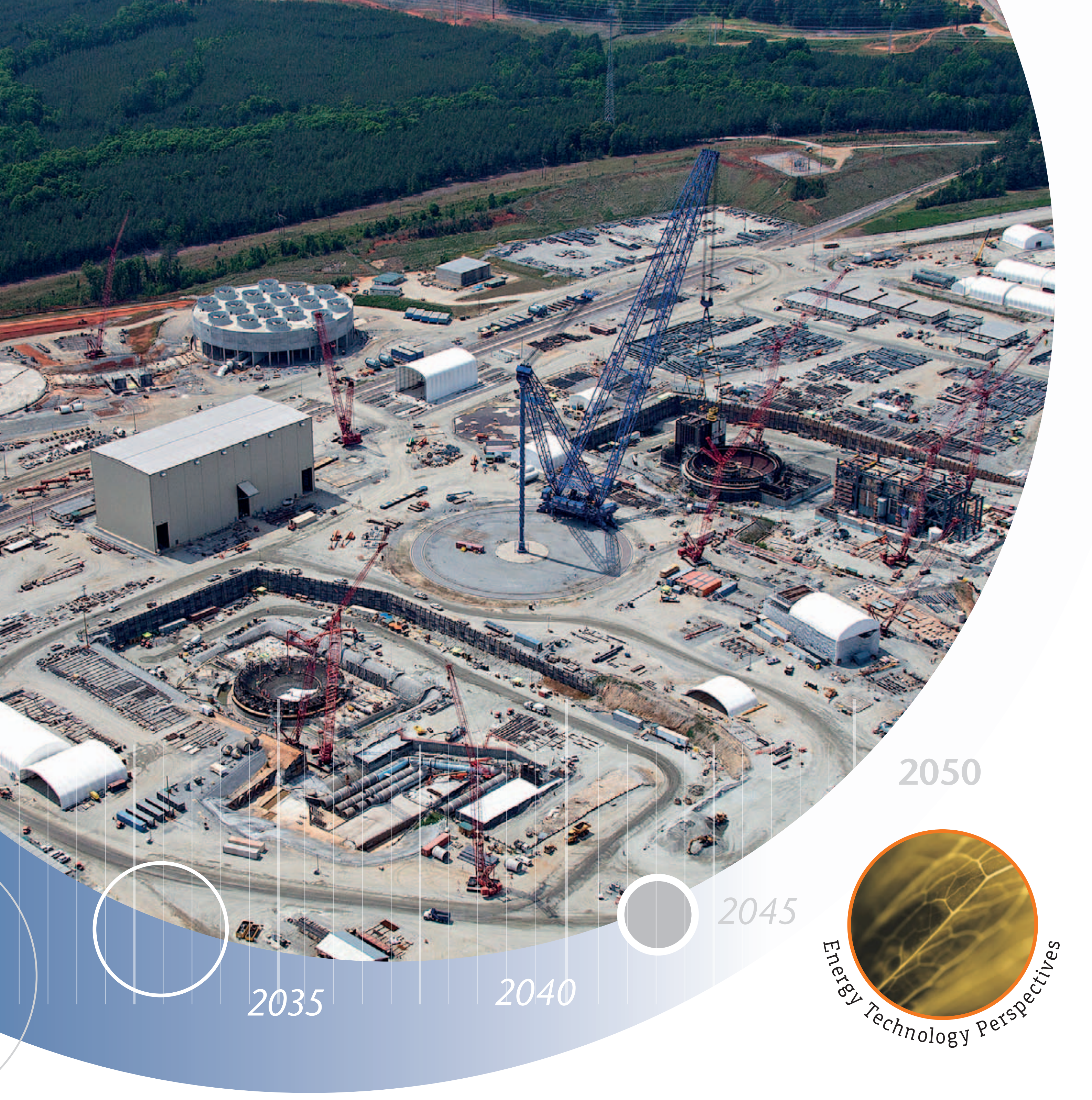

Technology Roadmap

Nuclear Energy

2015 edition

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Nuclear Energy Agency

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Foreword

Current trends in energy supply and use are unsustainable. Without decisive action, energy-related emissions of carbon dioxide will nearly double by 2050 and increased fossil energy demand will heighten concerns over the security of supplies. We can change our current path, but this will take an energy revolution in which low-carbon energy technologies will have a crucial role to play. Energy efficiency, many types of renewable energy, carbon capture and storage, nuclear power and new transport technologies will all require widespread deployment if we are to sharply reduce greenhouse gas (GHG) emissions. Every major country and sector of the economy would need to be involved. The task is urgent if we are to make sure that investment decisions taken now do not saddle us with sub-optimal technologies in the long term.

Awareness is growing on the need to turn political statements and analytical work into concrete action. To spark this movement, the International Energy Agency (IEA) is leading the development of a series of *Roadmaps* for some of the most important technologies. By identifying the steps needed to accelerate the implementation of technology changes, these *Roadmaps* will enable governments, industry and financial partners to make the right choices – and in turn help societies to make the right decisions.

This *Roadmap* is an update of the 2010 *Technology Roadmap: Nuclear Energy* (IEA/NEA, 2010), and, similarly to the 2010 edition, it has been prepared jointly by the IEA and the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA). The nuclear energy landscape has changed since 2010, with a number of events affecting its development: the Fukushima Daiichi accident, which heightened public concern over the safety of nuclear energy in many countries, and the subsequent safety reviews and development of new safety requirements to ensure even higher levels of safety for existing and future nuclear power plants; the shift towards Generation III reactors for nuclear new build; and the economic and financial crises that have both lowered energy demand and made financing of capital-intensive infrastructure projects more challenging, especially in liberalised electricity markets. As a follow-up to this *Roadmap*, the NEA is initiating a highly technical survey to identify the critical research and development efforts that are needed to enable countries to consider advanced nuclear energy technologies as they attempt to reduce their reliance on fossil fuels.

Each country must decide what energy mix is optimal for its national circumstances. However, the fundamental advantages provided by nuclear energy in terms of reduction of GHG emissions, competitiveness of electricity production and security of supply still apply. The number of reactors under construction is currently the highest in 25 years, with the People's Republic of China leading the way in terms of new projects. There is also renewed interest in developing more innovative designs and advanced nuclear fuel cycles to address new markets and improve the competitiveness of nuclear power plants. The *Roadmap* is based on a scenario where long-term global temperature increases are limited to just 2 degrees Celsius (°C) and outlines a scenario that highlights nuclear energy's potential contribution to this low-carbon future. This scenario is not a prediction of what will happen.

Nuclear energy can play a key role in decarbonising our electricity systems by providing a stable source of low-carbon base-load electricity. By identifying major barriers and recommendations on how they can be overcome, this *Roadmap* aims to assist governments interested in maintaining or developing nuclear energy technologies. To get us onto the right pathway, this *Roadmap* highlights several key actions to be addressed in the next decade to ensure the conditions for a safe, publicly accepted and affordable deployment of nuclear technology in countries that already have the technology as well as in newcomer countries.

This publication is produced under our authority as Executive Director of the IEA and Director-General of the NEA.

Maria van der Hoeven
Executive Director, IEA

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Key findings

- Nuclear power is the largest source of low-carbon electricity in OECD countries, with an 18% overall share of electricity production in 2013 and second at global levels with an 11% share. The updated vision for the 2014 Nuclear Roadmap – based on the 2 degrees Celsius (°C) scenario (2DS)[1] of *Energy Technology Perspectives: Scenarios and Strategies to 2050* (IEA, forthcoming 2015) – sees nuclear continuing to play a major role in lowering emissions from the power sector, while improving security of energy supply, supporting fuel diversity and providing large-scale electricity at stable production costs.
- In the 2D scenario, global installed capacity would need to more than double from current levels of 396 gigawatts (GW) to reach 930 GW in 2050, with nuclear power representing 17% of global electricity production. Although lower than the 2010 Roadmap vision of 1 200 GW and 25% share of generation, this increase still represents a formidable growth for the nuclear industry.
- The near-term outlook for nuclear energy has been impacted in many countries by the Fukushima Daiichi nuclear power plant accident. Although the accident caused no direct radiation-related casualties, it raised concerns over the safety of nuclear power plants and led to a drop in public acceptance, as well as to changes in energy policies in a limited number of countries. This, together with an economic crisis that has lowered demand in many countries and a financial crisis that is making financing of capital-intensive projects challenging, has led to a decrease in overall construction starts and grid connection rates over the last four years.
- However, in the medium to long term, prospects for nuclear energy remain positive. A total of 72 reactors were under construction at the beginning of 2014, the highest number in 25 years. According to the 2D scenario, China would account for the largest increase in nuclear capacity additions from 17 GW in 2014 to 250 GW in 2050 and, by 2050, would represent 27% of global nuclear capacity and nuclear power generation. Other growing nuclear energy markets include India, the Middle East and the Russian Federation. According to 2DS projections, nuclear capacity would either decline or remain flat in most OECD countries, with the exception of the Republic of Korea, Poland, Turkey and the United Kingdom.
- Nuclear safety remains the highest priority for the nuclear sector. Although the primary responsibility for nuclear safety lies with the operators, regulators have a major role to play to ensure that all operations are carried out with the highest levels of safety. Lessons learnt from the Fukushima Daiichi accident have emphasised that regulators should be strong and independent. Safety culture must be promoted at all levels in the nuclear sector (operators and industry, including the supply chain, and regulators) and especially in newcomer countries.
- Governments have a role to play in ensuring a stable, long-term investment framework that allows capital-intensive projects to be developed and provides adequate electricity prices over the long term for all low-carbon technologies. Governments should also continue to support nuclear research and development (R&D), especially in the area of nuclear safety, advanced fuel cycles, waste management and innovative designs.
- Nuclear energy is a mature low-carbon technology, which has followed a trend towards increased safety levels and power output to benefit from economies of scale. This trajectory has come with an increased cost for Generation III reactors compared with previous generations, but this should also lead to better performance and economics for standardised Nth-of-a-kind (NOAK) plants, although this has yet to be confirmed.
- Small modular reactors (SMRs) could extend the market for nuclear energy by providing power to smaller grid systems or isolated markets where larger nuclear plants are not suitable. The modular nature of these designs may also help to address financing barriers.

1 The 2°C Scenario outlines the technologies needed across all energy sectors so that CO_2 emissions in 2050 are reduced by half compared to 2009 levels, allowing for long-term global temperature increases of just 2°C. See Box 5 for more details.

Key actions for the next ten years

In order for nuclear to reach its deployment targets under the 2D scenario, annual connection rates should increase from 5 GW in 2014 to well over 20 GW during the coming decade. Such rapid growth will only be possible if the following actions are implemented over the next ten years:

- The contributions of nuclear energy – providing valuable base-load electricity, supplying important ancillary services to the grid and contributing to the security of energy supply – must be fully acknowledged. It is important, therefore, to review arrangements in the electricity market so as to ensure that they offer investment frameworks as favourable to new nuclear build as they are to other low-carbon technologies and that they allow nuclear power plants to operate effectively.

- Vendors must demonstrate the ability to build on time and to budget, and to reduce the costs of new designs. Integrating lessons learnt from recent first-of-a-kind (FOAK) experiences in project management and planning, human resource allocation, supply chain set-up, qualification and oversight, as well as reactor design, construction simplification and optimisation, will be key.

- Enhanced standardisation, harmonisation of codes, standards and regulatory requirements, and the streamlining of regulatory licensing processes are needed to reduce costs and to improve new build planning and performance. At the same time, industry must continue to improve quality assurance and control for nuclear structures, systems and components, and nuclear safety culture must be enhanced across the whole nuclear sector, spanning the supply chain, the vendors, the utilities and the regulators.

- Information exchange and experience sharing among regulators, and among operators of nuclear power plants, should be enhanced so as to improve overall safety and operational performance.

- Countries choosing to develop nuclear power for the first time must be prepared to set up the required infrastructures prior to the start of a nuclear programme. Building capacities in terms of trained, educated and competent staff for future operation and regulatory oversight is an absolute necessity and requires long-term planning.

- Actions to improve public acceptance must also be strengthened. These include implementing post-Fukushima safety upgrades in existing reactors and demonstrating that nuclear regulators are strong and independent. It will also entail improving outreach to the public by providing transparent and fact-based information on the risks and benefits of nuclear power, and on the role that it can play with respect to energy security, affordability, climate change mitigation and air quality.

- Governments that have not yet finalised their strategies for managing nuclear waste, should do so without delay. For high-level waste, deep geological disposal (DGD) is the recommended solution. If the geology and the safety case allow, and if it makes economic sense, governments should implement a DGD at national level. Alternatively, they might consider a regional solution, making use of another country's planned or operational DGD site for waste management. Long-term planning, political commitment and strong engagement with local communities are central to this strategy.

Introduction

Since the release in 2010 of *Technology Roadmap*: *Nuclear Energy* (IEA/NEA, 2010), a number of events have had a significant impact on the global energy sector and on the outlook for nuclear energy. They include the Fukushima Daiichi nuclear power plant (NPP) accident in March 2011, the global financial and economic crises that hit many industrialised countries during the period 2008-10 and failings in both electricity and CO_2 markets. The Fukushima Daiichi accident has had a detrimental impact on public opinion and the overall acceptance of nuclear power as a source of energy, causing a few countries to establish policies to phase-out nuclear power. The financial crisis led to the introduction of new financial regulations that have made financing of capital-intensive projects such as nuclear new build even more difficult than in the past. The economic crisis that followed reduced the demand for electricity, which, combined with strong policy support for renewables, has resulted in a situation of overcapacity in generation for many OECD countries. Furthermore, in liberalised electricity markets, the lack or inefficiency of carbon pricing and subsidised alternative technologies, as well as falling wholesale prices, are making investment in nuclear power less attractive.

In parallel, the rapid development of unconventional gas and oil has lessened the urgency of developing new energy technologies in some parts of the world. Cheap shale gas in the United States, for example, has helped to dramatically reduce power sector emissions and lower electricity costs in certain parts of the country. As a consequence, both the demand for and price of coal have dropped in the United States. This drop has resulted in an increase in exports, especially to Europe where coal consumption has increased, in part to replace lost nuclear capacity (e.g. in Germany). Despite these additional challenges, nuclear energy still remains a proven low-carbon source of base-load electricity, and many countries have reaffirmed the importance of nuclear energy within their countries' energy strategies.

