs, the fuel cost component is typically in the range of USD 6.5-13/MWh as a function of the price of fuel inputs and the average burn-up of the fuel (NEA/IEA, 2010).

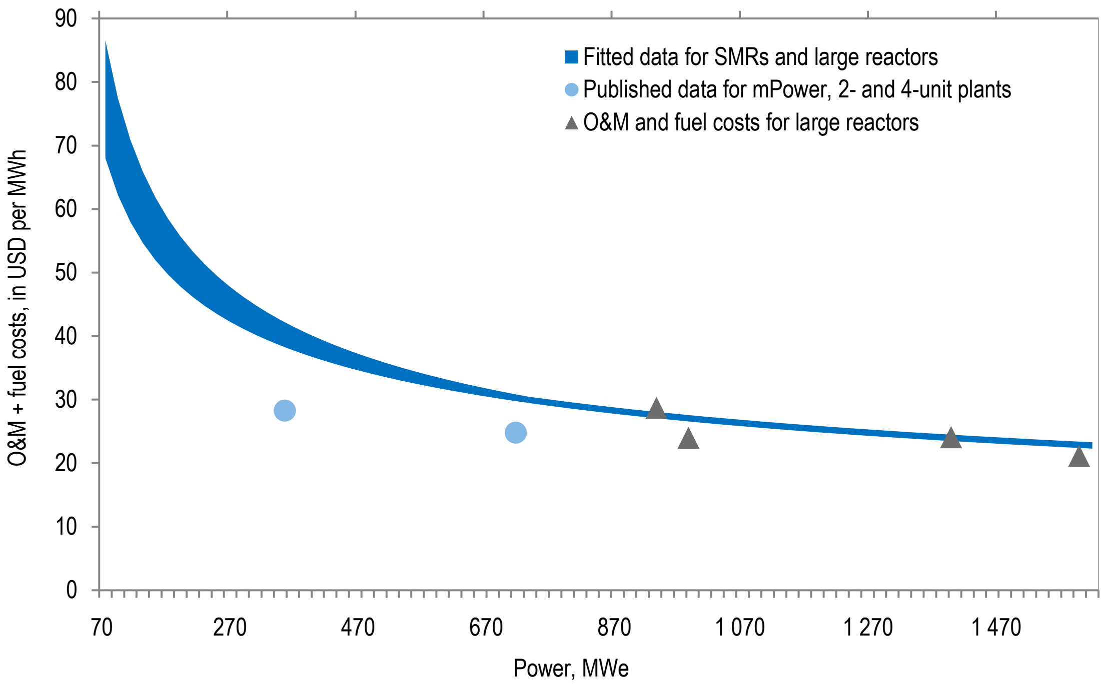
It is difficult to provide estimates for the fuel costs of innovative SMRs, especially given that for many of them the design is not yet finalised. Taking into account the smaller average burn-up of fuel and the cost of fabricating fuel, the cost of fuel per MWh could be higher for integrated light water SMRs than for Advanced LWRs (Rothwell, 2016: 172).

Figure 2.1 shows the sum of O&M and fuel costs for ALWRs, the previously published estimates for the mPower project, and the fitted data that were received from the SMR vendors and designers through questionnaires. With respect to the commercial sensitivity of these data they were cleared of design-specific values so that only average, fitted data are used throughout the report. These data include values for some of the transportable reactors (e.g. KLT-40S) that have particularly high O&M costs, partly because of their mode of deployment (see Chapter 6).

2.3. Total electricity generation cost

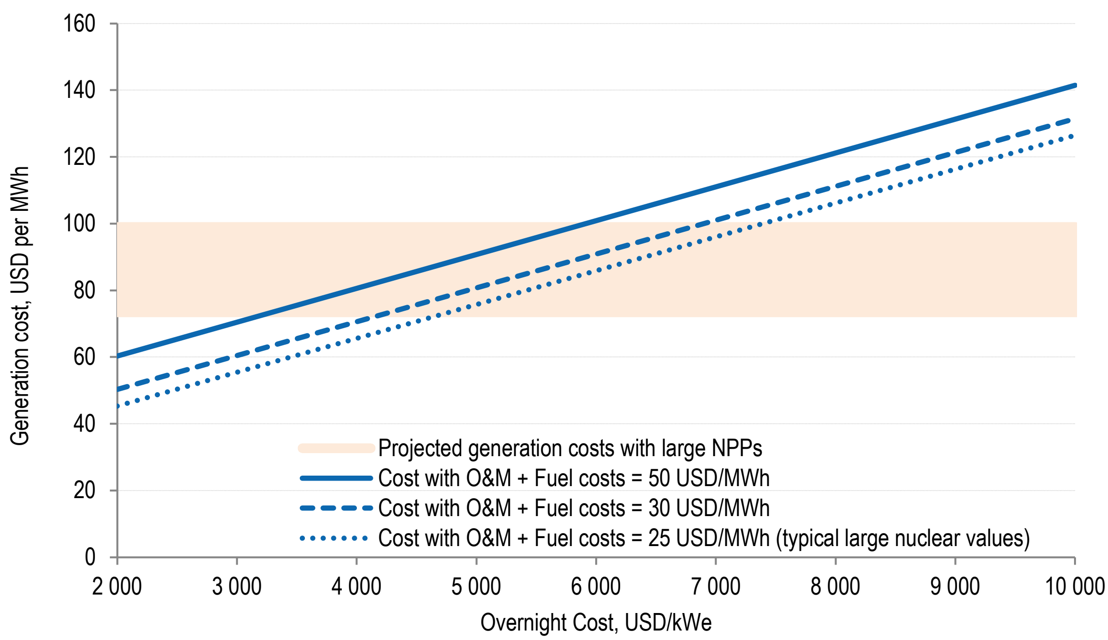
There is uncertainty regarding the components of SMR generation costs. However, if the expected competitive advantages are realised, SMRs could be cheaper to build than large nuclear reactors in terms of both absolute and per kWe total construction costs. The first-of-a-kind (FOAK) overnight cost estimates per kWe might be higher for SMRs than for ALWR NOAK costs, but decreases could be achieved from lower contingencies and shorter construction times as SMR construction matures. With respect to variable cost, SMRs are likely to have higher costs than ALWRs for O&M and fuel costs. Figure 2.2 presents the levelised cost of electricity (LCOE) for NOAK SMRs with real capital costs of 5% for different values of variable costs. These values can be compared with projected generation costs of ALWRs and other power sources in NEA/IEA, 2015. Given these findings, in the following chapter, the potential applications of SMRs with such economic characteristics are analysed, and the consequences for the electricity generation portfolios are assessed.

Figure 2.1: Fitted sum of O&M and fuel costs of pressurised water reactors and SMRs as a function of power



Source: Based on information from NEA/IEA, 2015, and from a survey of vendors.

Figure 2.2: Electricity generation cost with SMRs as a function of capital costs, at a 5% real discount rate



Source: Based on information from NEA/IEA, 2015.

Note: Assumed capacity factor is 95%.

Chapter 3. Factors influencing the small modular reactor market

The economic factors influencing the choice of nuclear, as part of the national energy mix, will be similar for both large nuclear reactors and small modular reactors (SMRs). However, SMRs are expected to be more flexible and ease some of the regulatory requirements. Regardless of the size, nuclear reactors can only be constructed in countries that already have a nuclear power programme or are willing to develop one. Hence, the market analysis is limited to markets in those countries who have expressed an interest in developing a nuclear programme.

In this section, the various factors (see Table 3.1) influencing the choice of SMR technology and the SMR market are discussed including various conditions for SMR vendors and potential customers followed by more global factors, such as challenges for SMR deployment and competitiveness issues.

Table 3.1: Summary of factors influencing the SMR market

SMR customers	**Factors at the national level:** Gross domestic product and gross domestic product growth Per capita electricity consumption Credit rating of the economy, e.g. Standard and Poor's Self-sufficiency of energy supply, e.g. production/total primary energy supply Environmental protection (greenhouse gas emission policies) IAEA membership and Non-proliferation Treaty status Nuclear power programme development, IAEA milestones **Factors at the utility level:** Utility financial profile and credit capability Level of electricity prices Electricity grids: size, voltage, quality of the grid, interconnections, load factor, typical single-unit installed capacity
SMR vendors	Technology readiness and demonstration Financial capability of the vendor Supply chain readiness and procurement structure Competitiveness
Challenges	Nuclear regulatory barriers Public attitude towards nuclear power Infrastructure development in the host country Availability of nuclear sites with good-quality cooling Labour, education and training of potential nuclear facility workforce Advanced orders (over which to amortise production facilities)
Competitive environment	Type of electricity market: regulated, liberalised, etc. Other electricity generation options and system effects

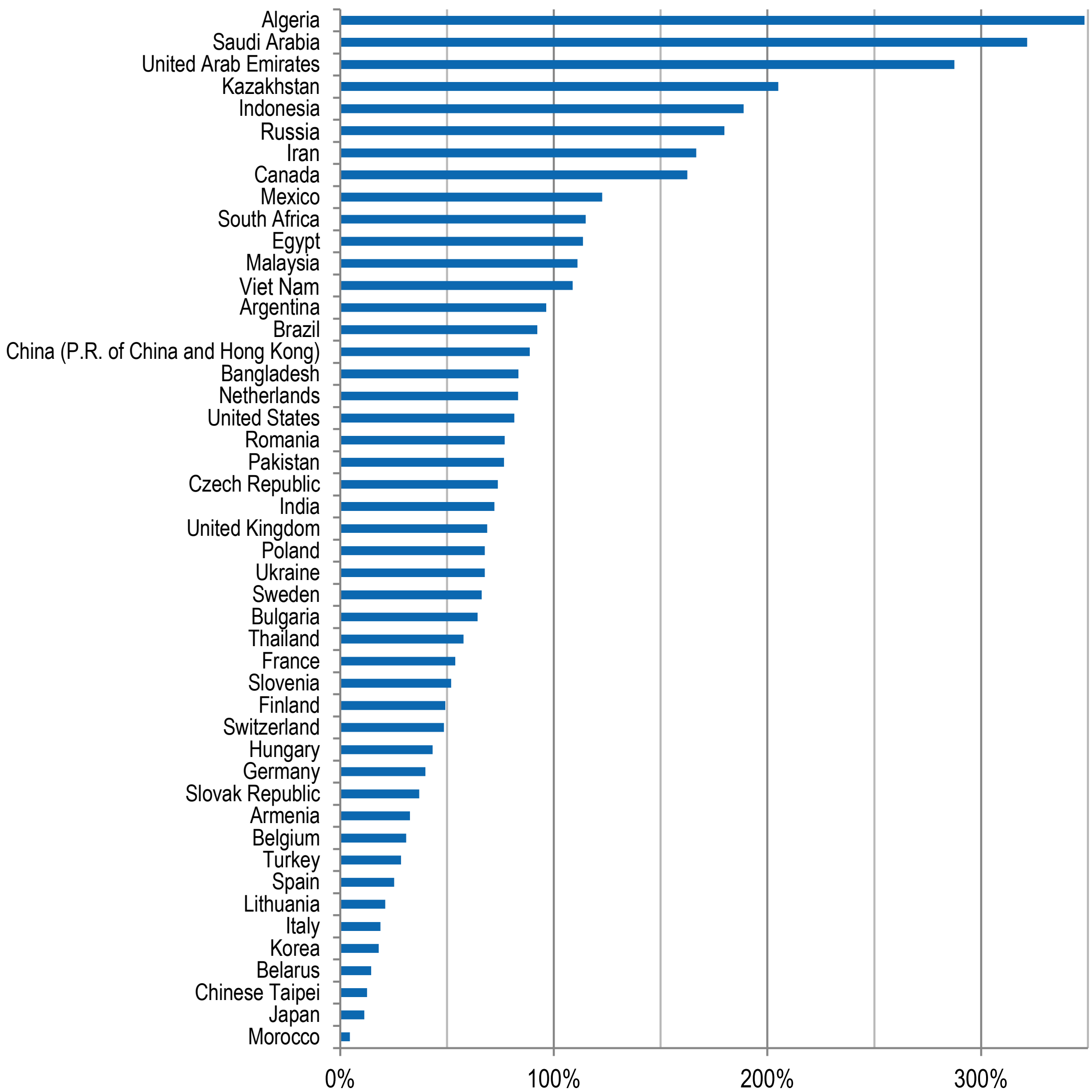
Source: NEA, 2011.

3.1. SMR customers

Factors at the national level

At the national level, development of the national nuclear power programme is a necessary requirement for either large or small reactors. The necessary steps to be performed by a newcomer country are described in the IAEA milestone document (IAEA, 2007) and include, in particular, establishment of an independent national nuclear regulator with sufficient resources (human and financial) and a scientific base. In the past, going through these steps took at least several years, but the most recent newcomers, in particular, the United Arab Emirates with the Korean APR1400, have demonstrated that a faster pace of deployment is possible if nuclear development is considered a national priority and financial capabilities are sufficient.

Figure 3.1: Self-sufficiency in energy ([energy production]/total primary energy supply) in 2011, for countries having or considering nuclear power development



Source: IEA, 2011.

An important condition for SMR deployment is the need for domestically produced electricity. This need could arise from:

- Low share of the population having access to electricity.
- High growth of the economy and/or increase of electricity consumption per capita.
- Priority for improving the long-term security of energy supply and domestic electricity production. The simplest indicator of self-sufficiency of energy supply is the ratio [energy production]/total primary energy supply (see Figure 3.1).

Depending on the size of the economy and rate of increase of energy needs, an analysis of the choice between large nuclear power plants (NPPs) or SMRs should be done. In particular, one of the first steps for newcomer countries was the construction of a research reactor. Such reactors perform different tasks including personnel training for future power plants, technical support organisations and the regulator, but also provide basic and applied research, and, in some cases, production of isotopes. Some of these functions could be performed by an SMR, which could be an attractive option for newcomer states, at least for the first units.

Factors at the utility level

At the level of the utility, the most important factors that could influence the choice between large and small units are the following.

- **Utility financial profile and credit capability**

  For utilities, SMRs present the possibility of a new financial model for NPP deployment – one that allows generating assets to be built and installed on a more predictable basis. SMRs could be an attractive option for utilities willing to invest in nuclear power, but not having enough financial capability to fund the construction of an advanced light-water reactor (ALWR).

  Utilities are also attracted by the idea that reactors could be deployed one by one, avoiding the large, upfront costs inherent to today's nuclear plants. Furthermore, building several SMR units at the same site could provide additional benefits by reducing risk premiums for loans on subsequent units, provided the first units have been successfully built and operated. Utilities could also benefit from smaller debt accumulated because of incremental capacity build-up. The on-site work is expected to be shorter for SMRs than for ALWRs. These factors contribute to reducing the overall cost of financing.

- **Level of electricity prices**

  The level of electricity prices is crucial for SMRs. To recoup investment, long-term electricity prices must be at least as high as levelised costs (including a reasonable rate of return on investment). Given that the variable cost per MWh of SMRs could be higher than for ALWRs, there is a risk that SMRs might not be producing enough electricity in a liberalised market to recover their fixed costs. However, the difference between the variable cost of SMRs and large nuclear reactors is probably not great enough to make SMRs more sensitive to electricity prices than large nuclear reactors. Thus, the level of electricity prices is an important factor for nuclear in general. Another important aspect is the predictability of the electricity prices, particularly in liberalised markets (this is discussed below).

- **Electricity grids: Size, voltage, quality of grid, interconnections, load factor, typical single-unit installed capacity**

  Nuclear power plants require robust and reliable grids for safe operation. Installing a large unit on a weak grid is problematic and might require large investments in grid reinforcement. The "rule of thumb" is that a single generating unit should not exceed 10-15% of demand. Thus, SMRs would be suitable for small grids (or isolated parts of grids) with a few gigawatts of total capacity. In such grids, i.e. interconnected zones in which the maximum single-unit capacity is lower than typical large-scale nuclear plants capacity (around 1 GW), integration of an NPP with an ALWR would not be possible. For SMRs, particularly those to perform safely in a load-following mode, the size of the grid is potentially less of a concern.

On the other hand, utilities operating a fleet of ALWRs in a well-developed grid might be less interested by small reactors, unless specific characteristics of the SMR (such as flexibility) have a particularly strong weight in a multi-criteria evaluation (for an example of such as evaluation see discussion of the Evaluation Methodology Group's assessment of advanced nuclear energy systems in GIF, 2002: 8). In this case the flexibility of SMRs should be assessed against the flexibility requirement of electricity systems and compared to the load-following performance of the new generation of large-scale power plants. The issue of optimising the electricity capacity portfolio is discussed in Ganda and Rothwell, 2014.

3.2. SMR vendors

Technology readiness and demonstration

Technology readiness and demonstration is a key factor that will determine market perspectives for the SMR vendor. Proven technology and advanced designs are necessary to attract potential customers, but also allow building the supply chain and determining the procurement structure (EC, 2014).

Financial capability of the vendor

SMR vendors in the United States estimate that the total cost of an SMR development to be between USD 1-2 billion. Its first phase includes design development and preparation of the set of documents for certification. This stage takes about ten years, and requires investment of about USD 0.5-1 billon. At the end of this stage about 50% of design is complete.

The next step is the pre-deployment preparation phase that consists of finalising the design and setting up the supply chain. This phase takes several additional years and investment of approximately USD 0.3-0.6 billon is needed for successful implementation. Finally, the early market adoption phase consists of building the first-of-a-kind (FOAK) units and working with early clients. Expenses of approximately USD 0.3-0.5 billion per plant are needed at this stage.