To achieve the goal of limiting global temperature increases to just 2 degrees Celsius (°C) by the end of the century, a halving of global energy-related emissions by 2050 will be needed. This will require an unprecedented transition in the way energy is consumed and produced. A wide range of low-carbon energy technologies will be needed to support this transition, including a variety of renewable energy technologies, energy efficiency, advanced vehicles, carbon capture and storage and nuclear energy. Notwithstanding government commitments to this target, action continues to fall short of what is needed to transition the energy sector, and many technologies, including nuclear, are not on track to reach the long-term 2°C target.

Purpose of the *Roadmap* update

When the *Nuclear Technology Roadmap* was released in 2010, there were 16 new construction starts – a number that had not been reached since 1985 – and many were anticipating a "nuclear renaissance". However, the accident at the Fukushima Daiichi NPP had an immediate impact on the short- to medium-term development of nuclear power in many countries, and four years after the publication of the first *Roadmap*, the IEA and NEA have undertaken an update of the nuclear energy *Roadmap* to take into account recent challenges facing the development of this technology.

This nuclear *Roadmap* update aims to:

- Outline the current status of nuclear technology development and the need for additional R&D to address increased safety requirements and improved economics.
- Provide an updated vision of the role that nuclear energy could play in a low-carbon energy system, taking into account changes in nuclear policy in various countries, as well as the current economics of nuclear and other low-carbon electricity technologies.
- Identify barriers and actions needed to accelerate the development of nuclear technologies to meet the *Roadmap* vision.
- Share lessons learnt and good practices in nuclear safety and regulation, front- and back-end fuel cycle practices, construction, decommissioning, financing, training, capacity building and communication.

Rationale for nuclear energy and *Roadmap* scope

Nuclear energy remains the largest source of low-carbon electricity in the OECD and the second largest source in the world. Its importance as a current and future source of carbon-free energy must be recognised and should be treated on an equal footing with other low-carbon technologies. As a proven and mature technology that can supply firm electricity capacity, nuclear can play a key role in future energy systems in many parts of the world. However, public acceptance of nuclear energy decreased significantly in many countries after the Fukushima Daiichi accident, although it has partly recovered since 2011. The simultaneous challenges of financing such large capital-intensive projects have made the development of nuclear power even more difficult today.

The focus of the vision presented in this *Roadmap* is centred on the IEA *Energy Technology Perspectives 2015* (IEA, forthcoming 2015) 2°C scenario (2DS) vision for nuclear energy and the contribution that nuclear power can make to the decarbonisation of the power system. *ETP 2015* projects that 930 gigawatts (GW) of gross nuclear capacity will be needed globally to support the transition of the energy system. Although lower than the vision outlined in the 2010 *Roadmap*, this growth still represents a formidable challenge for governments and industry compared to the current capacity of 396 GW.

The *Roadmap* focuses essentially on nuclear fission technologies for electricity generation, and although nuclear's potential for other energy applications such as combined heat and power, district heating, hydrogen production and desalination are very promising, the actions and milestones identified in this *Roadmap* focus mainly on the electricity sector. Other energy applications are mentioned only briefly in the technology development section of the *Roadmap*. Nuclear fusion is outside the scope of the *Roadmap* and although a promising technology in the long term, it is not expected to make any contribution to power generation before 2050.

Roadmap process, content and structure

This *Roadmap* was compiled with the support of a wide range of stakeholders from government, industry, research institutions, academia and non-governmental organisations. Three expert workshops were hosted by the IEA and NEA to provide input to the development of this *Roadmap*, two workshops at the IEA in Paris, and one in Hong Kong, China, with a focus on developments in Asia. The findings and recommendations in this report reflect the discussions and key messages that emerged from the three workshops as well as from additional input gathered during the drafting and review of the *Roadmap*.

This edition of the *Roadmap* provides an update on the status of nuclear development since 2010 and highlights technology development needs for nuclear reactors, as well as front- and back-end fuel cycle issues, including decommissioning. Industrial issues such as standardisation, harmonisation of codes and standards, development of global and local supply chains, quality assurance, and integration of feedback experience from current new build projects are also covered in this report. Newcomer countries, especially in the Middle East and the Southeast Asia regions, are expected to represent a significant share of the projected growth of nuclear energy, and special attention has been paid to the conditions in which nuclear energy can be developed in these countries. Identified barriers to this development include financing, public acceptance in the wake of the Fukushima Daiichi accident, higher costs due in part to enhanced safety regulations after Fukushima Daiichi, human resource capacity building, and a lack of favourable energy policy and electricity market incentives.

Case studies have been developed together with various nuclear energy stakeholders to help illustrate lessons learnt and good practices in the development of nuclear energy. A summary of these case studies is included in the *Roadmap* document, with the full versions available in Annex[2]. These case studies aim to provide additional insights and practical support for the recommendations and proposed actions in this *Roadmap*. They cover lessons learnt from new build projects, best practices in decommissioning and waste management, setting up of geological repositories for high-level waste, financing, education and training skills programmes, and the establishment and reinforcement of the supply chain. It also covers the benefits of peer review processes among operators or regulators, allowing them to share knowledge and improve safety.

2. www.iea.org/publications/freepublications/publication/technology-roadmap-nuclear-energy.html.

Nuclear energy progress since 2010

When the International Energy Agency (IEA)/ Nuclear Energy Agency (NEA) *Technology Roadmap*: *Nuclear Energy* was published in 2010, nuclear energy was experiencing a so-called "nuclear renaissance". Reasons for the increased interest in nuclear power in the decade leading up to 2010 included concern over greenhouse gas (GHG) emissions from the power sector and security of energy supply, as well as the need for affordable base-load electricity supply with stable production costs. However, this trend slowed considerably in 2011, to a large extent because of the Fukushima Daiichi nuclear power plant (NPP) accident in March, which had an impact on public acceptance and on nuclear policies in several countries. Other reasons for this slowdown include the aftermath of the financial crisis of 2008-09 and the ensuing economic crisis, which led to a decrease in financing capabilities on the part of lending institutions, as well as decreased electricity needs in countries affected by the economic crisis. More than three years after the accident in Japan, the global situation is improving for nuclear energy with the number of construction starts again on the rise. Yet, the grid connection rate is still too low to meet the 2 degrees Celsius Scenario (2DS) target for nuclear power by 2025 (IEA, 2014). This updated *Roadmap* aims to identify actions that could help bring nuclear back on track to meet the 2DS target.

Fukushima Daiichi NPP accident: 11 March 2011

The Fukushima Daiichi accident was the result of the Great East Japan earthquake that registered a magnitude of 9 on the Richter scale – the largest ever recorded in Japan – and the ensuing tsunami that hit the power plant. Units 1, 2 and 3 at the power plant were in operation at the time of the accident and shut down safely following the earthquake, with emergency power generation units kicking in when the off-site power supplies were lost. However, most of these failed when the tsunami hit the plant and the basements of the reactor buildings were flooded. As a consequence, the decay heat removal capabilities of the reactors were lost, leading to a severe accident with core degradation, hydrogen generation (and subsequent explosion), and release of radioactive material into the environment following the partial destruction of the reactor buildings.

The accident was the worst of its kind since the Chernobyl accident in 1986, rating 7 on the International Nuclear Event Scale (INES), at the same level as the Chernobyl accident. However, unlike the accident in the Ukraine, tens of thousands of people were evacuated from the vicinity of the plant and sheltered before most of the release of radioactive material into the environment. In 2014, the United Nations Scientific Committee on the Effects of Atomic Radiation released its final report on the radiological consequences of the accident (UNSCEAR, 2014), which concludes that radioactive releases were between 10% and 20% of the releases of the Chernobyl accident. No fatalities were considered to have arisen from overexposure to radiation, although some injuries and deaths occurred at the NPP as a result of accidents related to the earthquake and tsunami. Large areas around the Fukushima Daiichi power plant were contaminated by the fallout from the accident, and the imposition of very low radiation exposure standards prevented evacuees from returning to their homes and villages. A multibillion USD "remediation" programme has been undertaken to decontaminate the environment, but it will take several years to complete before people are allowed to return to their homes. In parallel, work is ongoing to decommission the Fukushima Daiichi nuclear power plant and to prevent any further radioactive releases from the destroyed units.

In spite of the limited number of casualties caused by the Fukushima Daiichi accident, there has been worldwide concern about the consequences of the accident, and more generally, about the safety of nuclear power. Actions to assess the safety of operating nuclear facilities in the event of extreme external events have been taken at both national and international levels. They include comprehensive safety reviews – called "stress tests" in the European Union – of existing reactors as well as reactors under construction and other fuel cycle facilities. These reviews have reassessed the safety margins of nuclear facilities with a primary focus on challenges related to multiple external events such as those experienced at the Fukushima Daiichi NPP (i.e. the loss of safety functions, including cooling of the reactor core) or capabilities to cope with severe accidents.

The reviews examined the adequacy of design-basis assumptions, as well as provisions for beyond-design-basis events. These assessments were carried out by the operators under the guidance of their national regulators. They were then reviewed by the regulators and peer reviewed at the international level, for instance, by the European Nuclear Safety Regulators Group (ENSREG) for facilities in the European Union and neighbouring countries (Switzerland, Turkey, Ukraine) or upon request by the International Atomic Energy Agency (IAEA). Following these safety assessments, it was found that the vast majority of NPPs could continue to operate safely, but that some safety upgrades were necessary to improve the resistance of the NPPs to extreme or multiple external events. These safety upgrades are currently being implemented by the operators and reported to national regulators.

Only a few months after the accident, the IAEA Action Plan on Nuclear Safety was adopted by the IAEA's Board of Governors and subsequently endorsed unanimously by the IAEA General Conference in September 2011. The ultimate goal of the Action Plan is to strengthen nuclear safety worldwide through 12 targeted actions that address *inter alia* safety assessments, peer reviews, emergency preparedness and response, the effectiveness of regulators and operators, and safety standards.

The IAEA is nearing completion of the IAEA Fukushima Report (to be published in 2015). The NEA has already released a report entitled "OECD/NEA Nuclear Safety Response and Lessons Learnt" (NEA, 2013), describing immediate actions and follow-up actions taken by its members and by the NEA. The report provides key messages and recommendations to improve nuclear safety. Operators are also drawing on lessons learnt from the accident and sharing information and best practices as well as subjecting themselves to peer review. In particular, these peer reviews are often performed by the World Association of Nuclear Operators (WANO) (see Box 1).

Nuclear power generation and new build at the end of 2014

Global nuclear generation declined to around 2 478 terawatt hours (TWh) in 2013, a 10% decrease from 2010 levels, essentially due to the permanent shutdown of eight reactors in Germany and to Japan's operable reactors remaining offline for the majority of 2013. Japan's 48 operable reactors have remained idle since September

Box 1: Peer review process among nuclear operators: WANO (Case study 1)

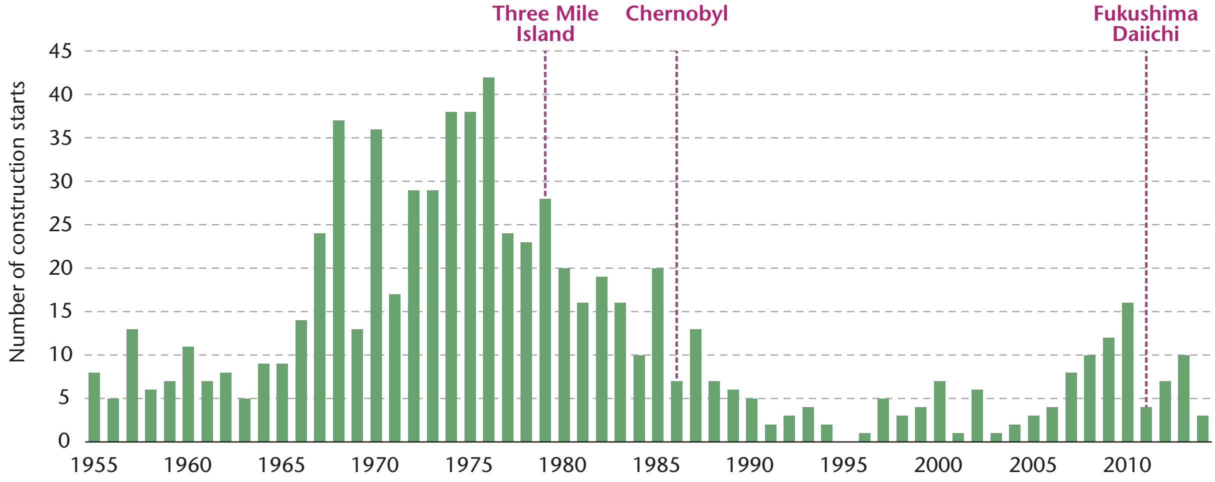
WANO brings together operators from every country in the world that has an operating commercial NPP with the objective of achieving the highest possible standards of nuclear safety. WANO helps its 130 members accomplish the highest levels of operational safety and reliability. With safety as its only goal, WANO helps operators communicate effectively and share information openly to raise the performance levels of all operators.

For the past 25 years, WANO has been helping operators through four core programmes:

- Peer reviews: these reviews help members compare their operational performance against standards of excellence through in-depth, objective analyses of their operations by an independent team from outside their organisations.
- Operating experience: this programme alerts members to mistakes or events that have occurred at other NPPs and enables them to take corrective actions to prevent similar occurrences at their own plants. Members share their operating experience for the benefit of other operators.
- Technical support and exchange: this programme has many facets, including technical support missions, which are carried out at the request of a plant or utility and allow WANO members to help each other resolve identified issues or problems.
- Professional and technical development: this programme provides a forum for WANO members to enhance their professional knowledge and skills so that they can deal with potential safety issues before they become problems.