Thus, SMR development takes time and requires large investments before achieving NOAK deployment. The financial capability of the vendor is, therefore, an important factor for the successful development of SMRs. For most of the actively developed SMR projects, the governments provide some form of support. For example, in the United States, US DOE has made available USD 452 million in matching grants to support the licensing of the mPower and NuScale SMR projects (both sides of the grant can contribute in-kind support, i.e. labour employed by the vendor for design and labour from the US government for licensing). In Russia and Korea, the SMRs are developed by state-owned nuclear institutes and corporations.

Supply chain readiness and procurement structure

The key element for SMR competitiveness is the serial production in factory conditions. Town and Lawler (2013), discuss the organisation of factory-assembled SMRs and the associated challenges.

It is obvious that an assembly plant that does not operate at a sufficient level will fail to achieve economic competitiveness. In a similar way, establishing multiple SMR assembly facilities (for example, to fulfil a localisation requirement, consider the fabrication of the Korean SMART SMR in Saudi Arabia) could potentially dilute the total number of orders (i.e. production volume) for each assembly facility, again threatening the achievement of competitiveness.

The intended assembly mode for SMRs represents a drastic change from the existing nuclear supply chain that is set up around construction of complex equipment in limited batches for a specific NPP. The SMR manufacturing supply chain is built around a relatively constant production rate of units.

Town and Lawler (2013) show that a "just-in-time" supply chain inspired by the automobile industry would be challenging for the nuclear business, where part supply is frequently set up and regulated on a national (not international) basis. Another approach could be a scalable assembly factory. Since the initial production rate of SMRs will probably be low, the supply chain should be designed to expand as the technology matures and SMR orders increase.

An example of such a supply and assembly strategy is the production of transportation equipment. It consists of a single-track flow system to the assembly of a product, using individual workstations or process steps to progress the assembly procedure. The flow moves continuously or in a stop-start-stop approach, defined by the production cycle ("*takt* time"). During the assembly process minimum inspection is preferred, using instead online validation/testing of components or assemblies.

There are many prerequisites for successful implementation of such assembly schemes. The products should be highly standardised or belong to the same family of products. In particular, this implies that the SMR vendor will have limited capability to cope with customisation demands without destroying the business model. Second, no rework is possible. Next, all components/parts/kits required for the ongoing work should be available at the due time (in addition, an optimal inventory of buffer stock of critical parts could be required). Finally, the workstation equipment, tools, etc., should have a high level of reliability, and the teams working on the assembly lines should be well-trained and highly qualified.

One of the most important issues for the SMR factory assembly is nuclear regulation. Current regulatory practices might not be compatible with factory assembly, for example, if the assembly process is automated. Regulators and manufacturers must work together to the greatest extent possible at the assembly design stage to reduce potential rework.

Competitiveness

As suggested in the previous chapter, SMRs could be comparable with large nuclear reactors in terms of electricity production cost if their competitive advantages were realised. However, the cost structure is expected to be different from ALWRs. If produced in series, SMRs have the potential of competitive overnight capital costs. The overnight cost might be higher for SMRs than for large nuclear reactors but the total capital investment cost could, in principle, become attractive as a result of lower contingency and shorter construction time. With respect to variable cost, SMRs are expected to have higher values of operation and maintenance (O&M) and fuel costs than ALWRs.

It does not necessary imply that SMRs could directly compete with large nuclear reactors but in some grid compositions and energy mixes they could represent an interesting alternative to large nuclear reactors, in particular for replacement of retiring coal plants in the United States (see Chapter 5 for details).

Because SMRs could have lower capital expenditure (because of an optimised supply chain and smaller financing costs, USD per kWe) and higher O&M costs (e.g. USD per MWh) than large NPPs, they are expected to stand in the merit order between large-scale NPPs and fossil plants depending on the cost of fossil fuels and CO_2 emissions costs.

Assuming that investors are not necessarily committed to nuclear energy, the flexibility and size arguments for SMRs cannot prevail against natural gas-fired plants that are based on a well-established technology. Fuel cost could thus be a determinant.

Assuming that investors are committed to nuclear energy, the main advantage of SMRs is presumably the lower risk profile that results in a lower financing cost than for large-scale power plant financing compared to the size of the owner-operator.

To reach critical size, traditional markets in well-developed grid zones will be targeted by SMR developers. However, in these markets, SMRs must compete against fossil fuel plants, that could be small and flexible, but emit greenhouse gases, on one hand, and large-scale nuclear, on the other hand.

Another type of SMR application could be energy solutions for remote or isolated areas and islands where small-sized units are required and the cost of electricity produced with non-nuclear sources is high (see Chapter 6 for illustration). Because of the specific requirements for this kind of application, the cost of electricity produced by such an SMR is estimated to be quite high but competitive compared with the costs of alternatives.

Niche markets are isolated or remote non-interconnected zones. In these markets, competitors to SMRs are not large-scale NPPs but smaller fossil fuelled plants (possibly diesel generators) sometimes installed on a deck barge. They are often dedicated to supplying power to a city or an industrial installation (for example, a mining installation in a remote area).

In these markets, the alternative solutions are quite expensive and the modularity, flexibility and low grid requirement of SMRs make them viable. However, niche markets are rarely found within countries with a well-developed nuclear programme (Canada and Russia are notable exceptions). Therefore licensing issues would be critical.

Serial SMR production for the niche market might become an issue because by definition these markets are small. Any local conditions either because of the regulation or the geography might endanger the serial production in factory conditions necessary to make the SMRs competitive.

Niche markets represent an interesting segment for SMRs, although they might not allow for the development of serial production. Standardisation of SMRs is a necessary condition for the development of this industry and might not be achieved in this segment because of its fragmented nature.

3.3. Challenges

There are many challenges that are independent of the attractiveness of SMR technology and general willingness of the customer to purchase SMRs.

Nuclear regulatory requirements

The first and most important challenge are regulatory barriers. Many SMR designs offer innovative features such as enhanced passive safety systems and multi-modular deployment (i.e. several reactor modules on the same site or in the same pool, e.g. NuScale). The SMR vendors argue that these features could reduce staffing requirements for operation (see discussion in Rothwell, 2016: 168) and reduce the size of emergency planning zones motivated by the application of today's regulations. It is clear that safety and security requirements are the same for SMR as for any NPP, but the question is how the SMR will demonstrate that they can meet those requirements. Regulators and technical support organisations will also need time to determine judgements on these options and innovations that could delay the licensing process.

Irrespective of technology, the manufacturing and deployment of SMRs differ greatly from traditional construction of large NPPs. To achieve economic competitiveness, most SMRs rely on series of standardised factory-produced modules. While in large NPP construction projects modules are also used allowing manufacturing of different parts in parallel, in many SMR designs the entire reactor is one module, the turbine-generator-condenser is another module, etc. These modules could be then deployed at the same site with modules previously installed. The business case for many SMR designs relies on such modes of fabrication and deployment, but the current regulatory model might not be suited for them. Regulators treat all nuclear reactors, small or large in the same way, and while the safety features of SMRs could be addressed generally within the existing regulatory framework, there are issues that must be resolved. In particular, the current regulatory practices might not be fully compatible with the factory assembly mode, especially if the assembly process is automated.

Ideally, for the successful deployment of SMRs, a new approach to licensing should be developed to allow factory-based manufacturing and serial deployment. It might require strong co-ordination not only between safety, health and environmental regulators, but also between manufacturers. An additional challenge arises for exported SMR units, in which case two or more regulators from both the exporting and the importing countries could be involved.

Among proposed schemes, the example of certification or airplanes and engines is often cited. Indeed, there is vast experience in licensing of aircraft and their components, with well-established mutual validation processes between Europe (European Aviation Safety Agency – EASA), the United States (Federal Aviation Administration – FAA) and other countries. If an aircraft is certified by one authority, the certificate is then validated by the other. Compared to recertification this is a simpler process. This is only possible because of high degrees of mutual confidence and strong working relationships between aviation authorities in different countries.

An application of aviation-type schemes to nuclear installations is not straightforward. In particular, effective full factory assembly of SMRs might not allow regulators to inspect all steps (for optimisation of the factory assembly process, an on-site inspector could be preferred).

With respect to SMR deployment, an innovative licensing scheme should separate the general approval or licensing of the SMR fabrication facility, the SMR itself and the site for the SMR (such an approach is proposed in Söderholm, 2013).

Licensing features that could suit SMRs are "pre-licensing" instruments, and, as a further development of this idea, compartmentalising licensing elements to better reflect SMR characteristics. Ideally, breaking the SMR licensing process down into sufficiently independent "modules" could be a good simplification. SMRs present the possibility of creating an equivalent standard design certificate that is replicable for licensing standard module designs (see Section 6.2, "SMR Licensing Process Step-by-Step", WNA, 2015).

Other important regulatory issues include validation of enhanced passive safety systems and multi-modular deployment, size of the emergency planning zone and the staffing requirements for operation and security. This validation could be obtained with existing procedures, using a risk-informed approach similar to larger nuclear plants. However, SMRs must demonstrate that they can meet safety requirements. Regulators and technical support organisations will need time and resources to form opinions on these options and innovations, and this process could lead to delays in SMR licensing.

Public attitudes towards nuclear power

The issue of public acceptance is extremely important for the successful development of any nuclear project. Public acceptance of nuclear designs with innovative technologies must rely on the expertise of independent safety authorities. The use of passive safety features and massive deployment of SMRs could, however, improve the overall public attitude towards nuclear power plants.

Infrastructure development in the host country

Infrastructure development becomes particularly important if the SMRs are exported to emerging or developing countries. SMRs remain nuclear reactors, and there are strict requirements for their deployment overseas. As discussed above for newcomer countries willing to launch a nuclear programme, there is a well-established process of developing civil nuclear power with assistance from the IAEA (2007).

Nuclear power also imposes more stringent requirements on the quality and reliability of the power grid. Although SMRs have a smaller power output (and thus they could be fit to smaller grids), grid reinforcement is often needed to achieve the level of reliability and quality required for safe operation of the power plant (key requirements are redundant supply of power and high stability of the frequency).

In terms of localisation of production, infrastructure development and the degree of localisation will depend on the level of economic and industrial development in the host country. Although the host country will often prefer to maximise the localisation of nuclear power plant production, this might contradict the business model of SMRs in which units are factory assembled (in a limited number of plants operating at large volumes of production) and shipped to sites. However, non-nuclear reactor modules (e.g. turbine-generator-condenser or cooling system switchyard) could be manufactured locally.

Availability of nuclear sites with good-quality cooling

Availability of sites with good-quality cooling conditions has been gradually becoming an issue for the nuclear new builds because of water shortages in potential market countries and increased environmental protection requirements. For SMRs, as a result of their smaller power, the availability of large amounts of cooling water is less of a concern. Some designs have the capability using passive cooling systems only, e.g. below-grade designs use the earth as a heat sink.

Labour, education and training

In terms of human resource management of teams involved in operation and outage management, there are benefits in having several identical SMR units instead of one large unit. SMRs have an advantage of potentially reduced human resource requirements because of their modular design and simplified construction. This is especially true when implementing the build-own-operate (BOO) option (NEA, 2015: 77), considered as a preferred option by some SMR vendors. The focus is shifted to labour at the factory where SMRs are constructed.

Potential market size (for factory SMR production)

Factory production of SMR modules is important for the competiveness of these technologies. According to SMR vendors, about 5 to 15 plants would be required before achieving Nth-of-a-kind costs. The typical construction times expected by SMR designers are about three years, of which about two years would be dedicated to factory assembly. The initial production rate for the SMR modules is expected to be low. However, there should be a minimum production rate that would allow the construction of a factory. It is currently not possible to estimate the minimum production rate that would make SMRs competitive.

3.4. Competitive environment

Type of electricity market: Regulated, liberalised, etc.

In regulated markets the energy producers have more certainty of their revenue flows than in liberalised markers. The uncertain nature of liberalised markets combined with decreasing prices for electricity (observed in several countries because of low prices for natural gas and/or the massive introduction of subsidised renewables) and rising prices for advanced nuclear reactors has resulted in the slowdown of nuclear development with large nuclear power plants. The large upfront investment required and long lead times of nuclear projects greatly limit nuclear development in liberalised markets. While it might not be economically reasonable in most cases, SMRs could be more flexible performing load-following when compared to larger nuclear reactors.

Other electricity generation options and system effects

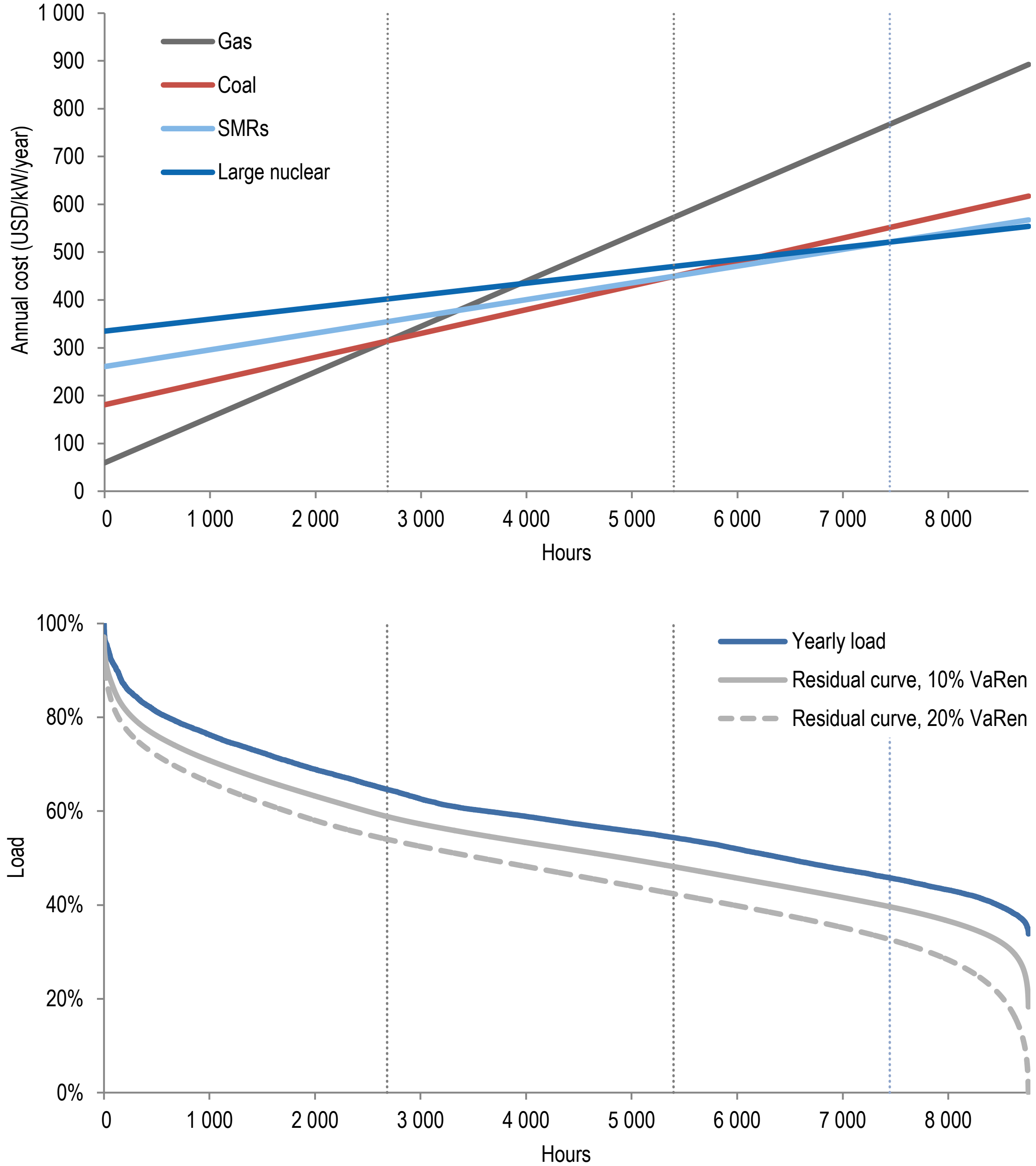
Present and future energy mixes will include both intermittent and dispatchable energy sources (nuclear, coal, natural gas and hydro) with different fixed and variable costs of electricity production. Interaction between different energy sources is optimised taking into account the costs of generation, security and reliability of supply, externalities (including CO_2 emissions) and other factors.

Energy mix planning is a complicated task that is, to some extent, performed by national or regional authorities with electric utilities where the role of SMRs would be determined on a country-by-country basis. With a simplified model adopted from NEA (2012), it is possible to estimate the optimal share by minimising the total cost of electricity produced by a system of SMRs and ALWRs, depending on the share of electricity produced by variable renewables.

The model is based on the analysis of the residual load curve, i.e. the load curve from which the generation of electricity of variable renewables is subtracted (see Figure 3.2) estimated using data from the French transmission system operator, RTE (Réseau de Transport d'Électricité). Having this remaining residual curve (different for each penetration level of variable renewables) and the annual cost data for different energy sources (here large nuclear, SMRs, coal and natural gas – see Figure 3.2), one could obtain the composition of the energy mix minimising the total cost of electricity. (The same cost data as in NEA, 2012, was used for coal and natural gas; the latter averaged data between open-cycle natural gas turbines and combined-cycle natural gas turbines was taken to yield a single figure for natural gas, and the same price on carbon dioxide.) This idealised situation could be interpreted as long-term effects of introduction of variable renewables into an existing energy mix.

It is assumed that SMRs have achieved a degree of maturity and are competitive with other energy sources. Moreover, large nuclear plants and SMRs were assumed to have the same LCOE of USD 70/MWh (at an appropriate weighted average cost of capital) with a load factor of 85%, but slightly different distributions between fixed and variable costs. This translates the idea that SMRs might have lower capital costs because of factory production, shorter construction period, easier financing schemes, etc., and higher variable costs: larger per MWh O&M costs because of the fixed cost component of O&M costs, lower fuel efficiency, etc. In this example, SMRs are most competitive at load factors of 60-85%, and thus, replace coal and large nuclear plants in this range.

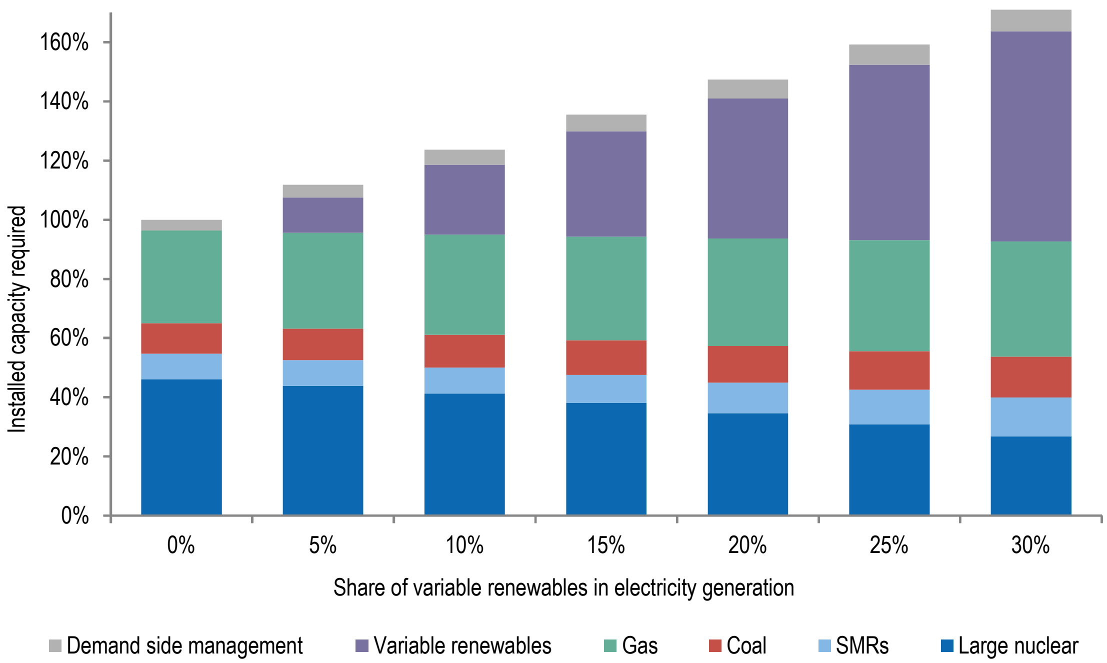
Figure 3.2: Cost data for dispatchable energy sources (above) and load curves (below) used in the power mix optimisation



Source: Based on model in NEA, 2012.

The resulting optimal energy mixes (for dispatchable energy sources), depending on the postulated share of power production with variable renewables, are presented in Figure 3.3. As the share of SMRs increases if larger shares of variable renewables are introduced into the system. In addition, the share of SMRs in the total installed nuclear capacity also increases, but the overall contribution of nuclear power decreases. Figure 3.3 shows the share of SMRs increases from about 16% (= 8.65% / (8.65% + 46.09%)) of the total installed nuclear capacity for energy systems without variable renewables to about 33% (= 13.15% / (13.15% + 26.79%)) for an energy mix with 20% electricity production from variable renewables, and up to 33% for a 30% penetration level of variable renewables.

Figure 3.3: Installed capacities of optimal (i.e. yielding lowest cost) energy mixes depending on the share of power production with variable renewables



Source: Based on information from NEA, 2012.

A possible SMR deployment scenario

Present and future energy mixes will include both intermittent and dispatchable energy sources (nuclear, coal, natural gas and hydro) with different fixed and variable costs of electricity production. Interaction between different energy sources is optimised taking into account the costs of generation, security and reliability of supply, externalities (including CO_2 emissions) and other factors.

As a possible deployment scenario of the 12-unit NuScale plants, consider Table 3.2 (from Rosner, Rothwell and Hezir, 2011a). Table 3 presents discounted costs and benefits from subsidising the LEAD plant (prototype plant not built in a dedicated factory) and FOAK plants (built in a dedicated factory). Net benefits, benefits minus costs, are discounted at 3%, the "social discount rate" (NEA/IEA 2015, Chapter 8: 137). Here there are 12 reactor modules in the single LEAD plant (with a construction start in 2015 and completion in 2018), 4 FOAK plants with 60 reactor modules (with construction starts in 2018 and completion in 2024) and 16 NOAK plants with 192 reactor modules (with construction starts in 2025 and completion in 2035) for cumulative number of 21 plants, 252 reactor modules and 11.34 GW. Given that all values are discounted to 2011, one can simply add an appropriate number of years to account for the difference between the end of construction of the LEAD unit and 2018 (assumed in Table 3.2). For example, if the first FOAK plant is ordered in 2024, then add 6 to each year and discount values at 3% from "Present value at the time of the FOAK order" to an appropriate start year of R&D.

Subsidies for the LEAD plant include USD 200 million for recurring FOAK costs of USD 200 million (a portion of the Design Certification costs) and a purchase power agreement that guarantees a price of USD 79.25/MWh. Subsidies for the FOAK plants are limited to USD 18/MWh for eight years, which are equal to the Production Tax Credit provisions for advanced reactors in the Energy Policy Act of 2005. There are no subsidies for the NOAK plants, which earn an economic profit (above the corporate weighted average cost of capital) of USD 3.10/MWh. Revenues (based on levelised costs) and subsidies are discounted to the "start of R&D", i.e., 2011, when the US DOE selected SMR designs for matching funds. There is a positive net social benefit of USD 523 million with public investments of USD 200 million in design and licensing, USD 3 403 million (discounted) to build the prototype and Production Tax Credits (PTCs) of USD 1 972 (discounted). See discussion of NuScale in Chapter 5.

Table 3.2: SMR discounted costs, benefits and present values for a NuScale fleet

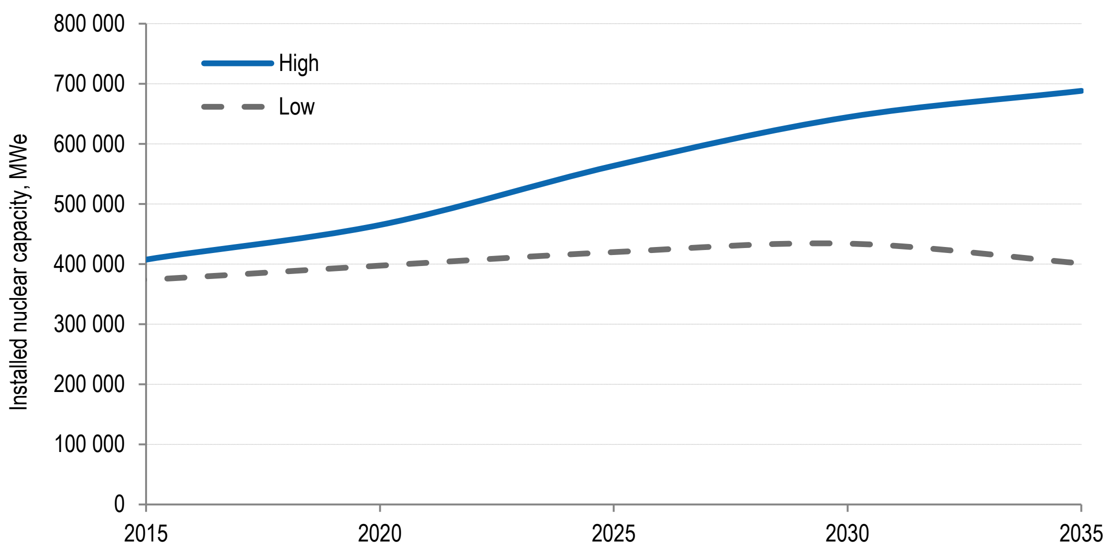
Stage	Units	Total	RD&D	LEAD	FOAK	NOAK
Plants in stage	Number			1	4	16
Cumulative number of plants	Number			1	5	21
Cumulative number of reactor modules	Number			12	60	252
Electricity capacity in stage	GW			0.540	2.700	11.340
Capacity factor	%			85%	90%	95%
Anticipated stage start year, base year =	2018		2011	2015	2018	2025
Activity starts at the beginning of year	Years		7.00	-3.00	0.00	7.00
Starts generating at beginning of year	Year =			0.30	3.30	10.30
Anticipated stage completion year			2015	2018	2024	2035
RD&D (FOAK funding discounted to 2011)	USD million	3 403	200	3 952	0	0
PTC (USD 18/MWh for 8 years, discounted)	USD million	1 972		0	2 686	0
Cost in USD/MWh	USD/MWh			122.05	91.77	76.15
Assumed market target cost (MTC)	USD/MWh			79.25	79.25	79.25
Economic benefit (EB) = cost – MTC	USD/MWh			-42.80	5.48	3.10
Millions of MWh generated per year	Million MWh			4.02	21.30	89.47
Economic benefit per year (EB x MWh)	USD million			-172	117	277
Present value at stage operation start	USD million	9 042		0	2 679	6 364
Present value at time of FOAK order	USD million	7 098		0	2 426	4 672
Present value at start of R&D – subsidies	USD million	523		0	2 171	3 727

Source: Rosner, Rothwell and Hezir (2011a).

Chapter 4. Projected nuclear capacity and the share of SMRs

According to updated projections from NEA/IAEA (2014), taking into account the developments that occurred between January 2013 and August 2014, the nuclear capacity in 2035 will be almost 700 GWe in the high-case scenario and about 400 GWe in the low-case scenario (see Figure 4.1). In the high-case scenario, almost 300 GWe of new nuclear capacity will be added in the next 20 years, about 245 of which in the period 2020-2035.

Figure 4.1: Projections of installed nuclear capacity up to 2035



Source: Based on updated figures from NEA/IAEA, 2014.

To estimate the size of the global market in 2035, the different factors discussed in the previous chapter could be applied on a country-by-country basis, in particular, taking into consideration the economic competitiveness of SMRs and infrastructure development, particularly, the electricity transmission grid. It is assumed that SMRs will be licensed in the early 2020s, that the supply chain will be established, and the labour trained for both construction and operation of SMRs. The results of such an assessment should be used with caution since the estimation is at a top level, and the real situation will depend on factors that are impossible to quantify on an a priori basis, e.g. the political situation or progress with licensing. The aim of these projections is to determine the possible share of the nuclear new build in the period 2020-2035 will be done with SMRs, and whether this market share is sufficient to build production facilities. Two scenarios are considered: *i)* a conservative low-case scenario where SMRs are not competitive (where NOAK costs are not achieved) and *ii)* an optimistic high-case scenario where SMRs are competitive (where NOAK costs are achieved).

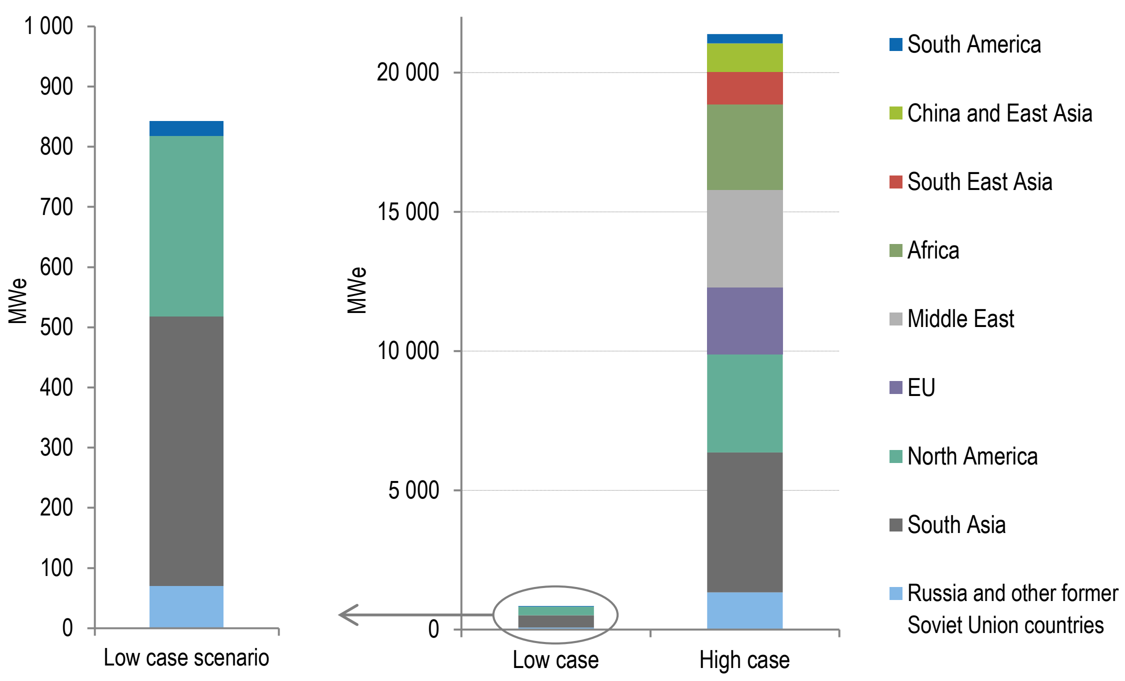
In the low-case scenario, it is assumed that SMRs are more expensive to build and to operate (when compared to other power sources) than currently anticipated, and thus only a limited number of projects are completed, including prototypes and generating plants in remote/isolated areas with high electricity prices.

In the high-case scenario, the share of SMRs is determined using the assumption that SMRs will be cheaper to build than advanced light-water reactors (ALWRs), but will have higher variable costs (operation and maintenance [O&M] and fuel costs). In terms of economics, we assume that the annual cost for SMRs are between those of coal plants and "large nuclear" (see Figure 3.2). Reviewing the results shown in Figure 4.1, the optimal share of SMRs in the nuclear capacity will depend on the penetration level of the variable renewables and ranges between about *i)* 16% for no renewables and *ii)* 33% for a 30% market penetration level of variable renewables. For simplicity, when estimating the share of SMRs in nuclear new build, a share of 15% was applied for countries with low planned penetration levels of variable renewables, and a 20% share of SMRs in the new build was assigned to countries planning to introduce large shares of renewables.

For countries initiating a nuclear programme, it is assumed that first units could be SMRs given that adequate experience from successfully operating the reactor is first achieved in the supplier country. However, examples of United Arab Emirates and Belarus, that have started their nuclear programme directly with large units, indicate that this assumption is strong, and thus it was only applied to the high-case scenario.

According to the analysis (see Figure 4.2 and Table 4.1), up to about 9% of the nuclear new build, in the period 2020-2035, could be done with SMRs in the high-case scenario, and about 2.3% in the low-case scenario. In total, about 21 GWe of nuclear new build could be done with SMRs in the high-case scenario (NEA/IAEA, 2014), i.e. SMRs will count for about 3% of the total installed nuclear capacity in 2035.

Figure 4.2: Estimated SMR capacity in 2035 by region



Source: NEA calculations based on analysis in the text.

These projections do not take into account the potential for further development of SMR technologies and regulatory frameworks that might lead to major changes in the NPP market. Other projections (e.g. UxC, 2013) provide similar estimates at 22 GW in the mid-case scenario in 2040 and less conservative estimates for a low-case scenario of 9 GWe. There are even more optimistic assessments, e.g. the report co-ordinated by the UK National Nuclear Laboratory (NNL, 2014: 3): "The size of the potential SMR market is calculated to be approximately 65-85 GW by 2035 […] if the economics are competitive."

Table 4.1: Projected share of SMRs in nuclear new build in 2020-2035

Country	New build in 2020-2035 (low case)	New build in 2020-2035 (high case)	Share of SMRs in new build in 2020-2035 (low case)	Share of SMRs in new build in 2020-2035 (high case)	Comment
Algeria	0	600	0%	100%	Algeria announced plans for NPP construction. As a newcomer state, it could be interested in starting the nuclear programme with SMRs.
Argentina	2 465	2 465	1%	13%	CAREM (a prototype) is under construction, and larger SMRs are anticipated.
Armenia	1 625	1 625	0%	0%	ALWRs are envisaged in Armenia.
Bangladesh	2 000	2 000	0%	30%	ALWRs are planned, but SMRs could be deployed.
Belarus	0	1 130	0%	0%	ALWRs are under construction.
Belgium	-4 099	-4 099	0%	0%	Nuclear power is being phased out.
Brazil	1 455	4 365	0%	0%	ALWRs are under construction and envisaged.
Bulgaria	-953	1 117	0%	0%	ALWRs are envisaged.
Canada	-3 955	2 000	0%	15%	If new nuclear build is developed, part of it could be done with SMRs.
China	43 800	50 800	0%	2%	ALWRs are planned but SMRs are also being considered.
Czech Republic	2 000	2 980	0%	0%	ALWRs are envisaged.
Egypt	0	1 000	0%	10%	Egypt announced plans for NPP construction. As a newcomer state, it could be interested in starting the nuclear programme with SMRs.
Finland	2 850	2 300	0%	0%	ALWRs are under construction and envisaged.
France	-25 035	-1 425	0%	0%	SMRs are not envisaged for domestic deployment.
Germany	-5 460	-8 100	0%	0%	Nuclear power is being phased out.
Hungary	0	2 200	0%	0%	ALWRs are envisaged.
India	8 665	25 840	5%	15%	Both large and small reactors are being developed.
Indonesia	0	2 000	10%	30%	Because of the grid structure, SMRs could be an attractive option.
Iran	3 800	2 850	0%	0%	ALWRs are envisaged.