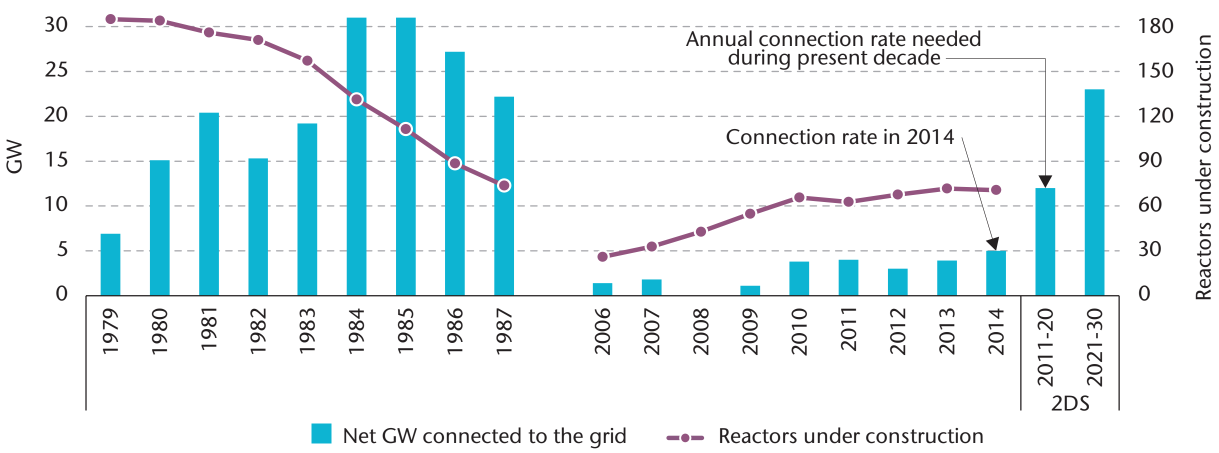
2013, and throughout 2014. Installed nuclear capacity increased only slightly between 2013 and 2014 at 396 GW (gross), and yet the number of construction starts dropped from 10 in 2013 to just 3 in 2014 (see Figure 1). A record 72 nuclear reactors were under construction at the beginning of 2014 but, in terms of grid connection, only 5 GW of nuclear capacity were connected in 2014 (4 GW in 2013), far below the 12 GW or so that would be needed each year during this decade to meet the 2DS target for 2025 (see Figure 2).

Figure 1: Nuclear reactor construction starts, 1955 to 2014



Source: IAEA Power Reactor Information System (PRIS).

Figure 2: Grid connection rates and required rates to reach the 2DS target



Source: IAEA PRIS Database, IEA and NEA analysis.

Construction of Generation III reactors

Nuclear construction projects are large complex projects involving a considerable number of suppliers and construction workers as well as high technological skills and strong architect-engineer management capabilities. Nuclear projects are also subject to strict regulatory and political control and approval. Hence, there are many reasons why new build projects can experience significant delays and run over budget. With the switch from well-established Generation II (Gen II) technologies that have established supply chains and construction planning to the potentially more complex designs of Generation III (Gen III) reactors, the nuclear industry faces additional challenges. Much publicised delays and cost-overruns for some of the first-of-a-kind projects are playing against public acceptance of nuclear power as well as investor confidence, and industry is well aware of the need to improve on its capability to deliver "on time and to budget". All vendors have taken steps to draw lessons from FOAK projects to optimise the designs of their reactors, improve the performance and quality of the supply chain, and improve project scheduling and management.

While a general perception may exist that Gen III reactors will take much longer to build than Gen II reactors because of the added complexity or improved safety and performance features that these reactors have over Gen II reactors, some of the shortest construction spans of any reactor have been achieved with Gen III designs (see Box 2).

Long-term operation of existing reactors

In addition to the need for new build capacities to be brought online, there is also a need to maintain the current fleet and to continuously improve its operation and safety. Most nuclear operators in the world are making investments to ensure the operation of their plants beyond the original design lifetime. In the United States, more than 70% of operating reactors have been granted a 20-year licence extension that allows reactors to operate for up to 60 years. In Europe, where periodic safety reviews are performed, many reactors reaching 40 years of operation will be allowed to operate for at least another 10 years. Long-term operation of existing reactors that meet certain safety requirements is very often a way to produce low-carbon electricity in the most cost-effective way for a period of 40 to 60 years (NEA, 2012a). As detailed in the technology section of this *Roadmap*, R&D in the ageing of systems and materials is being carried out to address 60+ years of operation. In some cases, however, and for single-reactor merchant plant operators in particular, market conditions can make it difficult to justify the continuous operation of NPPs.

Box 2: Lessons learnt from Generation III construction projects (Case study 2)

Vendors of Gen III reactors are aware of the need to deliver NPPs on time and to budget, and are benefitting from the experience gained during FOAK projects to optimise designs and supply chains, as well as to more effectively manage construction projects. For many vendors and equipment suppliers, especially in Europe and in the United States, Gen III projects represent the first nuclear new build projects for more than ten years, with much of the experience gained during the peak construction times of the 1970s and 1980s now outdated.

A four- to five-year construction span is a realistic target for Nth-of-a-kind (NOAK) Gen III reactors, in line with the proven construction spans of mature Gen II designs. This target has already been surpassed in Japan, where construction of Gen III units at the Kashiwazaki-Kariwa, Hamaoka and Shika NPPs were completed in less than four years.

The reasons for such impressive construction spans include the use of modularisation with very heavy lift cranes, open-top and parallel construction floor packaging, front-loaded construction engineering, detailed schedule management and an integrated construction management system. Modularisation gives a streamlined and effective on-site approach and open-top construction, and the use of heavy lift cranes allow large-scale modules to be placed directly into position. Lessons learnt during construction are also consolidated in an advanced integrated computer-aided engineering system that relies on a plant engineering database and on accumulated experience and management know-how. Finally, a quality assurance system that extends to design, manufacture, inspection, installation, and preventative maintenance after delivery contributes to better overall performance.

This was the case when two plants in the United States, Kewaunee and Vermont Yankee, shut down in 2013 and 2014 respectively, essentially for economic reasons.

For fleet operators, economies of scale can be gained by developing modernisation programmes across the fleet. This applies to both safety improvements, such as the post-Fukushima safety upgrades, as well as long-term operation investments. Maximising feedback experience across the different units of the fleet, as well as from other NPPs (through organisations such as WANO), can help optimise a modernisation programme and its cost. Nuclear utilities that have their own engineering capabilities and operate as an "architect-engineer" model can fully benefit from the return of experience and lessons learnt to optimise long-term operation investments and safety upgrades (see Box 3).

Box 3: The integrated architect-engineer model, a proven industrial model to optimise design, construction and operation of NPPs (Case study 3)

Électricité de France (EDF) has developed an industrial model called the integrated architect-engineer model – the basis of the success of the French nuclear programme, which includes 19 NPPs with a total of 58 reactors in operation and one under construction, providing 75% of the country's electricity. Thanks to strong interactions between design, procurement and operation, the operator can use this model to increase the safety and performance of the plants by maximising the use of experience feedback. Collecting experience feedback from its own plants or from other plants is the first step in the process. Then, engineering teams process this feedback and implement the measures to continuously improve the safety and performance of the facilities.

This approach was used immediately after the Fukushima Daiichi accident. EDF immediately mobilised 300 engineers who analysed each of the 19 EDF sites. A report of 7 000 pages was issued to the French Nuclear Safety Authority as part of the post-Fukushima "stress tests" evaluations. EDF was able to integrate lessons learnt from the Fukushima Daiichi accident into its lifetime extension programme and is currently investing to prepare its fleet to operate for up to 60 years. Continuous investments and improvements through integration of operational experience have meant that the cost of the Fukushima safety upgrades have been less than 20% of the cost of the lifetime extension programme.

Regional perspectives for nuclear energy

The drivers and challenges for the development of nuclear power will vary depending on a number of factors including a country's energy and environmental policy, outlook for electricity demand, availability of energy resources, the regulatory environment and the power market structure. For countries with mature nuclear operations, there will be a focus on plant modernisation and long-term operations. In nuclear newcomer countries, development of the necessary nuclear infrastructure and regulatory frameworks, of public acceptance and a skilled workforce will be important challenges. And for certain other countries, replacement of retiring plants and possible expansion of nuclear energy will be the main focus.

Given large upfront capital requirements, the financing of nuclear power plants (NPPs) is a major hurdle for most countries. The large size of Generation III (Gen III) nuclear reactors, typically in the range of 1 000-1 700 megawatts (MW), could limit the number of countries in which nuclear power is an option – the usual "rule of thumb" is that a nuclear reactor or any other single generating unit in an electric system should not represent more than 10% of the size of the grid. Smaller reactors such as small modular reactors (SMRs) could target countries or regions with less developed electric grids. This section aims to highlight some of the regional drivers and challenges for the development of nuclear power in major countries/regions that are expected to have significant nuclear power programmes in the future.

Table 1: Summary of characteristics for nuclear power development in various regions

	Current status and electricity market design*	***Drivers for future developments***	***Key challenges***
OECD Europe	25% electricity production (833 terawatt hours [TWh], with 132 reactors (122 gigawatts [GW]). Four units under construction; three countries phasing out (Belgium, Germany and Switzerland). Average age of fleet is 27 years; about 130 units to be decommissioned by 2050. Poland and Turkey are newcomer countries. The United Kingdom is planning one of the most ambitious new build programmes in the OECD. Mix of liberalised and regulated electricity markets.	Electricity decarbonisation; energy security; competitive electricity costs.	Financing in liberalised markets; developing technology-neutral policy for low-carbon investments; market distortion (due to subsidised renewables) and decreasing wholesale electricity prices; and public acceptance.
United States	19% electricity production (822 TWh) with 100 reactors (105 GW). Five units under construction. Mature nuclear fleet; most reactors licensed for 60 years. Mix of liberalised and regulated electricity markets.	Electricity decarbonisation; competitive electricity costs; security of energy supply; redevelop nuclear industry.	Financing in liberalised markets. Economics of long-term operation in competition with shale gas.
Russian Federation	17% electricity production (172 TWh), with 33 reactors (25 GW). 10 units under construction. Liberalised electricity market.	Policy to increase the share of nuclear electricity by 2030 to 25-30%; strong support for nuclear industry, including for export markets.	Managing the gradual replacement of Reactor Bolshoy Moshchnosti Kanalnyy (RBMK) reactors (nearly half the current electricity production) with Gen III Water-Water Energetic Reactor (VVER) reactors.

Table 1: Summary of characteristics for nuclear power development in various regions (continued)

	*Current status and electricity market design**	*Drivers for future developments*	*Key challenges*
Japan and Republic of Korea	11% electricity production (148 TWh), with 71 reactors (66 GW) All of Japan's 48 reactors are presently idle. Seven units under construction (two in Japan, five in the Republic of Korea). Regulated electricity market.	Energy security; electricity decarbonisation; competitive electricity costs; strong support for nuclear industry, including for export markets.	Public acceptance. Restart of Japan's nuclear fleet.
China, People's Republic of	2% electricity production (117 TWh), with 20 reactors (17 GW). 29 units under construction. Regulated electricity market.	Energy security; rapid growth in electricity demand; stable future electricity costs; local pollution concerns; strong support for nuclear industry.	Public acceptance; developing NPPs inland; domestic supply chains.
India	3% electricity production (32 TWh), with 21 reactors (5.8 GW). Six units under construction. Regulated electricity market.	Energy security; strong electricity demand growth; stable future electricity cost.	Public acceptance; financing; foreign vendors access to market (Indian nuclear liability regime).
Other developing Asian countries	Bangladesh and Viet Nam preparing for construction. Thailand and Indonesia have plans but are not yet committed. Malaysia is studying the feasibility of an NPP. Philippines built a reactor that was mothballed. Regulated electricity markets.	Energy security; diversification and strong electricity demand growth.	Setting up regulatory and other infrastructure; creating a skilled labour force; financing; public acceptance.
Middle East	One reactor in operation in Iran (1 GW), two more units planned. Two units under construction (out of four planned) in the United Arab Emirates. Up to 17 GW planned in Saudi Arabia. Other countries (Jordan, Egypt) considering nuclear option. Regulated electricity markets.	Strong electricity demand growth; stable future electricity costs; saving oil/gas reserves for export markets.	Setting up regulatory and other infrastructure, and training staff; financing for non-oil/gas-rich states; desalination.

* Values in parenthesis are shown for electricity generation in TWh and installed capacity in GW at the end of 2013.

OECD Europe

In OECD Europe, country policy on nuclear development varies widely with Belgium, Germany and Switzerland phasing out nuclear (in 2025, 2022 and 2035 respectively), while the Czech Republic, Finland and Hungary plan to increase their nuclear capacity. The United Kingdom has a significant new build programme (on the order of 15 GW by the late 2020s) to replace retiring plants. Nuclear newcomer countries such as Poland and Turkey are expected to have their first nuclear reactors in operation by the early 2020s. France, which today generates 75% of all its electricity from nuclear, still plans to reduce this share to 50% by 2025 while proposing to maintain nuclear capacity at its present level. Former nuclear country Lithuania is planning to build a new nuclear plant by the early 2020s.

For many countries in OECD Europe, the main focus for nuclear development will be on long-term operation and the eventual replacement of ageing fleets. While 30% of the nuclear reactors currently in operation globally are in OECD Europe, the region only accounts for four of the 70 nuclear reactors currently under construction (two Gen III EPR reactors and two Gen II VVER 440 reactors). Approximately half of the 132 reactors operating today are more than 30 years old, and many utilities are planning and investing in long-term operation as well as power uprates while regulators are assessing on a case-by-case basis whether these reactors can operate for another 10 years or more. Many reactors will be shut down and decommissioned in the next decades, probably at a higher rate than new build construction, and nuclear could see its share of total generation decline. This base-load capacity will be partially offset by renewable power, but also by increased gas and coal power generation, which would lead to higher CO_2 emissions from the power sector.

Although public acceptance of nuclear power is low in several OECD Europe countries, in others, such as in the United Kingdom, nuclear power is perceived as an important option for energy and electricity security as well as a key contributor to decarbonising the power sector. Europe's nuclear industry is mature, has strong well-functioning regulatory systems, and significant R&D capacities with highly experienced and skilled staff. These advantages make the development of nuclear power particularly attractive for the region.

With growing shares of variable renewables in Europe spurred by renewable feed-in tariffs (though many countries are now revising these tariffs downwards as they have proven to be very costly), the challenges of developing nuclear will be complicated by the need for more flexibility and load-following capacity. NPPs have the capacity to load follow to some extent, as has been demonstrated for many years in France and Germany, and new designs also comply with flexibility requirements. Compared to base-load operation, load following could impact the economics of nuclear plants and undermine the profitability of nuclear projects unless operators are adequately paid for services to the grid. The introduction into the grid of large amounts of renewable electricity has also led to falling wholesale prices, which affect the profitability of dispatchable technologies, including NPPs. As a consequence, many gas-fired power plants (i.e. those having the highest marginal costs) have been mothballed, with the market capitalisation of Europe's utilities deteriorating over the last decade. This poses a challenge to future investments and profitability of dispatchable technologies. Governments will need to help manage these risks through policy mechanisms that can help to provide predictability on electricity prices.