Table 4.1: Projected share of SMRs in nuclear new build in 2020-2035 *(cont'd)*

Country	New build in 2020-2035 (low case)	New build in 2020-2035 (high case)	Share of SMRs in new build in 2020-2035 (low case)	Share of SMRs in new build in 2020-2035 (high case)	Comment
Italy	0	0	0%	0%	No nuclear development is envisaged.
Japan	-16 450	-520	0%	0%	SMRs are not envisaged.
Jordan	1 000	2 000	0%	0%	ALWRs are envisaged.
Kazakhstan	300	1 200	0%	25%	SMRs are being considered as an option for the nuclear development.
Korea	14 800	13 800	0%	0%	ALWRs are under construction and envisaged.
Lithuania	0	1 500	0%	10%	Although ALWRs are envisaged, SMRs could be considered, taking into account the size of the economy.
Malaysia	0	1 000	0%	10%	SMRs could be considered as a first step of the nuclear programme.
Mexico	0	1 000	0%	15%	If new nuclear build is developed, part of it could be done with SMRs.
Morocco	0	1 000	0%	10%	SMRs could be considered as a first step in the nuclear programme.
Netherlands	-480	-480	0%	0%	There are no plans for new nuclear power plants.
Pakistan	300	5 375	5%	10%	Small reactors are under construction and could be further deployed (given the grid).
Poland	7 000	10 000	0%	15%	Currently, SMRs are not considered in the 2035 time frame. SMRs could be developed in the high-case scenario only, assuming a high rate of localisation could be achieved.
Romania	700	1 400	0%	0%	ALWRs and PHWRs are planned.
Russia	6 350	13 485	1%	8%	Floating nuclear power plants are under construction, several others are envisaged.
Saudi Arabia	0	17 000	5%	20%	ALWRs are being considered, but SMRs could also be developed, especially if variable renewables are introduced in parallel.
South Africa	0	18 160	0%	15%	ALWRs are envisaged, but SMRs could also be developed, especially if variable renewables are introduced in parallel.
Spain	-5 020	245	0%	0%	There are currently no plans for ALWRs.
Sweden	-9 900	-2 300	0%	0%	There are currently no plans for new nuclear build in 2020-2035.
Switzerland	-2 175	-1 105	0%	0%	Nuclear power is being phased out.
Thailand	0	3 000	0%	5%	Thailand announced plans for NPP construction. As a newcomer state, it could be interested in starting the nuclear programme with SMRs.

Table 4.1: Projected share of SMRs in nuclear new build in 2020-2035 *(cont'd)*

Country	New build in 2020-2035 (low case)	New build in 2020-2035 (high case)	Share of SMRs in new build in 2020-2035 (low case)	Share of SMRs in new build in 2020-2035 (high case)	Comment
Chinese Taipei	-3 820	2 600	0%	0%	ALWRs are under construction.
Turkey	2 280	8 080	0%	0%	ALWRs are envisaged.
Ukraine	8 900	9 800	0%	0%	ALWRs are envisaged.
United Arab Emirates	0	2 690	0%	0%	ALWRs are under construction.
United Kingdom	-6 500	2 950	0%	20%	ALWRs are planned, but SMRs could also be developed, especially if variable renewables are introduced in parallel.
United States	6 000	16 850	5%	20%	ALWRs are planned, but SMRs could also be developed, especially if variable renewables are massively introduced.
Viet Nam	2 000	6 700	0%	5%	ALWRs are envisaged. As a newcomer state, it could be interested in starting the nuclear programme with SMRs.

Source: World Nuclear News, various dates.

Depending on the power output of SMR units (typically ranging from 50 MWe to 200 MWe), in total about 105-425 SMR units could be produced in the period 2020-2035 in the high-case scenario. Such a production level indicates that a SMR factory could be competitively viable, but only for a few SMR designs deployed simultaneously. Therefore, one should assume that the number of vendors of integrated pressurised water reactors will be less than the number identified in Table 1.1.

Chapter 5. Case study: United States

5.1. Electricity market in the United States

The electricity system in the United States (IEA, 2014a) includes the following components: electricity generation, transmission, distribution to industrial, commercial, public and residential customers. This system is measured and modelled by the US Energy Information Administration (US EIA). There are many electricity generators, see Table 5.1 and US EIA (2013) for geographical distribution.

Table 5.1: Existing capacity by energy source in the United States

(as of 2014)

Energy source	Number of generators	Generator gross capacity, MWe
Coal	1 212	329 815
Petroleum	3 601	49 794
Natural gas	5 700	488 169
Other gases	99	2 452
Nuclear	100	104 424
Hydroelectric conventional	4 002	78 581
Wind	977	60 712
Solar thermal and photovoltaic	874	6 674
Wood and wood-derived fuels	369	9 477
Geothermal	193	3 765
Other biomass	1 850	5 832
Hydroelectric pumped storage	156	21 602
Other energy sources	110	2 728
Total	**19 243**	**1 164 022**

Source: US EIA, *Electric Power Annual*, 2014.

In the United States, the electricity transmission assets are owned by individual utilities that generate electricity under the dispatch orders of independent system operators (ISOs) or regional transmission organisations, see Figure 5.1. The electric system in the United States is largely decentralised and the organisations dealing with electricity networks are diverse. Transmission lines might be built and operated by federal organisations, state organisations or privately owned enterprises. The market and regulatory environments are also diverse: some areas are served by vertically integrated utilities while others, for instance, have regional transmission operators in open markets.

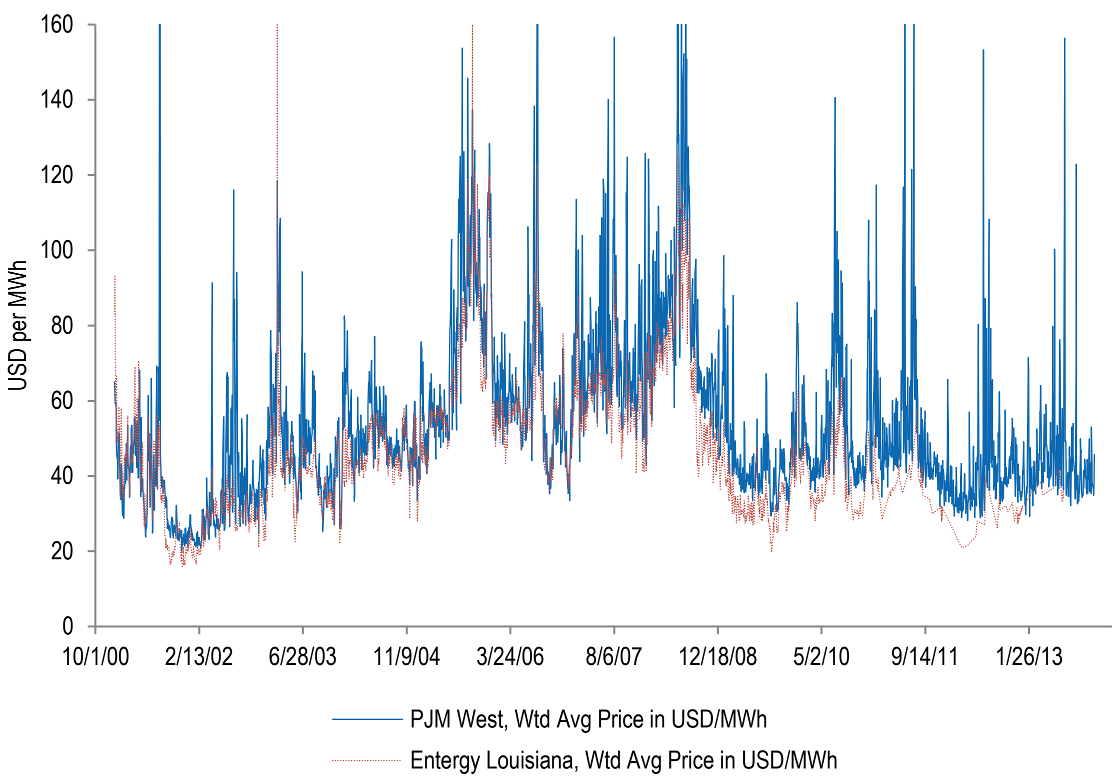
Transmission lines are state-governed but the Federal Energy Regulatory Commission (FERC) plays a critical role in interstate grid operation.

With respect to the liberalised markets, PJM is expanding its market footprint gradually and Midwest Independent Transmission Operator (MISO) covers now a large portion of the Midwest. (PJM Interconnection is a regional transmission organisation that co-ordinates the movement of wholesale electricity in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia.) However, this market area also includes vertically integrated utilities. Further, many smaller vertically integrated regulated utilities continue to operate small balancing areas under an old regulatory framework.

Low natural gas prices have resulted in lower wholesale electricity prices of between USD 40 and USD 50 per MWh (see Figure 5.1). Low prices for natural gas are not occurring for the first time in the United States. For example, in the 1990s prices for natural gas were comparable with today's level of prices (see Figure 5.2).

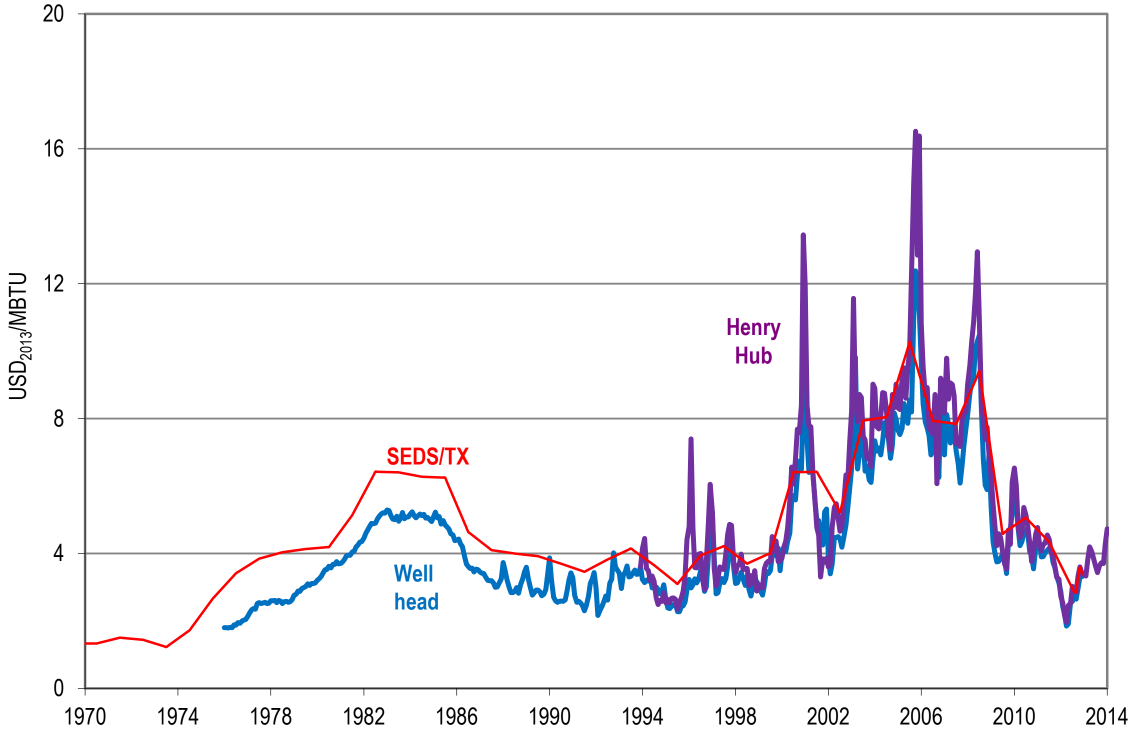
The electric system has adapted smoothly to the shift from coal to natural gas production and the rapid development of renewables. The shift to natural gas was partly absorbed by existing infrastructure, because natural gas-fired power plants were installed about 15 years ago (see Figure 5.3 and Figure 5.4). In 2015, the electricity generation from natural gas (33% of total electricity generated) was equal to coal (33% of the total).

Figure 5.1: Wholesale day-ahead electricity prices at selected hubs in 2001-2013



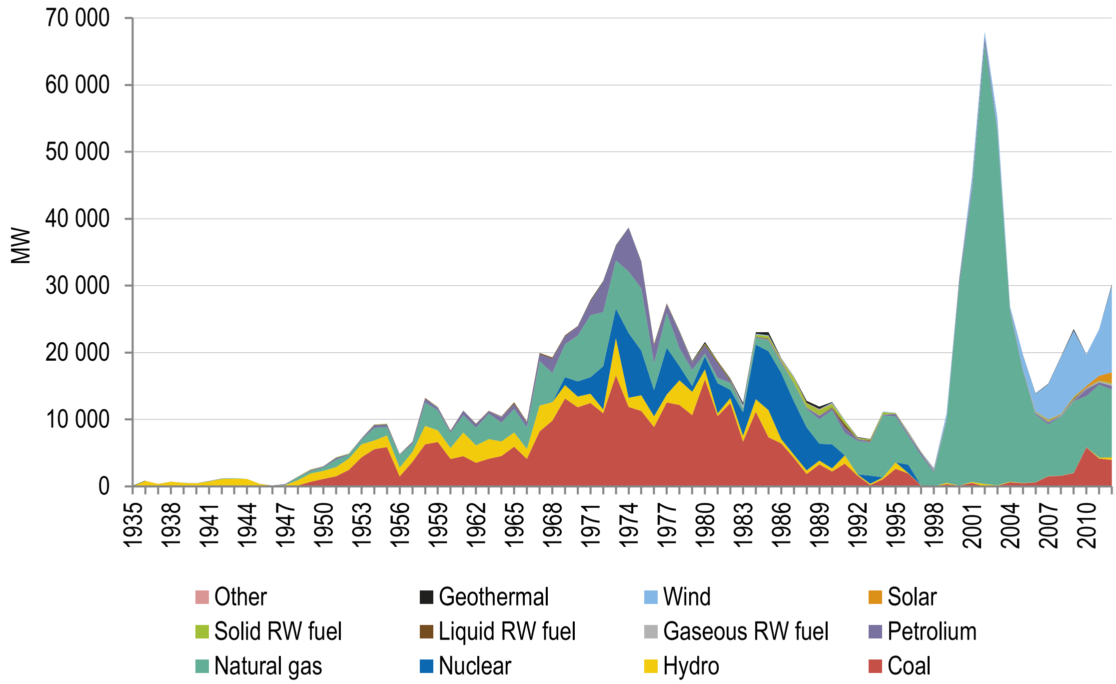
Source: US EIA, 2013.

Figure 5.2: Natural gas prices, 1970-2014



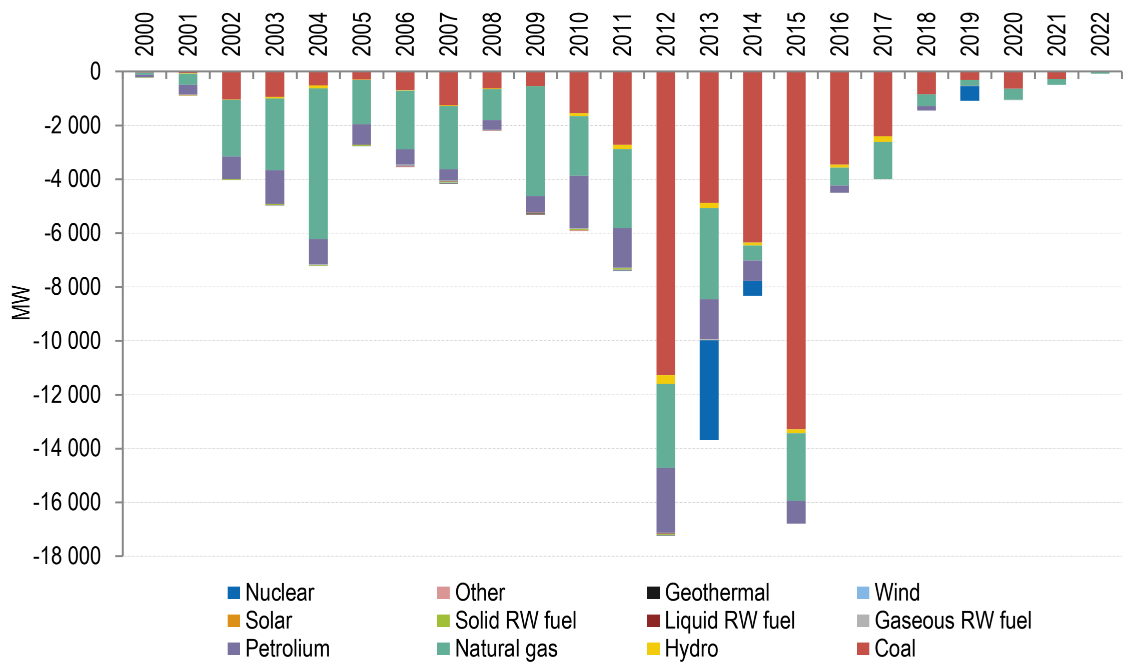
Source: US EIA, 2014 and 2015; Federal Reserve Bank of St. Louis, 2014.

Figure 5.3: US electrical gross capacity by initial year of operation and fuel type



Source: US EIA, Form EIA-860 Annual Electric Generator Report, 2012.

Figure 5.4: Reported US historic (as of 2012) and planned generator retirements, by fuel type



Source: US EIA, Form EIA-860 Annual Electric Generator Report, 2012.

Further introduction of new natural gas capacity and renewables might be more challenging, in particular because of the level of co-ordination between natural gas and electric infrastructures. As experienced during the colder-than-usual winter of 2014, shortages with natural gas supply could challenge the power generation. However, natural gas is envisaged to play a key role in the future energy mix of the United States, because the reserves of natural gas are large.