United States

The United States has the largest nuclear fleet of any country in the world. The first new build projects in more than 30 years are currently underway at the VC Summer and Vogtle sites in Georgia and South Carolina (each with two Gen III AP1000 units), with the first unit expected to be operating by the end of 2017. All new build projects in the country have been limited to regulated electricity markets, which are more favourable in terms of providing a stable long-term policy framework for capital-intensive projects such as nuclear, for they allow utilities to pass construction costs on to customers through rate adjustments.

In the absence of new build projects, significant power uprates[3] have occurred in the United States that have helped to increase capacity by over 6 GW between 1977 and 2012. The potential for further uprates is limited and expansion of nuclear generation will rely essentially on new builds. Shale gas development, and the resulting low energy prices, has posed additional challenges to the development of nuclear power as cheap gas has led to rapid growth of natural gas combined-cycle plants. Four nuclear reactors shut down in 2013: Crystal River, Kewaunee and San Onofre units 2 and 3. Kewaunee was shut down for economic reasons, Crystal River due to the cost of repairs to the containment, and San Onofre 2 and 3 due to regulatory uncertainty following problems encountered after the replacement of the units' steam generators. Another reactor, Vermont Yankee, was shut down in December 2014 after 42 years of operation, allegedly for lack of competitiveness and in spite of having received a licence renewal. It is also possible that more reactors could be taken out in the coming years because of unfavourable economics. However, gas

3. "Power uprate" is the term used when an existing reactor is modified to generate more power above its nominal output size.

prices are expected to increase in the mid to long term, making nuclear more attractive, particularly if tougher carbon dioxide (CO_2) emissions standards are also implemented.

There is strong interest in the United States to redevelop its nuclear industry, and particular attention has been focused in recent years by the US Department of Energy on the development of SMRs. SMRs could potentially replace coal-fired power plants that will need to shut down because of new, strict regulations on air pollution from the Environmental Protection Agency. Recently, however, the outlook for the deployment of SMRs has been revised, with some leading SMR design companies reducing developing efforts since no near-term deployment is expected in the United States.

Japan and Republic of Korea

Unlike the United States and Europe, which have generally struggled to build new nuclear plants on time and to budget, both Japan and the Republic of Korea were able to maintain successful new build programmes with impressive construction times thanks to sustained construction programmes over the last decades, increased modularity of designs, and well-managed supply chains. This contrasts with the situation in the United States and in Europe, where the last nuclear construction projects to be completed were launched in 1977 and 1991 respectively. With the exception of the two reactors currently under construction, prospects for new build in Japan are unclear and probably limited, given low public acceptance for nuclear after the Fukushima Daiichi accident and the challenge of restarting its nuclear plants as they await regulatory and local political approval. The government hopes that it will be able to restart several reactors at the beginning of 2015.

The Republic of Korea currently has 20.7 GW of nuclear capacity, accounting for 27% of total electricity generation in 2013. To reduce reliance on imported fossil fuels and to enhance energy security, the country has, for a long time, had a strategic goal to increase the share of nuclear generation. However, after the Fukushima Daiichi accident, a more moderate policy has been put forward which will see nuclear capacity increase up to 29% of the total electricity generation capacity by 2035, down from a previous target of 41%. With average capacity factors in recent years of 96.5%, the Republic of Korea has developed strong operating experience and competence. In 2009, the Republic of Korea won its first export contract from the United Arab Emirates and hopes to expand exports to other Middle East countries and Africa.

Under the terms of its co-operation agreement with the United States (the 123 Agreement), the Republic of Korea is currently prohibited from uranium enrichment and reprocessing activities, which constrains its ability to develop the full fuel cycle. If an agreement were reached, the ability to reprocess spent fuel would allow it to increase energy from its imported uranium by 30% and also reduce the amount of high-level waste.

Russian Federation

With Japan's nuclear fleet idle, the Russian Federation is currently the third largest nuclear power country – behind the United States and France – with 33 reactors in operation and a total installed capacity of 25 GW. The State Atomic Energy Corporation, Rosatom, is also one of the leading providers of nuclear technology globally with extensive industry experience. Most of Russia's reactors are being considered for lifetime extensions; to date, 18 reactors with total capacity of over 10 GW have received 15- to 25-year licence extensions. VVER reactors, which comprise half of the fleet, are also likely to be uprated, which would provide an additional 7% to 10% capacity. The oldest VVERs and all of the operating RBMK reactors are expected to be retired by 2030.

The main drivers for future nuclear energy development in Russia include the replacement of ageing reactors due to be decommissioned and the development of additional new capacity to increase the share of nuclear electricity from 17% today to 25% to 30% by 2030. Increased nuclear generation would also free up natural gas for export. Currently, there are ten reactors with a total installed capacity of 9.2 GW under construction (one of them, Rostov 3, was actually connected to the grid on 29 December 2014) and a further 24 reactors (about 29 GW) planned by 2030, including advanced Gen III VVER reactors and sodium-cooled fast breeder reactors, and a BN-800 under construction that reached criticality in June 2014. Russia has invested significantly in nuclear R&D and is one of the leading developers of fast breeder reactors and of small floating reactors that provide nuclear power to remote areas. Two floating SMR KLT-40S units on the Lomonosov barge are under construction in Russia.

People's Republic of China

The People's Republic of China is the fastest growing nuclear energy market in the world. According to the "Mid- to Long-Term Nuclear Development Plan (2011-2020)" issued in October 2012, China aims to have 58 GW (net) in operation by 2020, and 30 GW under construction at that time. China's nuclear energy programme began in the 1980s, and its first reactor started commercial operations in 1994. Of the 27 units currently under construction, eight are of Gen III design (four AP1000, two EPR, two VVER), 18 are of Gen II design, and one is a prototype reactor with Gen IV technology features. The country's nuclear fleet is based on technology developed nationally as well as technologies transferred from Canada, France, Japan, the Russian Federation and the United States.

Following the Fukushima Daiichi accident, China revised its targets for nuclear from 70-80 GW to 58 GW by 2020 with another 30 GW under construction. Safety requirements were also enhanced, and only Gen III designs will now be approved in China. The Hualong-1 and CAP1000 designs will represent the bulk of the new developments. The latter design is based on Westinghouse's AP1000 design. China will deploy the technology domestically, including on inland sites, and hopes to begin exporting the technology with a larger version, the CAP1400, also being designed. China's nuclear programme has evolved significantly in the last decade with more rapid development of domestic reactor designs and domestic supply chains. The country has made an impressive transition from importing nuclear technology to developing local capabilities that have already been exported.

Local air pollution concern from coal-fired plants is one of the main drivers today of nuclear power development in China. Other key drivers include improved energy security, and stable and economic electricity production costs. With China's impressive rates of economic development and continued urbanisation, the demand for electricity is expected to continue its rapid ascension. The attractive economics of nuclear power, stable base-load operations and siting near the main demand centres along the Eastern coast, combined with its environmental benefits, make it an attractive alternative to coal-fired power.

Continued training and development of a skilled nuclear workforce focused on safety culture will be the biggest challenge to meeting China's ambitious nuclear targets. Also, for the deployment of NPPs inland, the issue of cooling on rivers with degraded water quality due to pollution or low flow rates will need to be addressed.

India

India has been developing nuclear energy technology since the 1950s, and its first reactor began operations in 1969. As it is not party to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), India's nuclear industry has essentially evolved indigenously, with a longer-term objective of developing nuclear power reactors that can operate on the thorium cycle, the country having significant thorium reserves and very little natural uranium reserves. India has a long history of nuclear energy R&D and is currently constructing a sodium-cooled fast breeder reactor which could operate on the thorium cycle. India expects to have an estimated 20 GW of nuclear capacity by 2020 and has announced ambitious targets to increase the share of nuclear electricity in the following decades. It is estimated that India could become the third-largest nuclear energy country in the world by 2040.

Rapid economic and population growth, combined with increased urbanisation, are expected to fuel strong electricity demand. The need for reliable base-load electricity at competitive costs is the main driver for nuclear energy development in India. Other drivers include enhanced energy security and local pollution concerns. Financing and public acceptance are challenges that will need to be overcome as India seeks to expand its nuclear power supply. Opening the Indian nuclear market to foreign investment and technology is another challenge. Although the country has seen two Gen III Russian VVER reactors built at the Kudankulam site (in the frame of an intergovernmental agreement), other vendors have not yet penetrated the market. Many co-operation agreements have been signed and joint ventures set up between engineering and supply chain companies to prepare the ground for future projects with high levels of localisation. Remaining difficulties include the Indian nuclear liability legislation adopted in 2010 – more specifically, whether it is consistent with the internationally accepted nuclear liability principles – and the cost of foreign nuclear technologies.

Middle East

The Bushehr NPP in Iran that began commercial operation in September 2013 was the first nuclear power plant to operate in the Middle East. The United Arab Emirates (UAE) is the most advanced newcomer country in the region, with construction started on three of four units of the Korean-designed APR1400 (the construction of the third unit stated in 2014), which will have a total installed capacity of 5.6 GW, at the Barakah site. The first unit is expected to start generating electricity in 2017, and the final unit is scheduled for operation in 2020. With electricity demand expected to exceed 40 GW by 2020, nearly doubling 2010 levels, the UAE has identified nuclear energy as an important source of future electricity supply. Electricity needs are currently met almost exclusively by natural gas. As a proven, cost-competitive and low-carbon source of electricity, UAE is developing nuclear power to provide a significant source of base-load electricity.

With rapid electricity demand growth expected over the next decades, some countries in the region are looking at nuclear power to improve energy security through energy diversification and also to reduce domestic consumption of natural gas and oil, freeing up more resources for export. In addition to rising electricity demand, the region's rising demand for fresh water makes desalination from nuclear an attractive opportunity in the mid to long term. Saudi Arabia has announced plans to construct 16 nuclear reactors with a total capacity of 17 GW by 2032 and hopes to have its first reactor operating by 2022. Jordan is also planning the construction of up to two reactors and signed an agreement with Russia in October 2013.

For the Middle East, the main challenges in developing nuclear power will be in setting up the needed nuclear infrastructure and training, as well as the education of a highly skilled nuclear work force. The region is working closely with the IAEA to set up the necessary infrastructure and the UAE's implementation of the IAEA milestones has been recognised as exemplary (see Box 4). For oil- and gas-rich countries in the region, overcoming these challenges has been facilitated by the significant resources made available to attract foreign experts, who provide training thereby passing

Box 4: IAEA Milestone Approach for national nuclear infrastructure: UAE experience (Case study 4)

To help guide newcomer countries in the development of a nuclear energy programme, in 2007 the IAEA released a publication outlining the major milestones to be achieved in establishing the required infrastructure for the development of nuclear power.* This guideline, known as the IAEA Milestone Approach, consists of 19 elements that are central to the development of a nuclear programme. Each element contains detailed conditions that should be met over three milestone phases. The UAE has worked in close partnership with the IAEA in the development of its nuclear energy programme and the IAEA has provided support on legal and regulatory framework, licensing, infrastructure and capacity building, safeguards implementation and peer reviews. On the request of the UAE, the IAEA undertook an Integrated Nuclear Infrastructure Review (INIR) in January 2011.

The review team concluded that the UAE had accomplished all of the conditions to enter phase 2. The review team recognised 14 good practices, which other countries developing nuclear infrastructure should consider. The UAE's experience with developing a national nuclear infrastructure and its establishment of a regulatory framework and system has been impressive. However, it should be noted that the UAE's success implementing its nuclear programme in such a relatively short timeframe – nine years from the publishing of its nuclear policy to commissioning of the first unit, as opposed to the 10-15 years estimated by the IAEA – benefited from the ability to hire personnel with a cumulative experience of over 100 years in the Federal Authority for Nuclear Regulation (FANR) and the Emirates Nuclear Energy Corporation (ENEC), the owner and operator of the future plant. This was made possible by the availability of significant financial resources from the government. New nuclear countries are advised to work closely with the IAEA and other relevant organisations and countries with extensive operating experience in the development of their programmes.

* Further details of the IAEA milestones to be found at www-pub.iaea.org/MTCD/publications/PDF/Pub1305 _web.pdf.

their expertise and knowledge on so that local expertise and capacity are developed. However, there remains some concern about the availability of highly skilled and experienced nuclear experts if nuclear programmes are to develop extensively in the region.

Other developing Asian countries

Among developing Asian countries, Viet Nam is the most advanced with respect to its nuclear programme. The country has committed plans for developing nuclear and is in the process of developing its legal and regulatory infrastructure. Viet Nam is planning at least 8 GW of nuclear capacity by the end of the 2020s and hopes to have a first unit in operation by 2023. Bangladesh is also planning to start the construction of its first reactor by 2015. Thailand and Indonesia have well-developed plans but have yet to make a firm commitment, while Malaysia is currently studying the feasibility of developing an NPP. The Philippines, which began construction of a nuclear plant in the late 1970s (never completed), is suffering from electricity shortages and high electricity costs, and is still considering nuclear as a possible future option. Singapore is monitoring the progress of nuclear energy developments to keep its options open for the future. In these countries, SMRs could potentially offer an alternative to larger Gen III units, as they would be more easily integrated in small electricity grids.