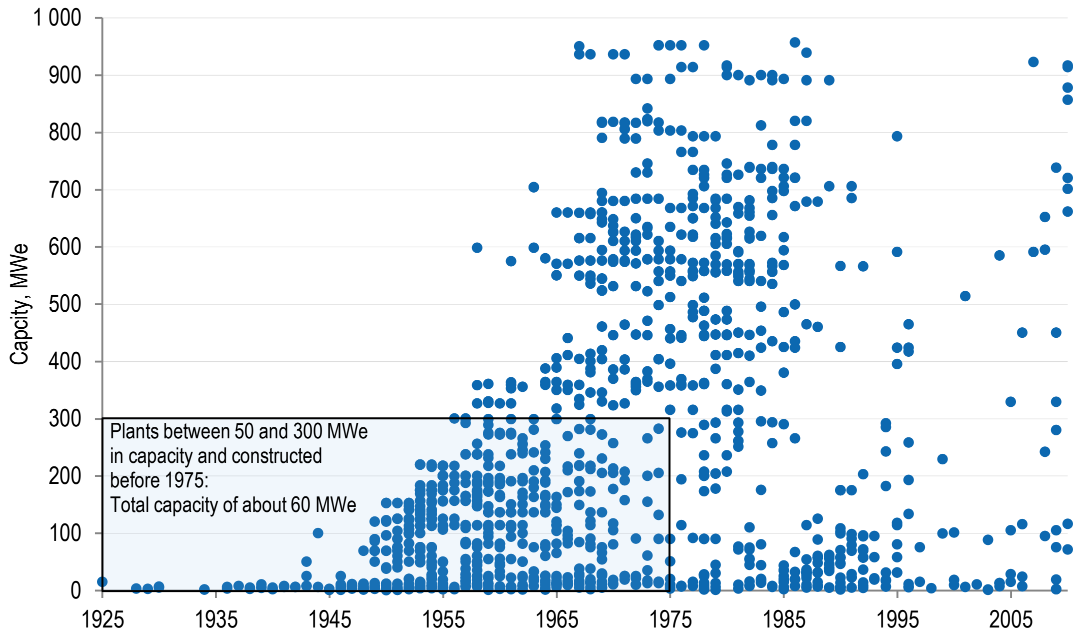
Environmental policies and regulations introduce greater uncertainty over the pace of retirement of ageing coal and nuclear generation capacity (see Figure 5.4 and Figure 5.5). Taking into account these uncertainties, there is a concern that liberalised electricity markets might fail to attract investment in large, high fixed costs investments with long lead times, such as nuclear. There are other reasons that impede the development of such technologies in all markets, in particular, low natural gas prices, excess capacity in some regions, the absence of a price for carbon dioxide, and the high upfront costs of large new NPPs.

5.2. Role of SMRs

There is strong interest in the United States to redevelop its nuclear industry, and particular attention has been focused in recent years on the development of SMRs that could potentially replace coal-fired power plants that must shut down because of new, strict regulations on air pollution from the US Environmental Protection Agency (US EPA). The United States has had an active SMR programme over the last few years. There are several SMR designs with near-term deployment potential including mPower, NuScale, Westinghouse and Holtec designs under development. The US DOE has made available USD 452 million in matching grants to the mPower and NuScale SMR designs to support their design development and licensing programmes. Recently, however, the outlook for the deployment of SMRs has been revised with some leading SMR design companies reducing developing efforts.

Small reactors could be an interesting alternative for new electricity generation capacity in the United States, in particular to replace some of the retiring coal plants. About 60 GWe of coal plants in the United States were constructed before 1975 and have capacities between 50 and 300 MWe (see Figure 5.5), i.e. having power capacities within the size range of proposed SMRs. This number is higher when considering broader power range, up to 500 MW. Many of these plants must shut down after 2020 following the new US EPA regulation standards.

Figure 5.5: US coal plants: Capacity vs commissioning date



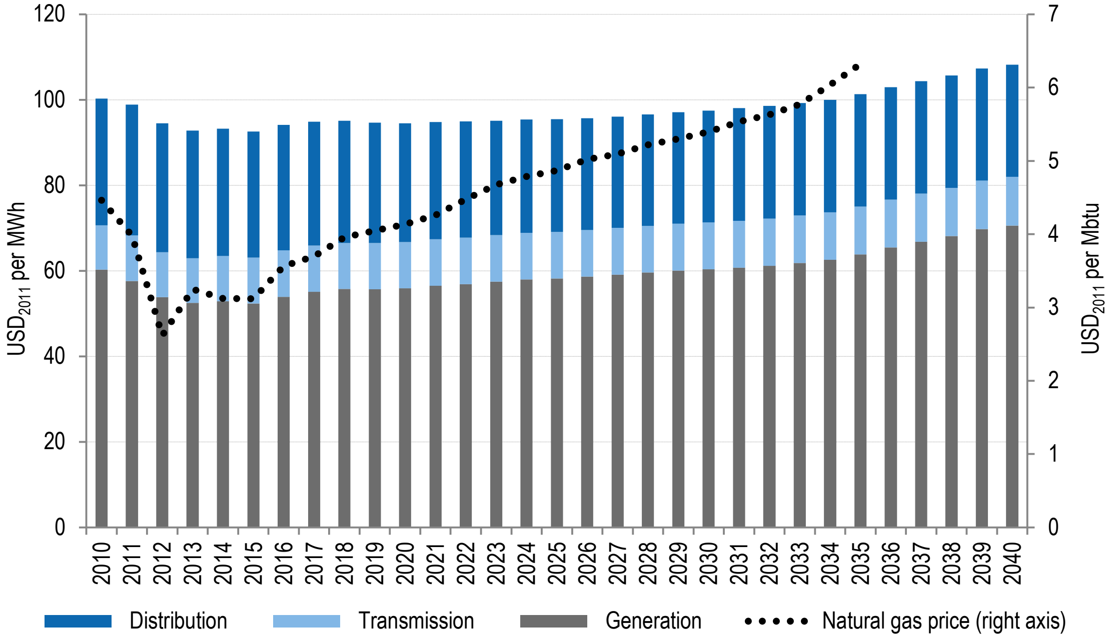
Source: US EIA, Form EIA-860 Annual Electric Generator Report, 2012.

If SMR technology pursues its development as expected by the designers, such reactors could be constructed faster and at lower costs than advanced light-water reactors (ALWRs). The variable cost component is harder to estimate since it will be strongly dependent on nuclear regulation. As discussed in detail in the following section, the SMR designers should be able to prove to the US NRC that the security requirements for SMRs and their operation could be performed with fewer personnel involved than for ALWRs.

At the current stage of development it is reasonable to assume that if SMRs will have attractive construction costs (both in absolute terms and costs per kWe), they will be successfully deployed, but are likely to have O&M and fuel costs higher than those at ALWRs.

The estimated generation cost should be compared with current and projected electricity prices in the United States (see Figure 5.6 and Figure 5.7). Although there are large variations in electricity prices across the United States (see Figure 5.7 and Table 5.8), according to the US EIA projections, the average generation component of the electricity price is estimated to be USD_{2011} 60/MWh when the natural gas price is about USD 4/MMBtu and it is likely to remain at this level for the next decade. According to Figure 3.1, and taking into account the uncertainty on the variable costs of SMRs, SMRs must have investment costs per kW well below the current construction costs for ALWRs to be competitive.

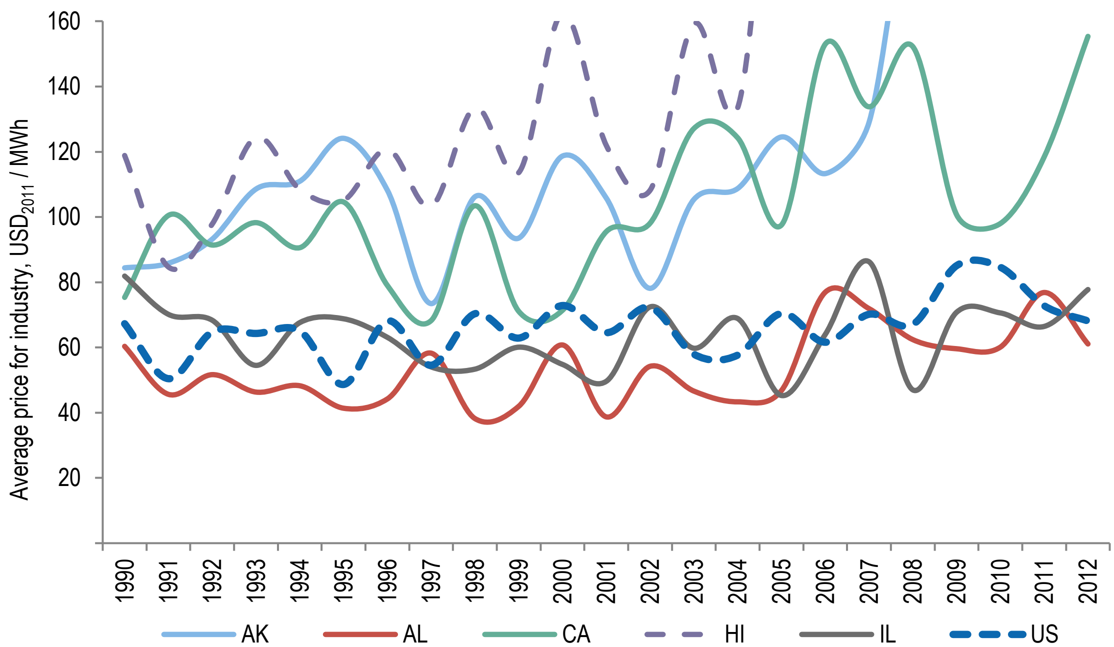
Figure 5.6: Major components of the US electricity price in 2010-2040 and the price of natural gas



Source: US EIA, Annual Energy Outlook 2013 (projections from EIA Annual Energy Outlook 2013, reference-case scenario 2013).

Figure 5.7: Average electricity price for industry in selected US states in 1990-2012

(in USD_{2011} per MWh)

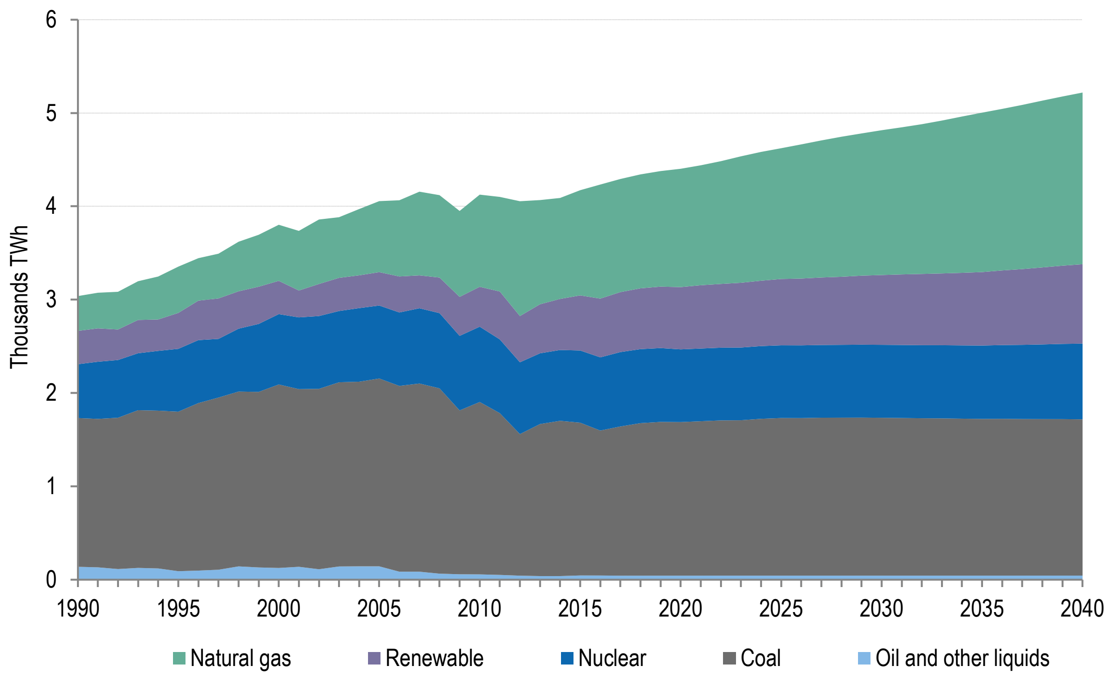


AK = Alaska; AL = Alabama; CA = California; HI = Hawaii; IL = Illinois; US = United States.

Source: Based on data from US EIA, www.eia.gov/electricity/annual.

One can attempt an order of magnitude estimation of the maximal competitive SMR overnight cost in different states in the United States. The departure point of the estimation is the average electricity price for industry in 2002-2012 in different states (e.g. averaged data from Figure 5.7). Assuming that the generation component of the price for industry is about 60%, one could estimate the generation cost that it is expected to be comparable to levelised cost of electricity (LCOE) in the state. Next, it is assumed that the SMR constructed in this state should have the same LCOE. Introducing a further assumption on the variable cost component (O&M and fuel cost), and assuming a 5% real discount rate, one could estimate the overnight cost that would yield the same value of LCOE. This value is interpreted as the maximal overnight cost of an SMR that would still be competitive in the state considered. The results of this simple analysis are presented in Table 5.2. Although there are many states in which the electricity prices are too low to allow SMR development, there are 15 states in which SMRs, with overnight costs above USD 4 000/kWe, could be potentially completive. Of course, the above mentioned analysis is based on retrospective assessments and that perspective could be different when considered from a forward looking posture.

Figure 5.8: Historical and projected electricity generation by fuel, 1990-2040



Source: US EIA, Annual Energy Outlook, 2014.

In the high-case scenario (NEA/IAEA, 2014), 16 850 MWe of new nuclear capacity is expected to be added in the United States in the period 2020-2035, and about 6 000 MWe in the low-case scenario. According to the US EIA projections, other power sources expected to be deployed in the next decades are natural gas plants and renewables (see Figure 5.8). As discussed in the previous sections, SMRs with smaller capital costs than ALWRs and larger variable costs (combination O&M and fuel costs) become more and more competitive in the systems with large shares of variable renewables. In the example of Figure 3.3, the optimal share of SMRs in the total installed nuclear capacity is ~23% when introducing ~20% electricity production from variable renewables, and ~16% with no variable renewables in the mix.

Although it is not appropriate to generalise the analysis behind Figures 3.2 and 3.3, it allows performing an order of magnitude estimation of the optimal market share of SMRs, given the uncertainty of other factors. In the estimate of the global market, a share of 20% (of nuclear new build capacity) was assigned to SMRs, yielding about 3.5 GWe of SMRs in the United States in the high-case scenario for the period 2020-2035. This will corresponds to ~3.5% of the total nuclear capacity installed in the United States in 2035-2040. The low-case scenario corresponds to a pessimistic case in which only the prototypes are constructed.

Table 5.2: Estimation of maximal competitive SMR overnight cost in different US states

State	Average electricity price for industry in 2002-2012, USD_{2011}/MWh (*)	Generation component in the price, USD_{2011}/MWh (**)	SMRs maximal overnight cost within different assumptions for (O&M and fuel costs), USD_{2011}/kWe		
			(O&M+fuel) = USD 25/MWh	(O&M+fuel) = USD 30/MWh	(O&M+fuel) = USD 35/MWh
AK	157	94	9 472	8 789	8 105
AL	60	36	-	-	-
AR	63	38	-	-	-
AZ	72	43	-	-	-
CA	124	74	6 709	6 026	5 343
CO	73	44	-	-	-
CT	145	87	8 470	7 787	7 104
DE	95	57	4 375	3 691	3 008
FL	91	54	4 011	3 328	-
GA	68	41	-	-	-
HI	235	141	15 890	15 207	14 524
IA	57	34	-	-	-
ID	55	33	-	-	-
IL	66	40	-	-	-
IN	64	38	-	-	-
KS	69	41	-	-	-
KY	50	30	-	-	-
LA	73	44	-	-	-
MA	150	90	8 851	8 168	7 485
MD	92	55	4 138	3 455	-
ME	109	66	5 561	4 878	4 195
MI	76	46	-	-	-
MN	65	39	-	-	-
MO	60	36	-	-	-
MS	71	43	-	-	-
MT	58	35	-	-	-

See notes on page 49.

Table 5.2: Estimation of maximal competitive SMR overnight cost in different US states *(cont'd)*

State	Average electricity price for industry in 2002-2012, USD_{2011}/MWh (*)	Generation component in the price, USD_{2011}/MWh (**)	SMRs maximal overnight cost within different assumptions for (O&M and fuel costs), USD_{2011}/kWe		
			(O&M+fuel) = USD 25/MWh	(O&M+fuel) = USD 30/MWh	(O&M+fuel) = USD 35/MWh
NC	68	41	-	-	-
ND	59	35	-	-	-
NE	63	38	-	-	-
NH	138	83	7 893	7 210	6 527
NJ	123	74	6 700	6 017	5 334
NM	66	40	-	-	-
NV	91	55	4 049	3 365	-
NY	94	56	4 285	3 602	-
OH	72	43	-	-	-
OK	60	36	-	-	-
OR	62	37	-	-	-
PA	78	47	3 007	-	-
RI	134	80	7 569	6 885	6 202
SC	59	36	-	-	-
SD	64	38	-	-	-
TN	68	41	-	-	-
TX	78	47	3 009	-	-
UT	53	32	-	-	-
VA	67	40	-	-	-
VT	107	64	5 375	4 692	4 008
WA	54	32	-	-	-
WI	75	45	-	-	-
WV	53	32	-	-	-
WY	57	34	-	-	-

Note: Only values higher than USD 3 000/kWe are shown. Source: US EIA, 2014.

(*) Based on data from the US EIA (2014). Average price of electricity for industry in 2002-2012.

(**) Assuming that the generation component represents 60% of the electricity price for industry.

AK = Alaska; AL = Alabama; AR = Arkansas; AZ = Arizona; CA = California; CO = Colorado; CT = Connecticut; DE = Delaware; FL = Florida; GA = Georgia; HI = Hawaii; IA = Iowa; ID = Idaho; IL = Illinois; IN = Indiana; KS = Kansas; KY = Kentucky; LA = Louisiana; MA = Massachusetts; MD = Maryland; ME = Maine; MI = Michigan; MN = Minnesota; MO = Missouri; MS = Mississippi; MT = Montana; NC = North Carolina; ND = North Dakota; NE = Nebraska; NH = New Hampshire; NJ = New Jersey; NM = New Mexico; NV = Nevada; NY = New York; OH = Ohio; OK = Oklahoma; OR = Oregon; PA = Pennsylvania; RI = Rhode Island; SC = South Carolina; SD = South Dakota; TN = Tennessee; TX = Texas; UT = Utah; VA = Virginia; VT = Vermont; WA = Washington; WI = Wisconsin; WV = West Virginia; WY = Wyoming.

Recently, the Utah Associated Municipal Power Systems (UAMPS) concluded that SMRs would be an important option to backup wind in the western United States. UAMPS is a consortium of forty-five utilities in Utah, Arizona, New Mexico, Idaho, California, Nevada, Oregon and Wyoming (www.uamps.com/). They are working with NuScale Power to deploy the first full-scale NuScale SMR plant in Idaho at the site of the Idaho National Laboratory. The consortium established a Carbon Free Power Project to encourage the deployment of clean baseload electrical power in response to the anticipated closure of coal plants over the next two decades.

Further, NuScale has produced a FOAK cost estimate of about USD 5 100/kWe (2014 USD) with a cost of USD 1 800 million for the balance of plant and the first two reactor-steam generator modules and USD 110 million for each additional reactor module for a total of about USD 2 900 million for a 600 MWe (gross) or 570 MWe (net) 12-module plant. However, the additional reactor modules do not include the installation labour, which could vary as a function of whether there are reactors operating while modules are being installed. The lead time for delivering reactor modules is about five years. NuScale (2016) estimates the levelised cost of electricity (LCOE) to be USD 110/MWh for FOAK plants and USD 90/MWh for NOAK plants. These cost estimates could change because of US NRC licensing requirements.

5.3. Licensing of SMRs in the United States

Licensing of SMR will play an important role in their competitiveness; in particular, the acceptability for the regulators of the innovative safety features, reduced personnel for the plant operation, factory manufacturing of SMR units, etc.

As a result of SMR pre-application activities and earlier work by the US NRC, many potential policy and licensing issues based on the preliminary design information has been identified and key areas for further discussion were identified by the US NRC in 2010 (US NRC, 2010, see updates at www.nrc.gov/reactors/advanced.html).

In US NRC (2011a) the US NRC staff considered three options for licensing of multi-module facilities by issuing a single facility licence, master facility licence and individual reactor module licences. The last alternative (i.e. licensing SMRs as is done with ALWRs) was considered the best option at the current stage.

With respect to control room staffing, the US NRC expects the reviews of staffing plans to be challenging for SMR designs because of the differences between the SMR designs and previously licensed reactor design (US NRC, 2011b). Dedicated rulemaking to change staffing requirements for SMRs is expected in the longer term. On the other hand, as the policy statement made in the report to Congress on advanced reactor licensing (US NRC, 2012), the Commission expects that innovative methods might be employed to meet these requirements.

Regarding the security requirements, US NRC (2011c) considers that the current security regulatory framework is adequate for certifying, approving and licensing SMRs, i.e. it appears that it will be challenging to reduce security-related staffing requirements.

Emergency planning and size of the emergency planning zone for different nuclear facilities in the United States is determined using a dose/distance approach (based on the US EPA Protective Action Guidelines). As explained in (US NRC, 2011d), the US NRC staff concluded that a similar technology-neutral dose/distance rationale would also be appropriate for the advanced designs including SMRs, and thus the emergency planning requirements could, in principle, be scaled to be commensurate with the hypothetical accident source term.

With respect to third party liability, the Price Anderson Act (PAA) requires the US NRC to treat a combination of facilities with a single-unit capacity between 100 and 300 MWe and with a combined rated capacity not exceeding 1 300 MWe, as a single facility. Similar to ALWRs, SMRs are thus required to carry the maximum level of primary insurance available from private sources (USD 375 million as of 2014) and are also required to participate in a secondary financial insurance programme (a retrospective premium after a nuclear accident up to about USD 121 million per reactor per nuclear accident as of 2014). However, PAA is silent about a combination of facilities below 100 MWe. There is thus a potential inequity in the insurance and liability requirements for SMR units below 100 MWe (that are only required to purchase primary insurance and do not participate in the secondary, “retrospective” insurance). Proposals for resolving this issue are presented in US NRC (2011e). One of the options is to treat multiple reactor modules at a site as a single reactor for insurance and liability purposes. The second option is to increase the amount of insurance required per licensee to account for multiple reactor modules.

Provisions for decommissioning are expected to be reviewed for SMR designs taking into account (US NRC, 2011f) the reduced size and quantity of components and equipment to be disposed, potentially smaller area to be decontaminated (depending on the number of modules), and possible challenges with accessibility for decontamination because of the small size of the components. In the near term, the US NRC staff proposes to allow SMRs to deviate from existing regulations through exemption requests. Based on the limited number of such exemptions, the US NRC could consider modifying the decommissioning fund assurance requirements in the long term.

Design Specific Review Standards (DSRS) are expected to be desired by SMR vendors so they will know what will be needed for the licensing process. The development of DSRSs engages SMR vendors, potential customers, licensees and stakeholders in intense pre-application interactions. To date, only the mPower design has had a DSRS developed by the US NRC. The NuScale DSRS is planned for completion about one year prior to the planned submission of the Design Certification Application (expected in the second half of 2016).

In addition, in the United States, full SMR assembly in factories might require changes in the US NRC licensing and oversight programmes, leading to a revision of the inspection procedures and practices for such plants.

In summary, the current approach to SMR licensing is similar to the one established for ALWRs. In the near term, the advanced features of SMRs are addressed through exemption requests and by developing DSRS. Based on the feedback from licensing experience for the first SMRs, a rulemaking dedicated to specific SMR issues could be envisaged in the longer term.

Chapter 6. Case study: Russia

This case study illustrates opportunities and challenges associated with the application of small modular reactors (SMRs) in remote, isolated regions, far from a transmission grid. This kind of application usually requires a specific approach to the design, construction and operation of SMRs, which must produce electricity and other energy products, e.g. heat or desalinated water, for islands or remotely located areas with isolated electricity grids that are usually small (by definition). One possible solution is to use transportable SMRs. (This report does not discuss the transportable SMRs proposed by China.)

This category of reactors is a factory-manufactured, movable NPP that is capable of producing energy. Transportable reactors are not designed to operate during transportation. This concept is not new, such plants have been manufactured and operated in the Soviet Union (TES-3, PAMIR-3D) and the United States (MH-1A "Sturgis") (see Bratton, 1961; Sinev at al., 1965; and Ereter, 1972). However, the designs that are considered today, in particular, for export, are innovative concepts, i.e. they might still need considerable time and effort for development and demonstration of their technical, safety and economic viability.

Transportable SMRs might have the advantage of considerably reducing the time gap between the government decision to introduce a nuclear power plant (NPP) and the start of its actual operation, typically 5-8 years for stationary reactors in countries that already have experience with the construction and operation of an NPP. For a first NPP in a country this period would range between 10 and 15 years (IAEA, 2013). With transportable NPPs this period could be shorter, especially for SMRs produced in series. This, along with other distinctive features, might result in the technology being especially effective for countries with immediate needs for energy but without the full infrastructure required for stationary NPPs. The interest shown by many developing countries demonstrates a real possibility to develop a potential market in the future for this category of reactors.

For the time being, the Floating Nuclear Power Plant (FNPP) project is the most advanced and close-to-deployment design of transportable SMRs. A unit is already under construction in Russia.

This case study highlights the current situation of the electricity market in Russia, describes economic and regulatory frameworks for the construction of first-of-a-kind (FOAK) SMR plants, reveals possible future challenges of FNPP deployment, and outlines the opportunities for niche application of SMRs in remote regions of Russia.

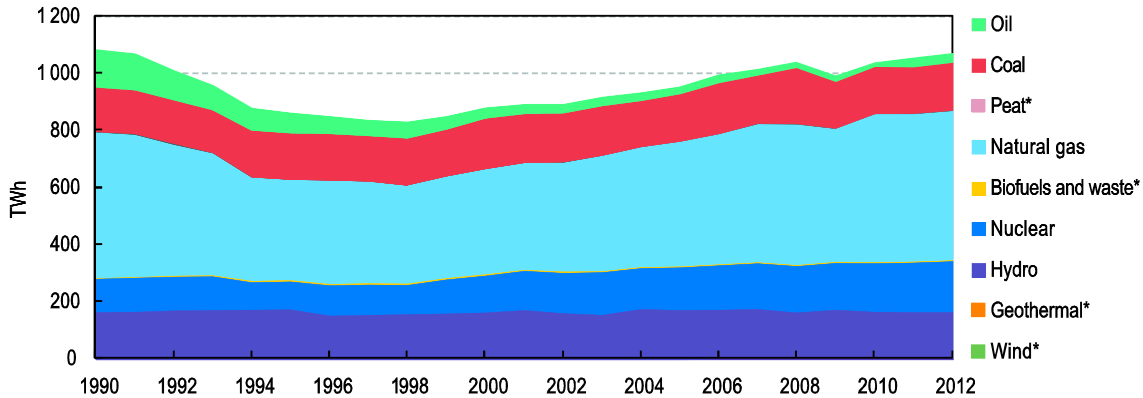
6.1. Electricity market overview

The electricity sector has been the backbone of Russia's economic and industrial development. The operation of Russia's power system is based on a combination of state-controlled technological and trading infrastructure, on the one hand, and organisations interacting among themselves in a competitive environment, generating and selling electric power, on the other hand.

Russia holds some of the world's largest resources of natural gas, oil and coal while nuclear energy also plays a vital role in energy policy and power generation. It represents about 17% of the electricity generation. Total electricity generation in Russia was 1 069 TWh in 2012. Electricity production has been increasing since the late 1990s, with a slight decline during the economic recession in 2009 (see Figure 6.1). Total electricity output increased by 20.2% from 2002 to 2012, notwithstanding a moderate increase of 3.8% in total generation capacity. Generation from nuclear power has also been on the rise since the late 1990s, increasing by 25.4% from 2002 (IAEA, 2013).

Total electricity consumption was 874.7 TWh or 63.7 Mtoe in 2012, or 13.7% of total final consumption of energy. The industry sector is the largest consumer of electricity, amounting to 45.7% of the total. The residential sector accounts for 17.9% of the total, and the commercial and public services sector accounts for 24%, while the remainder is consumed by the transport industry (12.4%).

Figure 6.1: Electricity generation by source, 1990-2012



Note: Data for 2012 are provisional. * Negligible.

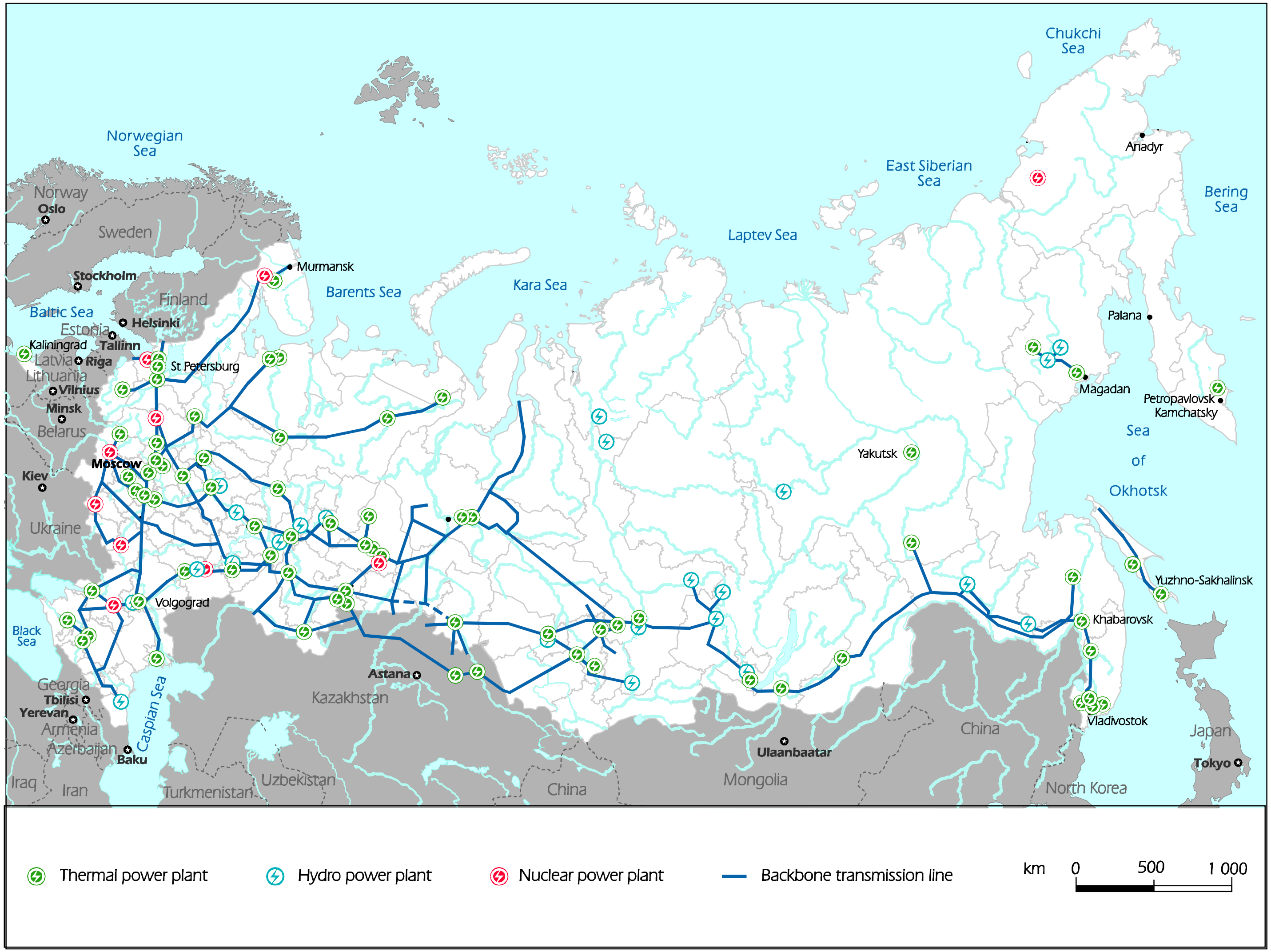
Source: IEA, 2014b.

According to the Ministry of Energy of the Russian Federation (2009) more than a doubling of nuclear generation capacity is planned from 24 GW in 2008 to between 52 GW and 62 GW in 2030. Taking into account current lifetime extensions and planned shutdowns, this new build programme should reach a 25% to 30% share of nuclear electricity by that time.

The majority of these nuclear new builds will be located within the European part of Russia, while the much bigger eastern part of Russian territory has almost no nuclear generation capacity. The reason behind this is the difference in population density and historical development of infrastructure resulting in the composition of electricity grid (shown at Figure 6.2).

This actually creates a good opportunity for SMR development that could take the role of autonomous sources of electricity and heat for small local communities and industrial customers located in isolated areas of the Far North (of Eastern Siberia) and the Far East.

Figure 6.2: Major transmission lines and generation capacities in Russia



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Source: IEA, 2014b.

6.2. Electricity market regulation and prices

At present there is a two-level (wholesale and retail) market of electricity and capacity in Russia. The wholesale market of electricity and capacity functions in regions consolidated into price zones. The first price zone includes the territory of the European part of Russia and the Ural region, the second price zone covers Siberia. In non-price zones (Arkhangelsk and Kaliningrad regions, Komi Republic, regions of the Far East), where it is currently impossible to create market conditions for technological reasons, electricity and capacity on the wholesale market are sold at regulated tariffs.

The Federal Tariff Service ("FTS Russia") approves and modifies regulated electricity transmission tariffs and price floors for the wholesale tariffs in non-price zones and for electricity retail tariffs and the ceilings for heat (cogeneration) tariffs. FTS Russia also sets the price caps for the capacity market. In isolated power systems that are not technologically connected to the United Power System, there is no wholesale electricity and capacity market. Electricity is supplied through regulated retail markets only.

In 2012, household electricity prices in Russia were low in comparison to OECD member countries (IEA, 2014b). Moreover, contrary to most OECD member countries, Russian household prices are consistently lower than industry prices, a fact that reveals the level of cross-subsidisation between industry and households in Russia.

In 2011, the end-user electricity bill was composed of the cost of wholesale or regional generation (energy and capacity, including for renewables, 60%), tariffs for distribution (28%) and transmission (5%) and cost of infrastructure operators' services. The electricity retail bill has been increasing by 15% to 20% over time, primarily from the rising distribution network cost, that amounts to around 30% of the final retail price. Depending on the region, supply cost on the wholesale market could be lower, and network tariffs could reach over 60%, reflecting higher losses.

The Russian government set out plans for the retail market to be fully liberalised by 2015. Today, prices remain regulated. All regions of Russia have their own regional regulatory authorities, the Regional Energy Commissions, in charge of tariff regulation, under the supervision of the regional government authorities. They approve the retail (electricity and heat) tariffs, including distribution network tariffs for the interregional distribution grid companies (MRSKs), within the established minimum or maximum tariff limits determined by the FTS.