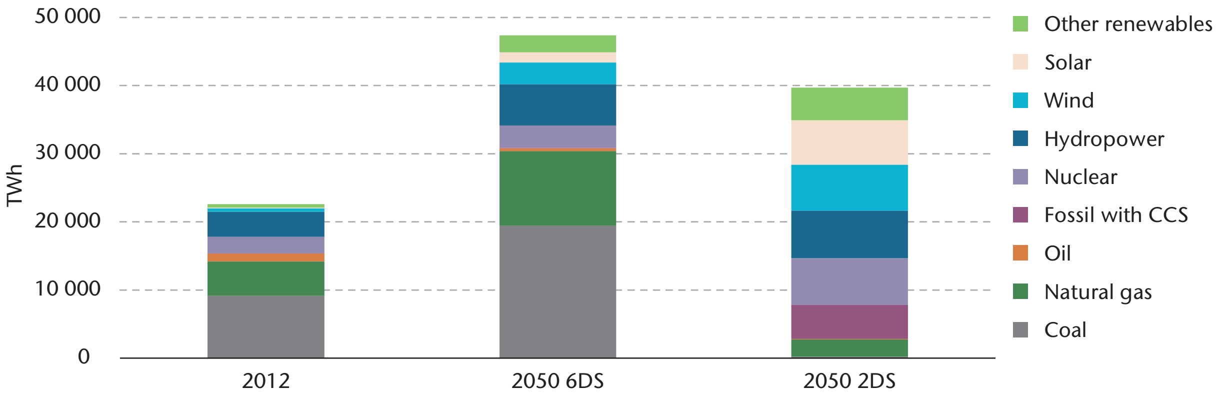
Strong expected electricity demand growth and stable electricity production costs are the main drivers for nuclear development in the region. For Viet Nam, Thailand and the Philippines, which import the majority of their energy needs, nuclear would help to improve energy security and reduce dependence on imported fossil fuels. For these newcomer countries, the development of the necessary nuclear regulatory infrastructure, a skilled nuclear workforce, financing, and public acceptance are major challenges to the development of nuclear energy. International collaboration to support the development of a regulatory infrastructure, as well as training and capacity building to develop local expertise, are needed.

Vision for deployment to 2050

The vision presented in this *Roadmap* is based on the *Energy Technology Perspectives 2015* (*ETP 2015*) (IEA, 2015) 2°C Scenario (2DS) which calls for a virtual decarbonisation of the power sector by 2050 (see Box 5). A mix of technologies including nuclear, carbon capture and storage, and renewables will be needed to achieve this decarbonisation. In the *ETP 2015* 2DS, the share of nuclear power in global electricity production is projected to rise from 11% in 2011 to 17% in 2050. Renewables will account for the largest share of production at 65%, with variable renewables supplying 29% of total global electricity production (see Figures 3). The high share of variable renewables, which in some countries reaches well over 40%, significantly changes the operating environment of nuclear. Nuclear power is traditionally operated to meet base-load demand, although it can be operated in load-following mode, with less flexibility than gas-fired peaking plants.

Regionally significant differences exist in terms of nuclear energy's contribution to decarbonising the electricity sector with many countries such as Finland, Russia and South Africa projecting shares of nuclear at 20% or above in 2050 under the 2DS. The Republic of Korea and countries in Eastern Europe have the highest share of nuclear reaching nearly 60% and 55% respectively. The share of nuclear in the three largest nuclear producers – China (19%), India (18%) and the United States (17%) – show similar or slightly higher shares to those reported globally.

Figure 3: Electricity production by technology in the 6DS and the 2DS



Revised targets for nuclear compared with the 2010 *Roadmap*

Since the release of the nuclear energy *Roadmap* in 2010, two major factors have led to a downward revision of the *ETP 2015* 2DS projections for growth in nuclear power capacity at the global level. The first is the Fukushima Daiichi accident, which led many countries to re-evaluate the role of nuclear power within their electricity mix, and the second is the faster-than-anticipated declines in busbar costs[4] of solar photovoltaics (PV) and onshore wind. Enhanced safety standards for nuclear plants following Fukushima Daiichi, as well as an increase in raw materials prices, design complexity, and supply chain quality requirements, have led the assumptions for nuclear costs to be revised upwards by about 20% compared with 2010 estimates. These factors, combined with reductions in the costs assumed for solar PV and onshore wind, have impacted the competitiveness of nuclear energy. As a result, the *ETP 2015* 2DS projections for nuclear power capacity in 2050 were revised to just over 930 GW, compared with 1 200 GW in the 2010 Nuclear *Roadmap*. Despite this downward revision, growth in nuclear still represents more than a doubling of nuclear capacity, which in 2014 was approximately 396 GW.

Under the *ETP 2015* 2DS, growth in nuclear capacity will be driven by non-OECD countries (see Figure 4). Currently, OECD member countries, Russia and the Ukraine account for over 90% of

4. Busbar costs, also known as levelised costs of electricity, refer to total costs of electricity generation including, fuel costs, operating and maintenance costs as well as total costs of financing.

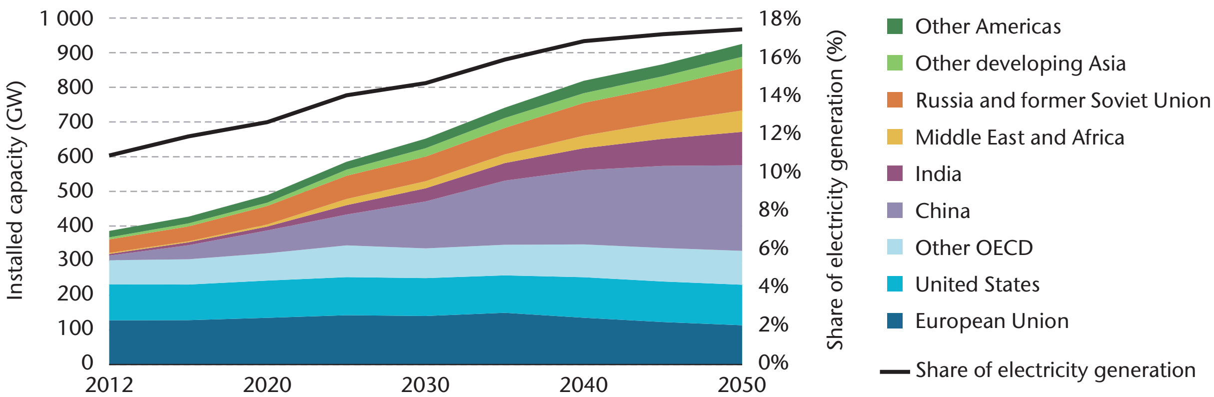
Box 5: *Energy Technology Perspectives 2015* 6DS and 2DS

This *Roadmap* is based on the IEA *ETP 2015* analysis, which describes diverse future scenarios for the global energy system in 2050. The base case scenario, the 6 degrees Celsius scenario (6DS), which is largely an extension of current trends, projects that energy demand will almost double during the intervening years (compared to 2009), and associated CO_2 emissions will rise even more rapidly, pushing the global mean temperature up by 6°C.

The IEA *ETP* 2DS describes how technologies across all energy sectors may be transformed by 2050 to give an 80% chance of limiting average global temperature increase to 2°C. It sets the target of cutting energy-related CO_2 emissions by more than half by 2050 (compared with 2009) and ensuring that they continue to fall thereafter. The 2DS acknowledges that transforming the energy sector is vital but not the sole solution: the goal can only be achieved if CO_2 and greenhouse gas emissions in non-energy sectors (such as agriculture and land-use change) are also reduced. The 2DS is broadly consistent with the *World Energy Outlook* 450 Scenario through to 2035.

The model used for this analysis is a bottom-up TIMES (The Integrated MARKAL-EFOM System) model that uses cost optimisation to identify least-cost mixes of technologies and fuels to meet energy demand, given constraints such as the availability of natural resources. The *ETP* global 28-region model permits the analysis of fuel and technology choices throughout the energy system, including about 1 000 individual technologies. The TIMES model is supplemented by detailed demand-side models for all major end uses in the industry, buildings and transport sectors.

Figure 4: Nuclear generation capacity in the 2DS by region



total installed capacity. In 2050, these countries combined will see only a modest increase in capacity from 350 GW to 400 GW. With a number of countries planning to phase out nuclear and with older plants reaching the end of their operating lifetimes in the next decades, the EU will see its capacity decline from 2040, while in Russia and the Republic of Korea, which show the largest increase in growth, capacity will more than double by 2050.

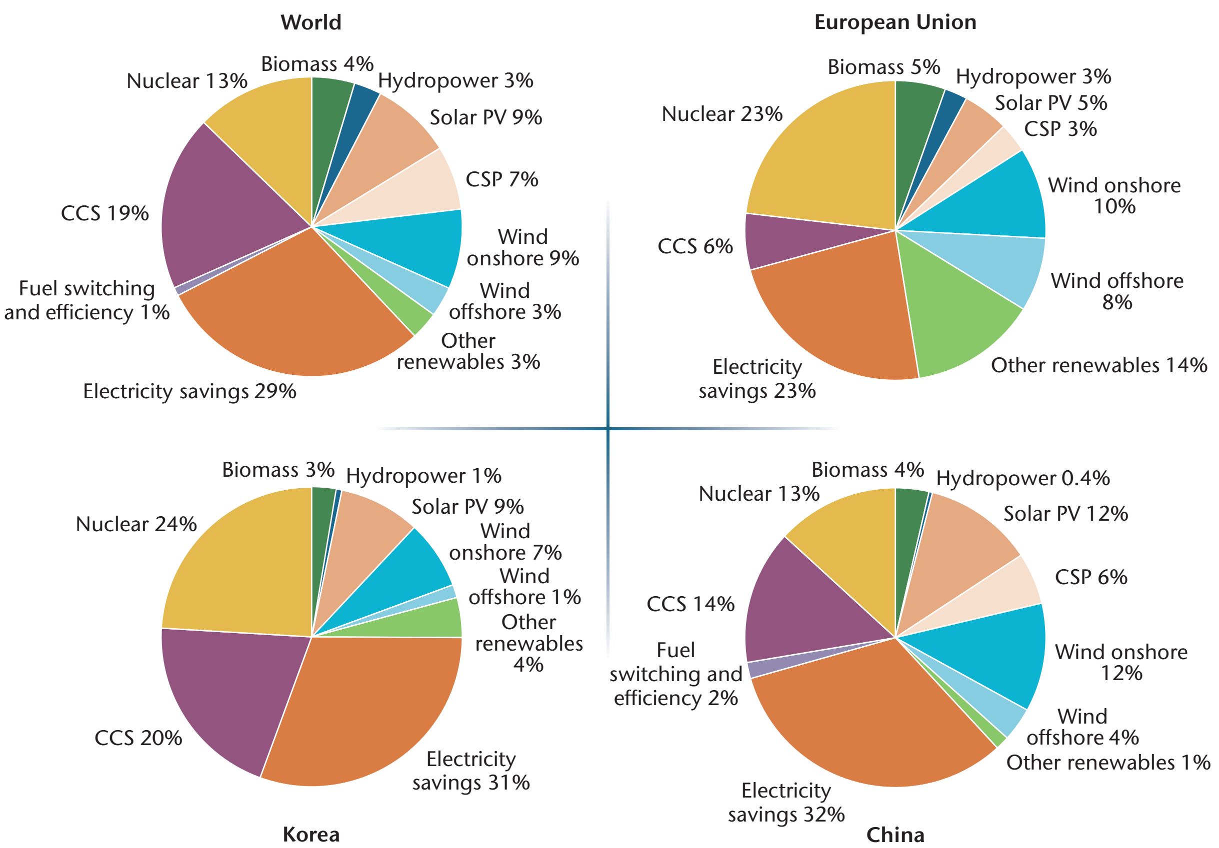
Growth in nuclear capacity will be led by China, which under the 2DS could surpass the United States by 2030 and, with 250 GW of nuclear, would have more than twice the installed capacity in the United States in 2050. India, which represents the second-fastest growing market for nuclear, would have about 100 GW of capacity in 2050, making it the third-largest market for nuclear after the United States. Other growth markets for nuclear include the Middle East, South Africa and ASEAN (Association of Southeast Asian Nations) countries.

Emissions reductions from nuclear

Nuclear energy currently contributes to a reduction of CO_2 emissions from the power sector of about 1.3 to 2.6 gigatonnes (Gt) of CO_2 every year, assuming it replaces either gas- or coal-fired generation. It is estimated that since 1980 the release of over 60 Gt CO_2 has been avoided thanks to nuclear power.[5] The contribution of nuclear energy to decarbonising the electricity sector would result in annual CO_2 emission reductions of 2.5 Gt CO_2 in the 2DS compared with the 6DS (see Figure 5). Globally, this represents 13% of the emissions reduction needed in the power sector with the contribution in different regions varying from as high as 24% in the Republic of Korea to 23% in the European Union and 13% in China. Nuclear clearly plays an important role in providing reliable, low-carbon electricity in most regions of the world.

5. The avoided CO_2 emissions were calculated by replacing nuclear generation by coal-fired generation.

Figure 5: Emissions reduction in the power sector in 2050 in the 2DS



Global investment in nuclear to 2050

An estimated investment cost of USD 4.4 trillion would be needed to reach the 930 GW of installed capacity under the *ETP 2015* 2DS by 2050. About 40% of these investments (USD 2.0 trillion) would be required in OECD member countries to extend lifetimes of existing plants, to replace retiring plants and to add new capacity. China, which accounts for one-third of capacity in 2050, would need to invest approximately a quarter of the overall investment cost, or just over USD 1 trillion in new nuclear capacity.

Table 2: Investment needs in the 2DS (USD billion)

Country/region	2012-20	2021-30	2031-40	2041-50	2010-50
United States	90	216	288	118	713
European Union	113	168	259	164	704
Other OECD	83	153	178	162	577
China	209	309	350	157	1 025
India	21	120	114	158	412
Middle East and Africa	18	70	82	133	303
Russia and former Soviet Union	96	94	176	182	548
Other developing Asia	14	68	40	31	153
Other Americas	12	5	3	6	25
World	656	1 210	1 493	1 115	4 473

Regional costs assumptions for nuclear

The lower share of total investments compared to capacity in China reflects the regional differences in overnight costs[6] for nuclear power. China's average overnight cost of approximately USD 3 500/kilowatts (kW) is less than two-thirds of the European Union's cost of USD 5 500/kW. Costs in the United States are about 10% lower than the European Union, but still 30% higher than in China and India, and 25% above the Republic of Korea. Higher costs in the European Union and the United States can be attributed to a lack of recent experience in building new nuclear plants compared to Asia, as well as to higher labour costs for engineering and construction. In the 2DS, 2050 assumptions for overnight costs of nuclear in the United States and European Union are estimated to decline somewhat, reaching levels closer to those in the Republic of Korea, while costs in Asia are assumed to remain flat.