Regional Energy Commissions set the price for household and industrial customers in a given region based on a FTS price and takes into account the actual costs of electricity generation, transmission and distribution. In the European part of Russia, the end-user electricity prices normally reflect the actual cost of generation, transmission and distribution. However, the situation is different in isolated areas with limited energy sources, e.g. Chukotka, Kamchatka and Northern Yakutia. End-user electricity prices for both industrial and residential customers in these regions could be lower than the cost of production because of subsidies that can be as much as ten times the cost of electricity.

When considering the deployment of SMRs in isolated areas within a regulated electricity market, it is important to take into account not only the electricity price, but also generation cost for competing energy sources.

Floating Nuclear Power Plant project

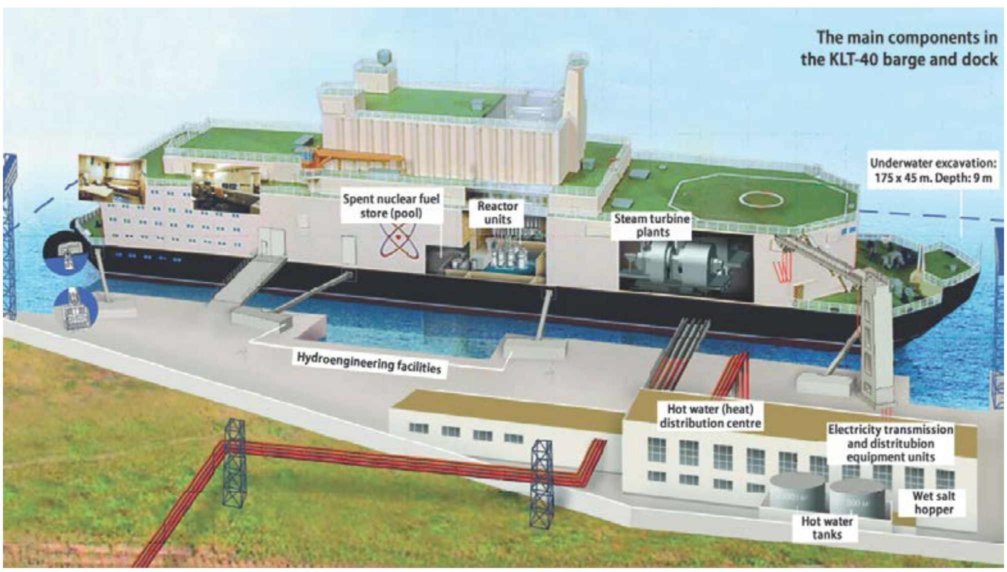
Russia has accumulated considerable experience in using nuclear power for propulsion of surface vessels and submarines. Besides that, Russia is the only country possessing a fleet of civil nuclear driven ships. Ten vessels have been constructed in the USSR and Russia. Nine of these are icebreakers, and one is a container ship (lighter carrier) with an icebreaking bow. Seven icebreakers and a lighter carrier, with 13 reactors installed on them, are currently in operation. All six nuclear-powered icebreakers of Arktika class have been built at the Baltiysky Zavod shipyard (Saint Petersburg). Vaigach and Taimyr were built at the Helsinki New Shipyard in Finland and then brought to Russia for installation of the reactors and turbines.

In 2012, Russia started building the world's largest universal nuclear-powered icebreaker capable of navigating in the Arctic and in the shallow waters of Siberian rivers. Powered by two RITM-200 pressurised water reactors the new icebreaker is being built at the Baltiysky Zavod shipyard with two more vessels of the same type contracted by Rosatom.

The experience of development and long-term operation of nuclear vessels has created a solid basis for the FNPP project. For the time being it is the most advanced and close-to-deployment design of transportable SMR. A first unit is already under construction in Russia.

FNPP (see Figure 6.3) is the unique power generating unit combining both shipbuilding and nuclear power technologies. It is designed specifically for providing heat and electricity supply on a stable and reliable basis for remote regions of the Far North and Far East of Russia.

Figure 6.3: Floating nuclear power plant layout



Source: OKBM, 2016. See also: www.okbm.nnov.ru/english/lomonosov.

The floating power unit (FPU) is an autonomous power generating unit that is end-manufactured at the shipbuilding yard as a non-self-propelled vessel towed by sea or river to the operation site. Thus, the customer receives a fabricated, tested and ready-to-use energy source with accommodation facilities and complete infrastructure for operation personnel living, i.e. the turnkey basis technology is implemented.

The most distinctive features of the project:

- FPU, as a whole, is factory fabricated at the shipyard, tested and delivered to the site;
- all the plant needs on-site is auxiliary facilities and lines to transmit electricity and heat to the shore;
- the maintenance and treatment of radioactive waste is carried out by specialised companies once every 12 years;

- the plant is mobile and can be stationed almost anywhere onshore or in the beds of big rivers;
- after retirement, the FPU is taken away to be decommissioned.

Normal operation of FNPPs requires an arrangement of water space and coastal infrastructure. The coastal infrastructure includes the following:

- hydraulic engineering structures, e.g. jetties, beacons, boom barriers;
- waterfront structures, e.g. sea walls, piers;
- transmission pylons intended for transmission of generated electricity to the consumers;
- coastal structures.

Hydraulic engineering structures are intended for safe offshore deployment of the FPU. Technical interconnections with the coast are implemented through special berthing facilities. Support and maintenance vessels can approach and moor alongside the FPU. The coastal infrastructure and special devices are introduced for transfer of electricity and heat from the FPU to consumers.

Coastal infrastructure is site-specific and designed to withstand the impacts and external threats that might occur in the chosen area. For FNPPs deployed in regions of the Far North, the pier protects floating power unit from waves, wind and floating ice fields. When FNPPs are deployed in the Pacific, the pier is designed to ensure protection from tsunamis (in addition to appropriate site selection).

The FPU has the necessary facilities to accommodate its crew – operative personnel living on board (one shift, 64 employees). The rest of personnel (second shift, administrative personnel and service and security staff) live in the city nearby. The total number of employees working at the FNPP is estimated to be 200-250 as a result of the necessity to comply with staffing requirements for both nuclear-propelled vessels and NPPs. For comparison, a typical nuclear icebreaker crew consists of about 90-130 employees, but this number does not include onshore personnel. The smallest NPP in Russia – Bilibino NPP – with 4 units of 12 MW rated electric power each has about 700 employees.

When constructed, the FPU is transported from the shipyard to the site of its deployment by tow-boats. After 10-12 years of service, the FPU is replaced by an identical power unit and then transported back to the factory for refuelling and maintenance. When the maintenance is completed (normally this period takes about one year, including transportation), the FPU could be moved back or to another location.

The transportation of a commercial reactor loaded with fuel is a new concept. FNPPs, while having similarities to both land-based NPPs and nuclear-powered vessels, are nonetheless distinct and might possibly represent a new category for which nuclear security norms and standards must be revised. At this point, however, the application of existing physical protection recommendations remains valid and sufficient to address the known concerns.

Being deployed domestically, FNPPs comply with the rules and regulations of Russia in the field of nuclear energy and nuclear-powered vessels. Because of the specific nature of FNPP project, there is a notable difference in its licensing process from the traditional land-based NPP approach. Normally in Russia NPP project implementation requires regulatory body Rostechnadzor to issue three consecutive licences: first for the deployment of nuclear installation, then for the construction of nuclear power units and finally operating licence.

FNPP (floating nuclear power plant, aside from auxiliary onshore structures) is constructed at the shipyard that is the subject to licensing by Rostechnadzor. The shipyard receives a single construction licence for each type of vessel that it builds. FPUs are constructed under supervision of the Russian Maritime Register of Shipping for nuclear-powered vessels and according to the existing regulations of the shipbuilding industry. Deployment of FNPPs follows national nuclear safety and environmental regulations of Russia and is implemented under the supervision of Rostechnadzor. Specific risks and threats associated with FNPP transportation and operation are taken into account and addressed by design, technical and organisational methods.

Infrastructure issues relevant to export deployment of transportable (and floating) NPPs have been thoroughly reviewed by the IAEA (2013). It was found that export transactions with transportable NPPs could involve not only the supplier state and the host state but, depending on the technical option used, other countries too, i.e. third parties to the transaction. The transport of non-irradiated components for NPPs is current practice and the fresh and spent fuel is transported under clearly defined and agreed upon standards. In contrast, third parties might consider that they also have an interest if factory fuelled reactors are transported through their territory or territorial waters. At the end of its operating life, the removal of a transportable NPP with the fuel in the core might also evoke similar interest. Thus the transportation of floating NPPs requires careful consideration by all involved countries (the supplier state, the host state, and the countries through the territories or territorial waters of which the plant is to be transported) and might require special legal arrangements.

Regarding nuclear security, the transport of a reactor loaded with fuel is sufficiently novel to generate security concerns. However, the existing legally binding norms and recommendations on nuclear security (physical protection) are of a generic nature. They have been carefully developed by the IAEA member states not to impede technological innovations of any kind. Therefore, lacking any rationale to the contrary, it could be concluded that the application of the existing legally binding and non-binding physical protection norms and recommendations remain valid to address the known concerns in the case of a transport of a floating NPP with a factory fuelled and tested reactor. Given the novelty of this option, existing recommendations should perhaps be more stringently applied until more specific, experience based norms and best practices are established, as established in IAEA (2013). The main characteristics of a FOAK FNPP with KLT-40S reactors are in Table 6.1:

Table 6.1: Main characteristics of FNPP with KLT-40S reactor

Parameter	Value
Reactor type	Pressurised water reactor
Thermal capacity (MW[th])	300 (2 x 150)
Electric capacity (gross, MW[e])	70 (2 x 35)
Heat output for district heating (gross, MW[th])	58 (2 x 29)
Peak electric capacity (MW[e])	77 (2 x 38.5)
Peak heat output for district heating (MW[th])	174 (2 x 87)
Design life (years)	40
Plant footprint (land, m^2)	30 000

Source: IAEA, 2014.

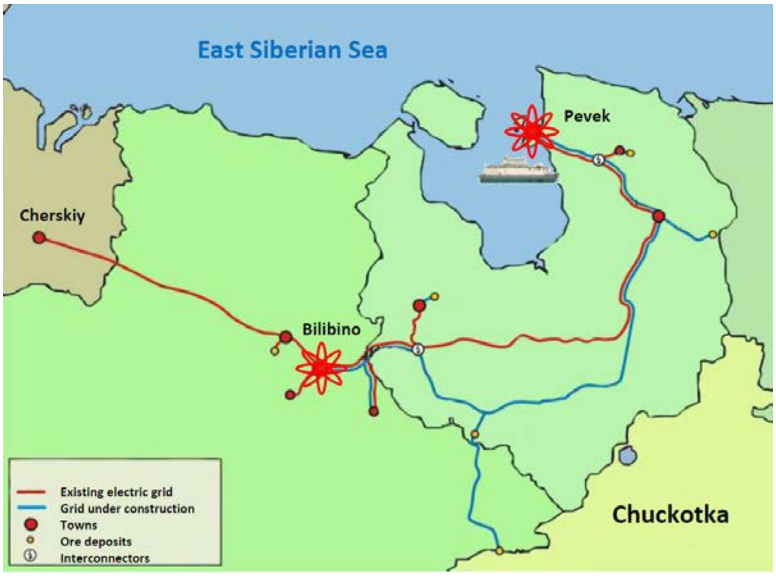
The first plant will be deployed in Pevek (Chukotka region) to replace the retiring Bilibino NPP that is located in the same area but inland. The Bilibino NPP is the smallest and the northernmost operating nuclear power plant in the world. It was built in the

1970s in a remote part of Russia with a severe climate characterised by permafrost conditions. Today, the Bilibino NPP produces about 80% of the electrical power generated in the isolated Chaun-Bilibino power grid (shown in Figure 6.14). It is a cogeneration plant and the only option and source of thermal power for the town of Bilibino.

The Bilibino NPP consists of 4 power units of 12 MW rated electric power each. The total electric capacity is 48 MW, simultaneously the plant could produce up to 67 GCal/hour (78 MW) for district heating. At air temperatures as low as -50°C, the NPP operates in heat-priority mode and can provide 100 GCal/h (116 MW) while the electric generation capacity is reduced to 38 MW.

The adjacent area is extremely rich in minerals, especially gold, silver, tin and copper, and was the reason behind its rapid development in the past. There are numerous mining sites around Bilibino and Pevek. On the other hand, the region has virtually no roads that are usable year-round. There are winter-only ice roads connecting Bilibino to mining sites, seaport Pevek and port Zelyony Mys (Chersky) located on Kolyma River in the Sakha Republic.

Figure 6.4: Chaun-Bilibino power grid



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Source: NEA calculations with mapping software; for overview, see Figure 6.2.

The power grid consists of a 100 kV backbone transmission line between Pevek, Bilibino and Zelyony Mys (about 800 km long) and several 35 kV interconnection lines to mining sites and ethnic villages. There are two major power generation sources in the area – the Bilibino NPP (48 MW) and coal cogeneration plant at Pevek (34 MW).

Chukotka's government plans to rebuild the major transmission line to 220 kV voltage and connect to the grid many new mining sites including Kupol, Dvoynoe and, most importantly, Peschanka (which by itself might require up to 200 MW additional electric capacity). To meet these demands for electricity, the introduction of new generation sources is needed.

The idea of floating NPPs is not new, construction of this kind of nuclear installations has been discussed since the 1970s. After decades, the development of transportable SMRs has reached the first landmark stage and the construction of FOAK FNPPs was started in 2007 at the Sevmash shipyard (Severodvinsk). The vessel was named

"Akademik Lomonosov" after the famous Russian scientist Mikhail Vasilyevich Lomonosov.

At that time, the plant was destined to produce 70 MW electric power as well as heat for industrial customers in the Arkhangelsk region (mainly supplying electricity and heat for the Sevmash shipyard itself). It was estimated that the plant would cost around RUB 6 billion (Russian roubles – USD 232 million). However, in 2008, because of delays in construction preparation and an overload of the Sevmash shipyard with other contracts, the project was subsequently transferred to the Baltiysky Zavod shipyard (Saint Petersburg).

The keel was laid for the world's first floating nuclear power unit in May 2009. The 21 500 tonne hull was launched in 2010, although construction work was frozen in mid-2011 amid bankruptcy proceedings against the shipyard. The company was subsequently acquired by the state-owned United Shipbuilding Corporation and Rosenergoatom signed a new contract in December 2012 with Baltiysky Zavod shipyard for the completion of the first FNPP. The timeline for the FNPP construction is shown in Table 6.2.

Table 6.2: Timeline for FNPP construction

2007	Construction started.
2008	Contractor was changed from Sevmash to Baltiysky Zavod causing a delay in construction.
2009 2010	In mid-2009, turbines were manufactured and installed into the vessel.
2011 2012	Delay in construction because of bankruptcy proceedings against the shipyard. A new contract was signed with the new owner of the Baltiysky Zavod shipyard.
2013 2014 2015 2016	In 2013, reactors were installed into the vessel.
2017	Construction to be completed in late 2017 with operation at site by 2019 (www.world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-power.aspx).

As a result of various organisational and administrative issues, the construction time of the FOAK FNPP was delayed for more than three years. This also led to the increase in construction cost that has been estimated at RUB 24.5 billion (USD 790 million). Without these difficulties, not directly related to the FNPP project, the construction cost could be closer to the amount estimated in 2007.

Another reason behind this increase was that the amount of time and effort needed to restore the supply chain and production capabilities in the civil nuclear shipbuilding industry were heavily underestimated. After the successful series of nuclear icebreakers were completed during the Soviet period in 1990-2000, only one icebreaker "50 Let Pobedy" was built and its construction took more than 17 years. Therefore, by the mid-2000s, the competence of Russian companies in civil nuclear shipbuilding was almost lost and many key suppliers lost their industrial capabilities. Thus, the contract for the first FNPP construction was in turmoil during its initial stage, but now it is up and running and the first plant is scheduled for delivery in 2019.

More important, the supply chain for Russia's nuclear shipbuilding industry has been restored and now the Baltiysky Zavod shipyard has been constructing a new type of nuclear icebreaker with next generation reactor RITM-200. There are two more icebreakers of the same type that have been ordered. It is expected that the construction process will continue without delay.

Another result of the construction delay was that the deployment scheme of FNPPs in Russia has been changed. Initially it was planned that the FOAK plant would provide electricity and heat to the Sevmash factory in the Arkhangelsk region, the second one would be deployed in the Kamchatka region to supply energy for Vilyuchinsk city and the third FNPP would be deployed in the Chukotka region to give momentum to the mining industry in the area.

However, because of delays in construction of the FOAK plant, Rosatom rescheduled its timeline, and the FOAK plant will finally be deployed near the port of Pevek on the Chukotka peninsula in the East Siberian Sea to replace the retiring Bilibino NPP that is scheduled to be retired in 2019-2020 (see Figure 6.4).

Up to six floating NPPs are envisaged to be deployed in Russia in the future. Potential sites for the deployment of FNPPs in Russia have been identified in the Kamchatka, Chukotka, Yakutia, Primorsk regions and include many coastal settlements and industrial clusters along the Northern Sea Route.

The use of floating NPPs is mostly expedient in regions lacking fuel resources or facing problems with stable energy supply. In Russia, areas not connected to energy transmission lines (decentralised energy supply zones) cover almost two-thirds of Russian territory. The living standard of local population – mostly small communities – heavily depends on energy supply and local industrial production (mostly mining facilities).

These areas are rich in mineral resources: Eastern Siberia and the Far East of Russia have produced about 14 billion tonnes of crude oil. However, most of the local deposits in the Far North have not been developed – for the moment this region produces 1% of Russia's total oil. However, the Chukotka region has mineral resources estimated at USD 1 trillion, but their extraction and processing also requires a large amount of energy.

These are large, sparsely populated territories with far-away pockets of electricity demand. For example, the Chukotka region has an area about 738 000 square kilometres (more than France), but its population is 50 000. In total there are more than 50 regions in Russia with a strong need for small-scale power sources. Obviously, the construction of a large-scale electricity transmission system from green field is not an option for this vast and scarcely populated area. Nevertheless, one might consider the extension of already existing grids as an alternative to the construction of autonomous generation sources.

One way to evaluate a transmission line is to determine the cost per megawatt hour to transfer the energy from the existing generation system, and to compare this to the cost of electricity generated locally by SMRs. Costs per megawatt hour increase as the distance between the existing grid and the new load increase, and as the amount of power decreases. So how far does it make sense to extend the power lines?

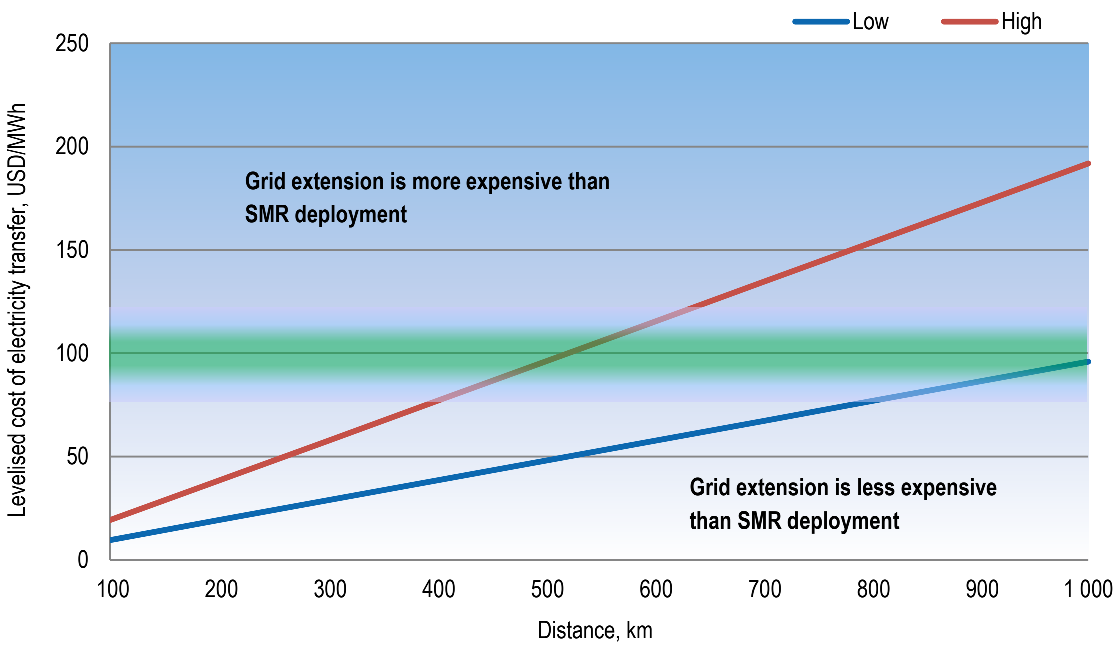
The following figure shows the cost to transfer a MWh based on the length of the line. Overland high-voltage line construction cost in Russia is about USD 0.5-1 million per kilometre. Typical power demand for isolated energy system is in range of 50-100 MW.

Levelised cost of electricity transferred through the extended power grid is calculated under the same assumptions as the levelised cost of electricity (LCOE) for SMRs (i.e. a 5% weighted average cost of capital, 60-year lifetime). Annual operation and maintenance [O&M] cost of power grid is estimated to be 10% of its capital cost. Thus, a load of 50 MW for a distance of 500 kilometres yields a delivered energy price of USD 43-87/MWh. This cost of electricity transfer must be added to the cost to produce electricity in the existing grid to get the total cost of delivered power to be compared to the cost of electricity produced by SMRs.

Given the estimated LCOE for SMRs is about USD 200/MWh and the electricity price in large grid is about USD 100/MWh, rough calculation shows that extending the grid becomes more expensive than building an SMR if the distance is more than 500-1 000 km, depending on the line construction cost (see Figure 6.5).

Figure 6.5: Levelised cost of electricity transfer depending on the transmission distance

Cost of electricity transfer at 5% discount rate

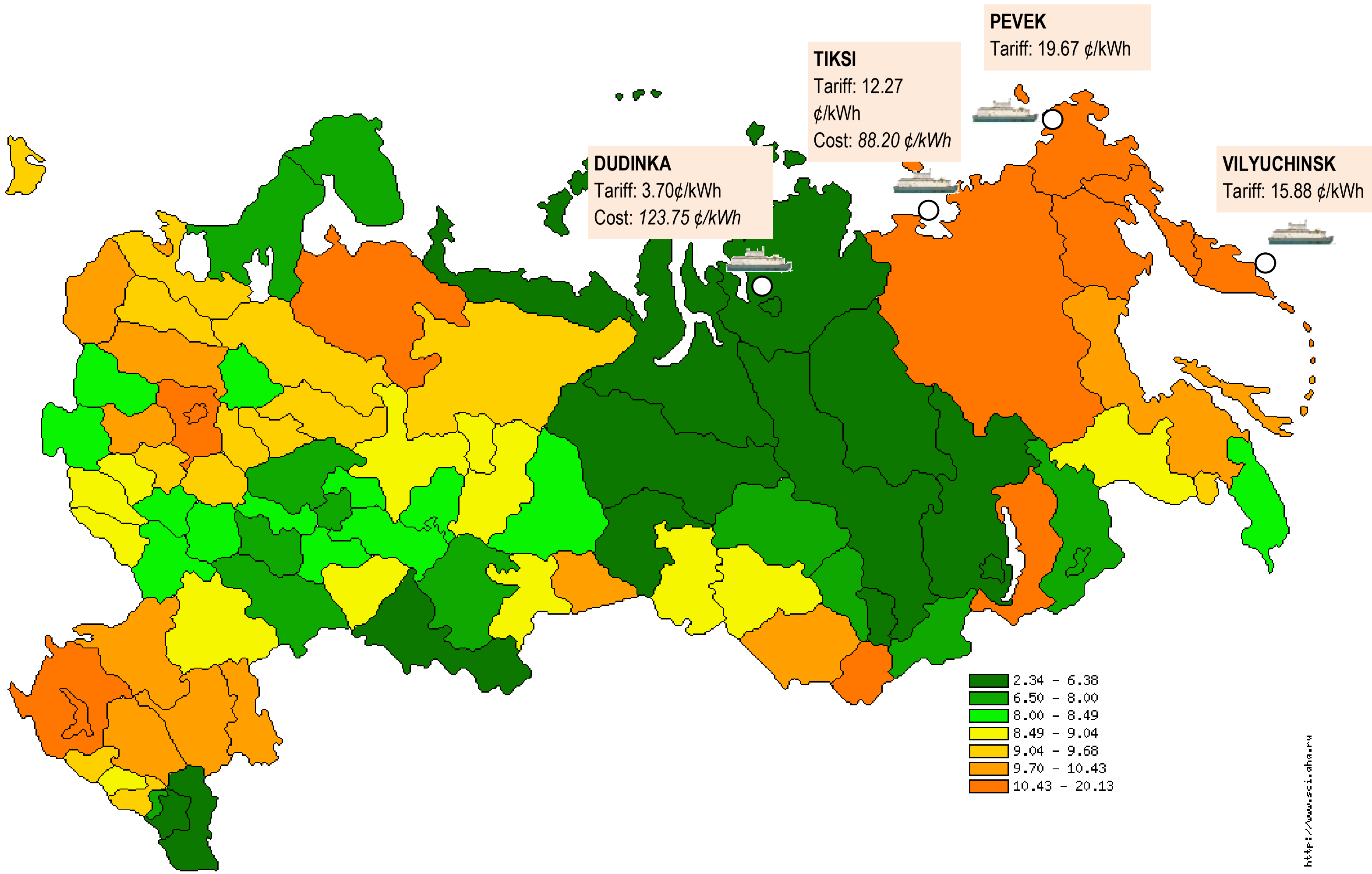


Source: NEA calculations.

SMR development might create a solid basis for the modernisation of decentralised energy supply systems in isolated regions of Russia and the world – Far North, Far East, deserts, ocean islands, etc. The key customers of SMRs in Russia are located along the Northern Sea Route that began to develop actively with the introduction of nuclear icebreakers. Remote regions of Chukotka, Polar Ural as well as numerous oil, natural gas and mineral deposits of Eastern Siberia and the Far East would also greatly benefit from small-sized, reliable and competitive generation sources. Potential sites for the deployment of FNPPs in Russia are shown in Figure 6.6 along with a map of electricity prices in 2014 according to the data from FTS Russia.

More importantly, the actual cost of electricity production in these areas could be ten times higher than the price level set by Regional Energy Commissions. This is mostly because of the extremely high cost of oil and other fuels in these regions. The use of transportable SMRs in these regions could solve the problem of fuel supply and will substantially improve the socio-economic situation in those areas.

Figure 6.6: Tariffs in regions where FNPPs are expected to be deployed



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Source: NEA calculations based on mapping software. Note: ¢ = US cents.

Conclusions and recommendations

Summary and conclusions

Small modular reactors (SMRs) are small reactors with unit power output below 300 MWe (with larger plant capacities) that can be built as modules in factory facilities. Several SMRs are currently being developed around the world, and they are believed to have a potential for broadening the ways that nuclear power is developed. This study focuses on light water SMRs that are expected to be deployed in the 2020s.

SMRs target traditional markets (on-grid deployment), in which case they must compete with other energy sources or niche applications in remote or isolated areas, or on islands that require small-sized units and where electricity that is produced with non-nuclear sources of power has a high cost.

SMR vendors present the following advantages of small modular reactors:

- SMR designers stress that their concepts offer enhanced nuclear safety and allow for the implementation of unique passive features.
- Many SMR designs benefit from a reduced number of structures, systems and components, and from simplified power conversion systems.
- Because of the smaller upfront investment required for one unit, plants with SMRs are expected to be easier to finance.
- Plants with multiple SMR units offer better flexibility for utilities operating in markets with large shares of variable renewable generating resources, or operating in small grids. Most SMR designs have high potential for operation in load-following regimes. In France and Germany, some nuclear power plants also operate in the load-following mode (see NEA, 2011: 55).
- Transmission infrastructure requirements could be smaller for SMRs than for advanced light-water reactors (ALWRs) because of lower electricity output, which makes them suitable for deployment in a larger number of locations.
- In terms of human resource management of the teams involved in operation and outage management, there are benefits in having several identical SMR units instead of one large plant. In addition, multi-unit configuration helps to avoid a long outage period (if compared with ALWRs) through unit-by-unit maintenance and refuelling.
- The energy output of SMRs is well suited to existing heat and water distribution networks, and thus SMRs could offer higher potential for cogeneration, such as water desalination and district heating.
- Modularity of construction and small-sized units facilitates decommissioning.

While the economics of SMRs, capital costs, operation and maintenance (O&M) costs and fuel costs are not yet known, SMR designers argue that per kWe overnight cost of SMRs could be lower than the overnight cost of ALWRs. This would be possible if SMRs were produced in large numbers, had optimised supply chains and had smaller financing costs. The number of SMR orders, which determines the economics of building production facilities, is thus particularly important for achieving SMR competitiveness.

According to the estimates available today, if the competitive advantages of SMRs are realised, SMRs are expected to have lower absolute and per kWe total construction costs than ALWRs.

There is a market for SMRs in national energy mixes with large shares of renewables. This can be seen from the analysis of the residual load curve (with generation of electricity by variable renewables subtracted), which would allow for an energy mix to be obtained that minimises the total cost of electricity generation. This approach demonstrates that the optimal share of SMRs in the total nuclear capacity increases when large shares of variable renewables are introduced (leading to reductions of capacity factors of traditional baseload sources, such as nuclear and coal). Although these values are not universal and greatly depend on the energy system under consideration, and the actual economic characteristics of the SMR, this example indicates that there is a potential market for SMRs with a strong development of variable renewables.

The share of SMRs in nuclear new build in 2020-2035 could be estimated by using the generic arguments regarding SMR competitiveness summarised above and applying those to different countries. Two scenarios are considered in this report: an optimistic high-case scenario (that assumes successful licensing of SMRs and establishment of their factory production and associated supply chain), and a more conservative low-case scenario in which SMRs are expensive to build and to operate, and thus only a limited number of projects are completed, including the prototypes and plants in remote/isolated areas.

In the high-case scenario (based on data from NEA/IAEA, 2014), up to 21 GWe of SMRs could be added by 2035, representing about 3% of the total installed nuclear capacity in the world. Thus about 9% of nuclear new build in 2020-2035 could be SMRs in the high-case scenario, and about 2.3% in the low-case scenario. These projections do not take into account the potential for further development of SMR technologies and regulatory frameworks that might lead to major changes in the NPP market.

One of the key elements for SMR competitiveness is factory production. It is obvious that an assembly plant that does not operate at a sufficient level of volume will fail to achieve economic competitiveness. An important challenge for the factory assembly of SMRs is nuclear regulation. While all safety features of SMRs generally could be addressed within the existing regulatory framework, there are issues that must be resolved. In particular, current regulatory practices might not be fully compatible with a factory assembly mode, especially if the assembly process is automated. Regulators must adapt their methods of work to test the units to the greatest extent possible at the assembly stage and reduce the potential for rework.

Other important regulatory issues include validation of enhanced passive safety systems and multi-modular deployment, size of the emergency planning zone and the staffing requirements for operation and security. This validation could be obtained with existing procedures, using a risk-informed approach similar to larger nuclear plants. However, SMRs must demonstrate that they can meet safety requirements. Regulators and technical support organisations will need time and resources to form opinions on these options and innovations, and this process could lead to delays in SMR licensing.

Two case studies were considered in this report. The first case study focuses on SMR development in the United States. Several SMR designs have been actively developed in the United States, and the US DOE has made available USD 452 million in matching grants to the Babcock & Wilcox mPower design and to the NuScale SMR design in support of their design development and licensing programmes.

Small reactors could be an interesting alternative for new electricity generation capacity in the United States, in particular to replace some of the retiring coal plants.

About 60 GWe of coal plants in the United States were constructed before 1975 and have a capacity of between 50 and 300 MWe. However, although there is variation in the electricity prices across the United States, the average generation component of the electricity price is estimated to be USD_{2011} 60/MWh when the natural gas price is about USD 4/MMBtu and it is likely to remain at this level for the next decade, according to projections by the US EIA. Despite the low level of electricity prices, about 3.5 GWe of SMRs could be deployed in the United States in the high-case scenario for the period 2020-2035. This will correspond to ~3.5% of the total nuclear capacity projected in the United States in 2035-2040. The low-case scenario corresponds to a pessimistic case in which only the prototypes are constructed.

The second case study is on the Russian barge-mounted KLT-40S, currently under construction (scheduled to be completed in 2017), and intended to be deployed by 2019 in the Chukotka region (in north-east Russia). This project is based on the well-established technology of icebreaker-type nuclear reactors. According to the latest estimates, the cost of electricity produced by this first-of-a-kind plant is expected to be about USD 200/MWh. Such high values are related to large staffing requirements (in total about 250 employees) motivated by the application of today's regulations in Russia. In addition, the fuel cost for such units is high, and maintenance of the barge and the coastal infrastructure requires a high level of resources.

Despite this high cost of electricity generation, the floating NPP is believed to be an adequate solution for bringing power to remote regions in Russia because the cost of alternatives, including power grid extension, is also high. Given the typical power demand of 50 to 100 MWe, estimates show that a 500- to 1 000-km grid extension is more expensive than deploying an SMR locally. In the future, up to seven floating NPPs (not necessarily of the same design) could be constructed in Russia, but the decision will be taken based on feedback from experience with the first unit.

Recommendations

Although the economics of SMRs are not fully known, there is a large potential for these technologies that can represent an alternative way forward for nuclear power development. In the high-case scenario, up to 21 GWe of SMRs could be globally added by 2035. Actual SMR market development will strongly depend on the successful deployment of prototypes and FOAK plants. To achieve the ambitious goals of SMR development, the following recommendations are being made:

- Governments and industry should work together to accelerate the construction of SMR prototypes that could demonstrate the benefits of this technology. Governments willing to develop nuclear power should consider supporting international collaboration and common R&D on SMRs, and work on national and international licensing frameworks for small nuclear reactors.
- SMR vendors and potential customers should work closely with nuclear regulators to allow early resolution of various issues of SMR development (including validation of innovative safety features and solutions) and factory assembly. In the case of overseas deployment of SMRs, both nuclear and non-nuclear regulatory authorities (e.g. export control agencies) should be associated with this process.
- SMR vendors and customers should work together to estimate the economics of small nuclear power plants, taking into account the role that SMRs could play in the new energy mixes, in particular when large shares of variable renewables are present. Detailed SMR market assessments should be performed, taking into account realistic estimates of SMR economics and the capabilities of the supply chain. These results must be carefully drafted for policymakers and the public.

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Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment

Recent interest in small modular reactors (SMRs) is being driven by a desire to reduce the total capital costs associated with nuclear power plants and to provide power to small grid systems. According to estimates available today, if all the competitive advantages of SMRs were realised, including serial production, optimised supply chains and smaller financing costs, SMRs could be expected to have lower absolute and specific (per-kWe) construction costs than large reactors. Although the economic parameters of SMRs are not yet fully determined, a potential market exists for this technology, particularly in energy mixes with large shares of renewables.

This report assesses the size of the market for SMRs that are currently being developed and that have the potential to broaden the ways of deploying nuclear power in different parts of the world. The study focuses on light water SMRs that are expected to be constructed in the coming decades and that strongly rely on serial, factory-based production of reactor modules. In a high-case scenario, up to 21 GWe of SMRs could be added globally by 2035, representing approximately 3% of total installed nuclear capacity.

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