6. Overnight costs include the cost of site preparation, construction and contingency costs.

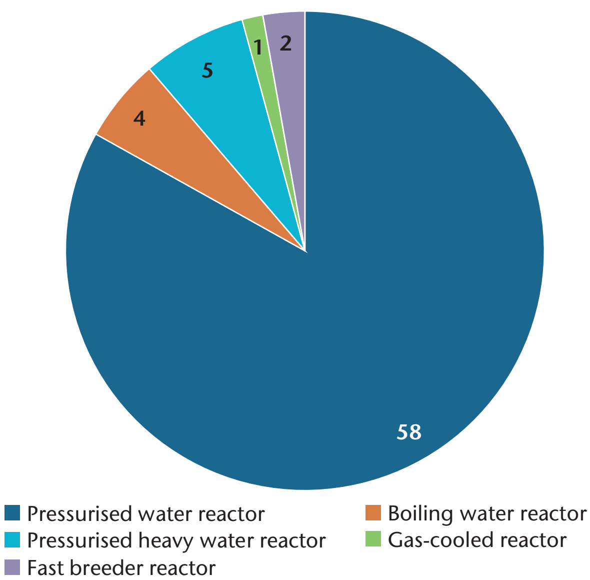
Nuclear energy technology development: Actions and milestones

Reactor technology

This Roadmap recommends the following actions:	Proposed timeline
Governments to recognise the value of long-term operation to maintain low-carbon generation capacity and security of energy supply, provided safety requirements are met. Clearer policies are needed to encourage operators to invest in both long-term operation and new build so as to replace retiring units.	2015-30
R&D in ageing of systems and materials is needed to support safe, long-term operation of existing nuclear power plants (NPPs) for 60 years operation or more.	Ongoing
Vendors to optimise Gen III designs to improve constructability and reduce costs. The learning rate from new build construction needs to be accelerated by rapidly integrating lessons learnt from FOAK projects (design optimisation, project management, supply chain, interactions with regulators) to ensure that NOAK plants are built on time and to budget.	Ongoing
To open up the market for small modular reactors (SMRs), governments and industry should work together to accelerate the development of SMR prototypes and the launch of construction projects (about 5 projects per design) needed to demonstrate the benefits of modular design and factory assembly.	2015-25
Governments to recognise the long-term benefits of developing Generation IV (Gen IV) systems in terms of resource utilisation and waste management, and support R&D and development of at least one or two Fast Breeder Reactor Gen IV prototypes.	2015-30
Public-private partnerships need to be put in place between governments and industry in order to develop demonstration projects for nuclear cogeneration in the area of desalination or hydrogen production.	2015-30
Incorporate feed-back from operation of Gen IV prototypes to develop FOAK Gen IV commercial plants.	2030-40

As of end of December 2014, there were 438 operable nuclear reactors in the world, representing about 396 GW (gross) capacity. Nearly 82% of those reactors are light water reactors (LWRs), 63% of which are pressurised water reactors (PWRs) and 19% boiling water reactors (BWRs). Eleven percent of the world's reactors are pressurised heavy water reactors (PHWRs), operating mainly in Canada (the CANDU technology ["CANada Deuterium Uranium"]) and in India. A little more than 3% of the world's fleet consists of gas-cooled reactors (GCRs), all in operation in the United Kingdom. Most of these will be retired within the next decade. Another 3% consist of graphite-moderated light water-cooled reactors (LWGR), which are better known under their Russian abbreviation RBMK. These reactors are today only in operation in Russia and will probably be retired before the end of the next decade. Finally, 1 out of the 438 reactors is a sodium-cooled fast breeder reactor (FBR), an example of one of the main technologies of future Gen IV reactors, and a further 2 are expected to be connected in 2015.

Figure 6: Reactor types under construction worldwide (2014)



Source: IAEA/PRIS.

Even more interesting are the technology types for the 70 reactors under construction (see Figure 6). Nearly 89% are LWRs, mostly PWRs, with PHWRs representing the second technology of choice (7%), all being built in India with indigenous technology. There are two FBRs under construction, one in Russia (BN-800) and one in India (PFBR), and both are to be connected to the grid in 2015. Finally, there is one GCR under construction, a high-temperature reactor being built in China.

From these trends, one can observe a consolidation of reactor technology towards LWRs. Nearly half the reactors under construction are Gen III LWR reactors, which have enhanced safety features (i.e. systems to mitigate the risk of severe accidents) and improved fuel economy performance compared to the Gen II reactors. There is also a continued but more limited development of PHWR as India continues its domestic programme. PHWRs are also being pursued in other countries as a means to derive additional energy from used PWR and BWR fuel through the development of recycled uranium (RU) and mixed oxides of plutonium and uranium (MOX) advanced fuel cycles. Both China and India are considering PHWR designs for a thorium fuel cycle. Advanced reactors such as FBRs or high-temperature reactors will be developed as well but at a much smaller scale. SMRs will also be developed, especially those that rely on LWR technologies, though their deployment is not expected to be significant by 2030. At that time, one can expect the world's nuclear fleet to be more homogenous than at the present time in terms of reactor technology, with the retirement of all the old GCRs (in the United Kingdom) and LWGRs (in Russia) expected by 2030.

Technological trends that will shape the future of the nuclear fleet include: managing the existing fleet to allow for safe and economical long-term operation; continuous development of Gen III water-cooled technologies with a focus on simplification, standardisation and cost reduction; more innovative development of reactor technologies including SMRs, Gen IV reactors and non-electric applications of nuclear energy to address the need for low-carbon process heat, actinide management, district heating, or desalination. R&D in nuclear fusion will continue for the next decades, but given the challenges still to be addressed, fusion reactors are not expected to be deployed in the first half of this century.

Safety upgrades and long-term operation

Nuclear reactor operators in the world today face two challenges. The first is to implement the recommended safety upgrades that were identified during the post-Fukushima safety evaluations, (with most operators having already started this work). Although the reviews concluded that these reactors were safe and could continue to operate, a number of actions and upgrades were recommended that include the reinforcement of NPPs against major seismic hazards and floods, multiple external events affecting multi-unit sites and severe accidents as well as improved emergency preparedness. Rapid implementation of these safety upgrades under the supervision of nuclear regulators, as well as better information on the safety of NPPs, are necessary to reduce public concern.

The second challenge is to continue to operate reactors economically, especially given the average age of the nuclear fleet. This means that operators have to address long-term operation issues. Provided safety requirements are met, long-term operation is needed to maintain capacity in low-carbon generation and is one of the lowest cost options to produce low-carbon electricity. R&D in ageing and improved safety is needed to support this objective. Research into back-fitting requirements for 60+-year operations is also required. Very often, long-term operation retrofits and safety upgrades can be combined to upgrade NPPs in a cost-effective manner.

In 2013, 316 out of the 434 operating reactors in the world (73%) were more than 25 years old, and many of those could be retired in the coming decades, leading to a dramatic decrease in nuclear capacity. Thus, extending the operating lifetime of reactors to enable them to operate safely beyond their original design lifetime until they are replaced by new reactors[7] is essential to maintaining low-carbon generation capacity. In 2012, the NEA published a report on the *Economics of Long-Term Operation of Nuclear Power Plants* (NEA, 2012b), concluding that, in nearly all cases, continued operation of NPPs for at least a decade more than the original lifetime is profitable, even taking into account the cost of post-Fukushima safety upgrades. However, this can be undermined by market conditions. In the United States, competitiveness of NPPs in deregulated markets

7. *ETP 2015* assumes 60 years for NPPs in the United States and 55 years for other countries, with the exception of NPPs already scheduled to shut down.

is being undermined by the low cost of gas. In Europe, introduction of large shares of renewables is driving down wholesale electricity prices, affecting the competitiveness of dispatchable technologies, nuclear included.

Power uprates have contributed to a significant increase in capacity over the last two decades at a time when new build rates were low – Sweden's current ten-reactor fleet capacity, for instance, was increased to compensate for the closure of two units. The potential for further uprates in the United States and in a number of other countries is now limited, but there is still potential to exploit uprates in other European countries and in Russia.

Regulatory processes to approve the extension of operating reactors' lifetimes vary from country to country, but essentially fall into two classes: periodic safety reviews (i.e. every ten years) or licence renewal. In the United States, where 93 reactors out of 100 in operation at the end of 2013 were more than 25 years old, a regulatory process has been developed under the so-called 10 CFR Part 54 rule, entitled "Requirements for Renewal of Operating Licences For Nuclear Power Plants", published in 1991 and amended in 1995. Environmental impact assessments are also required to examine the possible environmental impacts that could occur as a result of renewing any commercial NPP licence. As of December 2014, 74 reactors in the United States had been granted a licence renewal, allowing them to operate up to 60 years, and the applications for 19 other reactors were under review.

Extensive refurbishment and replacement of equipment is usually carried out as part of the process to extend the lifetime of an existing plant. In addition, a number of technical and scientific studies are necessary to assess the integrity and safety of components and systems that cannot be replaced, such as pressure vessels or containment buildings. Research has been carried out, for instance, by the European network NUGENIA ("NUclear GENeration II and III Association"), or in the United States, by the Electric Power Research Institute and Nuclear Energy Institute (see Box 6), and continues to be performed in the areas of material performance and ageing – for reactors 60 years of age or more – as well as monitoring and equipment qualification.

The prospect of obtaining regulatory approval for long-term operation is not enough to encourage operators to invest in the refurbishment needed to meet safety and performance requirements. There needs to be a clear national policy on long-term operation, whether it is allowed from a political point of view or whether limits are set as to the lifetimes of existing reactors. Some countries have clear policies. In Canada, for instance, the Ontario Long-term Energy Plan has committed to refurbish nuclear units at the Darlington and Bruce Generating Stations, with the potential to renew up to 8 500 megawatts (MW) nuclear capacities over 16 years.

Box 6: Research for extended operation (beyond 60 years) of NPPs (Case study 5)

The current fleet of US NPPs was licensed initially to operate for 40 years. To date, 74 reactors have received 20-year licence renewals and 19 applications are under review. Twenty-four reactors have already passed the 40-year mark and are operating safely and reliably with renewed licences in this extended period. By 2040, it is estimated that half the fleet will turn 60 and, if these reactors are retired, the country might face possible shortages of electricity and will certainly lose diversity of supply. Hence, research is ongoing to develop the technical and scientific knowledge needed to support nuclear plant operation beyond 60 years, up to 80 years or beyond. The Electric Power Research Institute, the US Department of Energy (DOE) (which has an extensive network of national laboratories), and several universities are conducting research on management of ageing in NPPs in order to understand and devise strategies to identify and mitigate the effects. The research is essentially dedicated to the long-lived components that are not replaced during regular refurbishments. These include the containment building and the reactor vessel, and can also include piping and electric cables.

New reactor development

Most of the anticipated growth in nuclear capacity in the coming decades will come with the deployment of "large" Gen III reactors (in the range 1 000-1 700 MW unit size, see Table 3), either PWRs or BWRs, though some deployment of SMRs, PHWRs or Gen IV reactors. Gen III reactors have enhanced safety features and higher efficiency, as well as improved fuel economy compared with Gen II reactors.

Only evolutionary changes and innovations in Gen III technology are foreseen up to 2050, with efforts to simplify and standardise the designs. This will help to improve their constructability and modularity which should reduce costs and shorten construction spans.

Following the Fukushima Daiichi accident, the safety of existing reactors was assessed by regulators for the type of events that led to the accident, as well as for other beyond-design-basis accident conditions and safety upgrade measures taken to improve the resistance of these plants. For Gen III reactors, very few design changes were recommended, since these plants already take severe accidents into account in their design. More focus is being placed, however, on the qualification of systems designed to mitigate severe accidents, and more research on severe accident management is being performed, in particular on decay heat removal, core degradation mechanisms and hydrogen risk management.

Table 3: Examples of Gen III reactor designs

Vendor	Country	Design	Type	Net capacity (MW)	In operation*	Under construction*
AREVA	France	EPR	PWR	1 600	0	4 (Finland, France, China)
AREVA/MHI	France/ Japan	ATMEA	PWR	1 100	0	0
CANDU Energy	Canada	EC6	PHWR	700	0	0
CNNC-CGN	China	Hualong-1	PWR	1 100	0	0
GE Hitachi – Toshiba	United States/ Japan	ABWR	BWR	1 400-1 700	4 (Japan)	4 (Japan, Chinese Taipei)
GE Hitachi		ESBWR	BWR	1 600	0	0
KEPCO/KHNP	Korea	APR1400	PWR	1 400	0	7 (Republic of Korea, United Arab Emirates)
Mitsubishi	Japan	APWR	PWR	1 700	0	0
ROSATOM	Russia	AES-92, AES-2006	PWR	1 000-1 200	1	10 (Russia, Belarus, China, India)
SNPTC	China	CAP1000, CAP1400	PWR	1 200-1 400	0	0
Westinghouse/ Toshiba	United States/ Japan	AP1000	PWR	1 200	0	8 (China, United States)

*: As of 31 December 2014.

Cost reduction of Gen III reactors is an objective shared by all vendors and operators which can be achieved through a number of options including design simplification, standardisation, improved constructability, modularity and supply chain optimisation, as well as by taking full advantage of lessons learnt during the FOAK projects.

In terms of operation, base-load power production is the most cost efficient way to operate an NPP. Having large shares of variable renewable electricity production will require more thermal plants to deal with backup and provide flexibility. Thus, there needs to be a better integration of nuclear, thermal and renewables from an electricity system and market perspective, to avoid loss of production and improve cost efficiency, taking into account the peculiarities of each technology. Operators supply electricity to customers in a competitive marketplace, where overall cost is an important parameter.

In the long term, there is also a need to take into account possible changes in the climate to ensure that NPPs are resilient both in the face of extreme weather events as well as under higher ambient air and cooling water conditions. Issues such as increased risk of flooding through intense precipitations, storms or sea level rise need to be addressed, by designing appropriate barriers and selecting less exposed sites. The availability and quality of water for cooling of NPPs will also be a matter for concern, especially for inland plants located on rivers that use once-through cooling. High cooling water temperatures reduce the thermal efficiency and electrical output of NPPs, and this can be compensated by more efficient heat exchangers. Closed cycle cooling or advanced cooling technologies that reduce the consumption of water, as well as the use of non-traditional sources of water (treated waste water, for instance), will need to be developed.

SMRs

SMRs could perform a useful niche role as they can be constructed in regions or countries that have small grid systems that cannot support larger NPPs, or they can address specific non-electric applications such as district heating or desalination. However, the economics of SMRs have yet to be proven. Interest in SMRs is driven both by the need to reduce the impact of capital costs and to provide power and heat in small or off-grid systems. For some SMR designs, the use of passive safety systems also represents an attractive feature, allowing, for example, decay heat removal in the case of accidents without the need for operator intervention. The creation of a market for SMRs will first require successful deployment of FOAK reactors in the vendor's country before other countries will consider deploying the technology. Unless governments and industry work together in the next decade to accelerate the deployment of the first SMR prototypes that can demonstrate the benefits of modular design and construction, the market potential of SMRs may not be realised in the short to medium term.

Table 4: Examples of small modular reactor designs (under construction or with near-term deployment potential)

Vendor	Country	Design	Type	Net capacity (MW)	In operation*	Under construction*
Babcock & Wilcox	United States	mPower	PWR	180	0	0
CNEA	Argentina	CAREM-25	PWR	25	0	1
CNEC	China	HTR-PM	HTR	210	0	Twin units
CNNC	China	ACP-100	PWR	100	0	0
KAERI	Korea	SMART	PWR	110	0	0
NuScale	United States	NuScale SMR	PWR	45	0	0
OKBM	Russia	KLT-40S	Floating PWR	2x35	0	Twin units (one barge)

*: As of 31 December 2014.

There are different types of SMRs, some already under construction in Argentina (CAREM), China (HTR-PM) or Russia (KLT-40S), others with near-term deployment potential such as mPower, NuScale, the Westinghouse SMR or the Holtec design in the United States, and SMART in the Republic of Korea, and others with longer-term deployment prospects (liquid metal-cooled reactor technologies) including designs of dedicated burner concepts for countries having to dispose of plutonium stockpiles. The KLT-40S (for electricity generation, heat processing and possibly desalination) are mounted on the Lomonosov barge and suited to isolated coastal regions or islands.

Table 4 gives an overview of SMRs under construction or with near-term deployment potential. SMRs can address complementary markets (countries with small grids, and/or geographical constraints, or cogeneration applications), and could be competitive with other forms of generation suitable for those markets, depending on the manufacturing and construction rates. The competitiveness of SMRs compared with large nuclear reactors, in countries where both could be accommodated, needs to be assessed in a systems approach, where both generation and grid requirements are accounted for.

The United States has had a very active SMR programme over the last years. Its objective is to accelerate the timelines for the commercialisation and deployment of these technologies by developing certification and licensing requirements for US-based SMR projects through cost-sharing agreements with industry partners, as well as to resolve generic SMR issues. SMRs in the United States could replace coal-fired power plants that do not meet newly released emissions regulations. Two SMR technologies have been selected so far by the DOE, Babcock & Wilcox's (B&W) mPower design and Nuscale's SMR design. Though industry was hoping to find customers for near-term deployment of their SMR designs, it seems that customers in the United States are not yet ready for SMR technology. B&W has reduced the scale of the mPower development programme, while Westinghouse, which also developed an SMR design, is concentrating its development efforts on the AP1000 design.

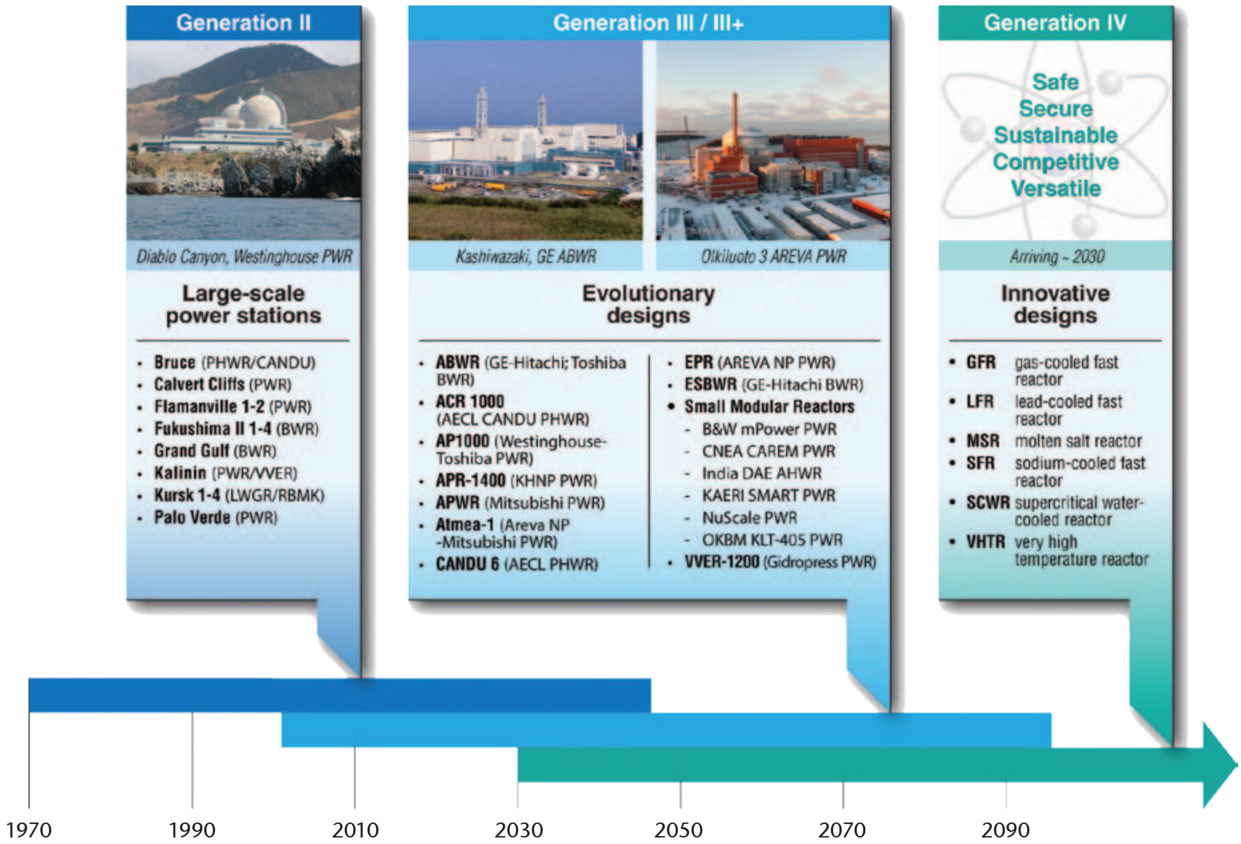
Generation IV reactors

The Generation IV International Forum (GIF), a framework for international co-operation in R&D for the next generation of nuclear energy systems, was launched in 2001 by Argentina, Brazil, Canada, France, Japan, the Republic of Korea, South Africa, the United Kingdom and the United States. Switzerland, the European Commission, China and the Russian Federation have since joined this initiative. The goals set forward for the development of Gen IV reactors are improved sustainability, safety and reliability, economic competitiveness, proliferation resistance and physical protection. GIF published *A Technology Roadmap for Generation IV Nuclear Energy Systems* in 2002, which describes the necessary R&D to advance six innovative designs selected as the most promising: the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), the molten salt reactor (MSR), the sodium-cooled fast reactor (SFR), the supercritical water-cooled reactor (SCWR) and the very-high-temperature reactor (VHTR). A *Technology Roadmap Update for Generation IV Nuclear Energy Systems* was published in 2014 (GIF, 2014), and assesses progress made in the first decade, identifies the remaining technical challenges and the likely deployment phases for the different technologies. It also describes the approach taken by GIF to develop specific safety-design criteria for Gen IV reactors, building on lessons learnt from the Fukushima Daiichi accident.

According to the GIF 2014 *Technology Roadmap Update for Generation IV Nuclear Energy Systems*, the first Gen IV technologies that are the most likely to be demonstrated as prototypes are the SFR, the LFR, the supercritical water-cooled reactor and the VHTR technologies. Benefits of fast reactors include a better use of the fuel – for the same amount of uranium, fast reactors can produce 60 or more times the energy than Gen III LWRs by multi-recycling of the fuel – and improved waste management by reducing long-term radiotoxicity of the ultimate waste. The main advantage of the SCWR is its improved economics compared to LWRs, which is due to higher efficiency and plant simplification. The benefits of VHTRs include the passive safety features of high-temperature reactors and the ability to provide very-high-temperature process heat that can be used in a number of cogeneration applications, including the massive production of hydrogen.

As seen in Figure 7, the start of the deployment of Gen IV reactors is not foreseen before 2030. For many decades after that, Gen IV reactors will likely be deployed alongside advanced Gen III reactors, but in far smaller numbers. Yet, because of the potential benefits that these reactors can bring, R&D and demonstration projects, especially in the area of fuels and materials that can withstand higher temperatures, higher neutron fluxes or more corrosive environments, are needed to bring concepts towards commercialisation. Prototype development and testing is seen as particularly important. Construction and operation of Gen IV prototypes in the period 2020-30 are necessary if Gen IV technology is to be deployed commercially from 2030 onwards.

Figure 7: Evolution of fission reactor technology



Source: Generation IV International Forum, www.gen-4.org.

A number of countries are already pushing ahead with the design and/or construction of reactor prototypes that prepare the ground for future Generation IV designs. For fast reactor technology, the Russian Federation, which has a long history of operating sodium-cooled reactors – the 600 MW BN600 reactor, connected to the grid in 1980, is the world's largest sodium reactor in operation – is in the process of commissioning the 800 MW BN800 reactor and designing an even larger reactor called BN-1200, which could be deployed by 2030. France is moving ahead with the detailed design study of the advanced sodium technological reactor for industrial demonstration (ASTRID) reactor, which could be completed by 2019. China is operating the China experimental fast reactor (CEFR), a 20 MW research reactor connected to the grid in 2011, and is designing a 1 000 MW prototype reactor. Finally, India, which is not a member of GIF, has been working on sodium-cooled FBRs for decades, for their potential to operate on the thorium cycle, and is planning to start the commissioning of the 500 MW prototype fast breeder reactor (PFBR) before the end of 2014. Modular SFRs, such as the PRISM reactor ("Power Reactor Innovative Small Module") based on the integral fast reactor technology developed in the United States in the 1980s, are also being considered by some countries as part of a plutonium (from reprocessed spent fuel) recycling strategy.

Box 7: Nuclear fusion: A long-term source of low-carbon electricity

Nuclear fusion, the process that takes place in the core of our Sun where hydrogen is converted into helium at temperatures over 10 million °C, offers the possibility of generating base-load electricity with virtually no CO_2 emissions, with a virtually unlimited supply of fuel (deuterium and tritium, isotopes of hydrogen), small amounts of short-lived radioactive waste and no possibility of accidents with significant off-site impacts. However, the road to nuclear fusion power plants is a long route that still requires major international R&D efforts. The International Thermonuclear Experimental Reactor (ITER) is the world's largest and most advanced fusion experiment, and is designed to produce a net surplus of fusion energy of about 500 MW for an injected power (to heat up the plasma) of 50 MW. ITER will also demonstrate the main technologies for a fusion power plant. According to the *Roadmap to the Realisation of Fusion Electricity* (EFDA, 2012), ITER should be followed by a prototype for a power-producing fusion reactor called DEMO. During the period from 2021 to 2030, exploitation of ITER and design and construction of a prototype for a power-producing fusion reactor called DEMO.

DEMO should demonstrate a net production of electricity of a few hundreds of MW, and should also breed the amount of tritium needed to close its fuel cycle. Indeed, while deuterium is naturally abundant in the environment, tritium does not exist in nature and has to be produced. Thus, it is essential that tritium-breeding technology is tested in ITER and then demonstrated at large scale in DEMO. DEMO will also require a significant amount of innovation in other critical areas such as heat removal and materials. Beyond the demonstration of fusion power, the success of the technology as a source of electricity will require that it is competitive with respect to other low-carbon technologies such as renewables or nuclear fission. Major efforts in reducing the capital costs of fusion reactors through optimised designs and materials will be needed.

As far as high-temperature reactors are concerned, China is building a first prototype (HTR-PM), a twin-unit 210 MW prototype to be used for electricity generation. China has been operating a 10 MW research reactor (HTR-10) for more than a decade. The deployment of high-temperature reactors will depend essentially on the development of non-electric applications such as desalination or industrial process heat (see section below).

Fusion reactors: Beyond 2050

The *Roadmap* covers the development of technologies for NPPs up to 2050 and their contribution to the decarbonisation of the global electricity generation sector in the 2DS. All of today's NPPs, whether Generation II-type plants that constitute the bulk of today's fleet or the new Gen III plants that are being deployed, rely on nuclear fission as the source of heat. More innovative nuclear technologies, such as SMRs or Gen IV nuclear energy systems also rely on nuclear fission. Fusion reactors have more long-term deployment perspectives than Gen IV reactors, which are anticipated to be deployed in parallel with more advanced light water reactor designs from around 2030-40. According to the recently published *Roadmap* on fusion energy (EFDA, 2012), no industrial fusion reactor is foreseen before the second half of the century (see Box 7).

Non-electric applications of nuclear energy

Nuclear cogeneration, in particular but not exclusively with high-temperature reactors, has significant potential, and nuclear energy could target markets other than just electricity production, offering low-carbon heat generation alternatives to fossil-fired heat production. This would have several benefits, such as reducing greenhouse gas emissions from industrial heat applications, and it would improve the security of energy supply in countries that import fossil fuels for such applications. Although not widespread, nuclear cogeneration is not an unproven concept; in fact, there is significant industrial experience of nuclear district heating, for example in the Russian Federation and in Switzerland. In the latter country, the Beznau NPP (2x365 MW) has been providing district heating for over

25 years. About 142 GWh heat is sold each year to nearly 2 500 customers, thus avoiding about 42 000 tonnes CO_2. Nuclear district heating is an option that is being considered for some new build projects, for instance in Finland or in Poland.

Cogeneration could also provide "energy storage" services by allowing NPPs to switch from electricity to heat or hydrogen production while maintaining base-load operation, depending on the price of electricity on the wholesale market (for instance, when a large inflow of wind-generated electricity enters the grid). Hydrogen can then be converted back to electricity using fuel cells, or it can be injected into natural gas pipelines, providing additional revenue streams to the operator of the NPP. These are just some concepts of so-called "nuclear hybrid energy systems" that optimise the co-existence of nuclear and renewable technologies in future low-carbon energy systems.

Process heat applications, in particular those with a view to producing hydrogen (for transport or for the petrochemical industry or for coal to liquids), are one of the major non-electric applications of nuclear energy – high-temperature reactors, and in particular the Gen IV concept of VHTR, are well suited for this purpose. At present, the Republic of Korea is pursuing a programme that has the interest of one of the major steel manufacturers of the country. Other initiatives, in Europe, in Japan and in the United States, are looking at attracting industry support to nuclear cogeneration. The lack of a demonstration programme with a prototype high-temperature reactor coupled with a process heat application is seen as a major hurdle. Public-private partnership could be an effective way to initiate such a programme and demonstrate the benefits of using nuclear reactors as a source of low-carbon electricity and process heat.

There is also a potential for desalination to become a new market for nuclear power. The production of fresh water during off-peak hours would allow NPPs to operate economically well above usual base-load levels. The Middle East region, which gathers half of the world's desalination capacities (using gas and oil-fired processes) is also likely to experience a significant growth in nuclear electricity generation, which could be coupled with desalination. Many SMR designs, for instance the Korean SMART, the Chinese ACP-100 or the Russian KLT-40S, target desalination markets, but no firm project has yet been launched. Challenges include the development of a robust business model that includes the operator of the NPP, the operator of the desalination plant and the customers of the electricity and water produced by the cogeneration plant.

Nuclear fuel cycle

This roadmap recommends the following actions:	***Proposed timeline***
Investments in environmentally sustainable uranium mining should be developed to address expected long-term demand.	2015-35
Governments to continue to co-operate to discuss international fuel services as a means to secure the development of nuclear power.	Ongoing
Governments should ensure that policies are in place for long-term storage and disposal, including deep geological disposal (DGD) of high-level waste, and should not defer nuclear waste planning – "wait and see" is not an option.	2015-50
Studies should be carried out to ensure that extended (dry) storage of spent nuclear fuel (SNF) satisfies the highest safety and security requirements.	Ongoing
Governments to continue to support R&D in advanced recycling technologies to reduce volume and toxicity of high-level waste.	Ongoing

Every year, about 11 000 tonnes of heavy metal (tHM) of used fuel is unloaded from the world's reactors. This annual discharge rate will increase as the number of reactors in operation increase.

Uranium supply is currently more than adequate to meet demand up to 2035 and beyond (NEA/IAEA, 2014). However, given the long lead time of mining projects, it is recommended that investments and the promulgation of best practices continue to be made so as to develop environmentally safe mining operations.

The current world market for fuel services (uranium supply, conversion, enrichment services, fuel fabrication) provides a considerable degree of security of supply and thus can play a major role in supporting the further development of nuclear energy. Increased security of supply can also be achieved through intergovernmental or international agreements dealing with fuel leasing and fuel banks. Maintaining the highest levels of nuclear security for transport of nuclear material from providers to customers is essential.

In terms of enrichment, laser enrichment is a technology that could potentially bring costs down, but this needs to be proven at industrial scale. There is no clear push at present to accelerate its deployment. Since the Fukushima Daiichi accident, there has been a renewed interest in the development of so-called accident-tolerant fuels, which is designed to offer additional coping times to operators in case of a severe loss of coolant accident. However, there is a long way ahead to develop and qualify these fuels and this will depend on the level of budgets devoted to this research.

Research into advanced fuel cycles, and in particular into partitioning and transmutation, is ongoing. The objective of this research is to allow for the recycling of reusable material from spent fuel and separate elements such as minor actinides that are responsible for the thermal load and radiotoxicity of high-level waste. These can be conditioned and disposed of, or burned within fast neutron reactors – as they are with some Generation IV concepts – or in dedicated burners such as accelerator-driven systems (ADS).

DGD is the recommended strategy for dealing with high-level waste, but it requires long-term planning, political commitment and strong engagement with local communities. Finland, Sweden (operating once-through cycles) and France (recycling route) will be the first countries to have operational DGDs in the 2020s (see Box 8). The Radioactive Waste Directive adopted by the EU in 2011 requires all member states to draw up national programmes for the management of spent fuel and radioactive waste. The directive advocates the disposal of high-level waste in geological repositories and opens the possibility for regional repositories.

Box 8: Progress towards implementation of a deep geological disposal site in Sweden (Case study 6)

Sweden has for many decades been actively pursuing research activities for the development of a safe long-term concept and technology for geologic final disposal of SNF from existing nuclear power reactors. A final repository is now planned in Forsmark (Östhammar municipality) as well as an encapsulation plant in Oskarshamn. The construction and testing of the DGD will take place between 2019 and 2029, with the transfer of spent fuel from Clab to the DGD facility to start around 2029 until 2075. The characteristics of the KBS-3 DGD site are as follows:

- Multiple barrier geologic final disposal system based on copper canister, buffer and bedrock.
- Deposition of canisters vertically in tunnels at a depth of around 470 metres below surface. Tunnels and shafts will be refilled with bentonite buffer, clay and rock spoils.
- No surveillance or monitoring should be needed for safety or security reasons after decommissioning and closure.
- Surface area will be restored and impact on land use will be limited during operation and afterwards.

To achieve a successful implementation of a DGD project, a stepwise process with clear roles and responsibilities based on dedicated funding is necessary. Time, consistency, patience and a transparent and open listening approach are needed. A process based on voluntary participation from host municipalities with clarified withdrawal possibilities/conditions is recommended. It is also very important to include and explain alternatives (e.g. disposal options, choice of sites) from the beginning.

The concept of regional repositories should be evaluated in more detail, as it would offer countries with small nuclear programmes and geological and geographical limitations, the possibility to pool resources and find the most appropriate DGD site – in terms of geology, safety and economics – in another country.

Finally, in countries where there are no short- to medium-term prospects for having an operational DGD site, studies should be carried out to ensure that extended (dry) storage of SNF satisfies the highest safety and security requirements. However, this cannot be considered an alternative to DGD.

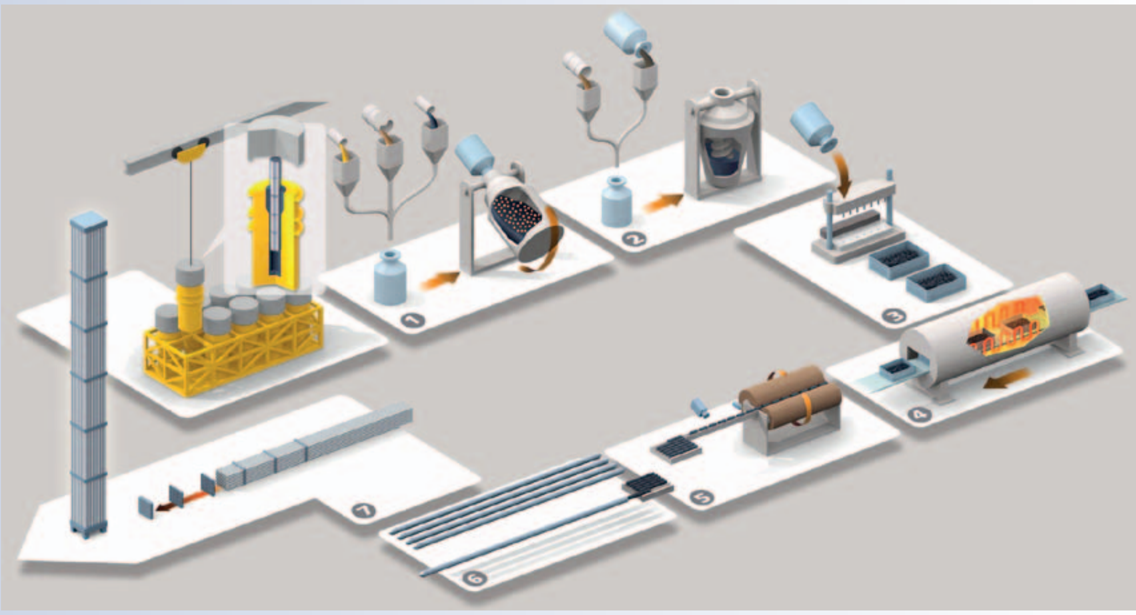
Recycling of spent fuel has advantages in terms of resource management (for instance, through the use of MOX fuel) but also in terms of conditioning of the high-level waste (vitrification process), and hence the sizing of the DGDs (see Box 9). Further progress is expected with the development of multi-recycling in fast neutron reactors (FNRs), and later with the industrial-scale demonstration of the use of minor actinide-bearing fuels, or targets in FNRs.

Other routes to recycling spent fuel can be offered by heavy water reactors operating in synergy with LWRs, as is currently being demonstrated in China, where a fuel consisting of recycled and depleted uranium was successfully irradiated in the Qinshan CANDU unit 1 (NEI, 2014).

Box 9: Recycling of spent fuel (Case study 7)

Used nuclear fuel recycling is today a fully industrial process with more than 45 years of experience, allowing reuse of uranium and plutonium to manufacture new nuclear fuel, while conditioning the non-reusable parts in a stable waste form. In France alone, more than 30 000 tonnes of used fuel has been reprocessed to date, of which 20 000 tonnes was from French reactors. This has effectively reduced the interim storage capacity for used fuel by 50%, while allowing up to 20% annual savings on natural uranium consumption. The main steps of the process are the separation of reusable and non-reusable materials, conditioning of the non-reusable material and the fabrication of new fuel.

Figure 8: MOX fuel fabrication



Source: AREVA.

Decommissioning

This roadmap recommends the following actions:	*Proposed timeline*
Governments need to ensure that dedicated funds are set aside for decommissioning activities and that operators accumulate sufficient funding during the operation of NPPs to cover the future costs of decommissioning these facilities. Operators should regularly review the adequacy of the accrued funds.	Ongoing
Nuclear operators to ensure that shutdown nuclear facilities are decommissioned in a timely, safe and cost-effective manner.	Ongoing

Decommissioning will become an increasingly important part of the nuclear sector activity in the coming decades, as dozens of reactors will be shut down. Industry must provide further evidence that it can dismantle these plants safely and cost-effectively. Further improvements in technology (for instance, robotics) and adaptation of regulations (for instance, allowing the clearance of non-radioactive material from a power plant as ordinary or municipal waste) can help to reach these objectives. It is important that decommissioning activities are covered by sufficient funds, and governments have a responsibility to ensure that this financial security is in place. In most countries, operators are required to set aside dedicated funds, the costs of which are internalised in the cost of nuclear electricity.

Once a nuclear facility is closed permanently, whether it is for technical, economic or political reasons, it needs to be put into a state where it can do no harm to the public, workers or the environment. This includes removal of all radioactive materials, decontamination and dismantling, and finally demolition and site clearance. This process, known as decommissioning, consists of several stages that can take place over many years. The general public is often not well informed about decommissioning activities, and the ill-founded belief that decommissioning of nuclear facilities is an unsolved issue is one of the factors that can explain poor public acceptance of nuclear power.

This *Roadmap* recognises that decommissioning is a significant challenge given the size of the fleet that will be retired in the coming decades. However, it is also a great opportunity for new business and skills to be developed. Demonstrating that NPPs that have been shut down can be dismantled safely and in a financially controlled manner is a key factor for allowing new build projects to move ahead. Today, decommissioning is a well-regulated activity of the nuclear fuel cycle, with specific safety guides and standards (e.g. IAEA, Western European Nuclear Regulators Association [WENRA]). As of December 2014, 150 power reactors had been permanently shut down and were in various stages of decommissioning. International information exchange forums exist, where processes are reviewed, lessons learnt and best practices shared. But it is also an area of technological expertise where operators and new industries compete (see Box 10).

There are essentially two main strategies for decommissioning: (i) immediate dismantling, where after the nuclear facility closes, equipment, structures, and radioactive materials are removed or decontaminated to a level that permits release of the property and termination of the operating licence within a period of about 10 to 15 years; (ii) deferred dismantling, where a nuclear facility is maintained and monitored in a condition that allows the radioactivity to decay – typically for about 30-40 years, after which the plant is dismantled and the property decontaminated. A third strategy exists called entombment, where all or part of the facility is encased in a structurally long-lived material. It is not a recommended option, although it may be a solution under exceptional circumstances (such as after a severe accident).

Increasingly, utilities are choosing the immediate dismantling option, to benefit from the knowledge of the plant's operating staff, as well as to limit the burden borne by future generations.

Box 10: Decommissioning in Germany (Case study 8)

German utility E.ON has gained substantial experience in the direct dismantling of Stade NPP (a 630 MWe PWR) and Würgassen NPP (a 640 MWe BWR) over the past 15 years. E.ON's NPPs Isar 1 (878 MWe BWR) and Unterweser (1 345 MWe PWR) reactors were both shut down in 2011 as a result of the phase-out policy, and the company has started the preparation for the decommissioning of these units. E.ON's expertise relies on a number of technologies that it has developed and mastered, as well as on qualified staff and established processes and practices, including radiation protection, surveillance, material and surface decontamination, and project and team management.

A key aspect of any decommissioning project is the planning phase, starting from the back end, in particular the disposal of the radioactive waste. Critical path analysis is required to avoid any bottlenecks in the project (related to easy-to-use decommissioning technology, interference between parallel dismantling work packages, licensing or staffing aspects) and ensure that all phases run smoothly. The purchase and delivery of containers and casks licensed for the storage and transport of waste also has to be planned and controlled carefully.

In addition to planning, challenges exist in managing financial and human resources: as funds are based on current decommissioning cost estimates, project management is crucial to ensure that the work is performed within the expected budget. From a human resource point of view, the challenge is to motivate staff who have worked part of their professional lives to maintain the existing asset. However, as decommissioning is the final end in the lifetime of the plant, the company has to develop career paths to keep staff motivated so that they will participate in the decommissioning project and remain within the company once the plant has been dismantled.

Although technologies and processes for decommissioning an NPP exist today, further technological developments and process improvements can help accelerate future decommissioning activities and reduce costs. For example (E.ON, 2014):

- improve standardisation in the design
- improve automation
- develop more flexible remote controlled tools
- develop tools to measure decontamination during the processes
- improve techniques for decontamination.

Facilitating the deployment of nuclear technologies: Actions and milestones

In this chapter, actions that can facilitate the deployment of nuclear technologies by 2050 are identified. They cover a wide range of areas such as licensing and regulation, nuclear safety, financing, training and capacity building, codes and standards, supply chain and localisation issues, communication and public acceptance. International collaboration plays an important role in facilitating information exchange between governments and experts to ensure the development of nuclear energy in countries wanting to use nuclear power is efficient and meets the highest standards of safety, security and non-proliferation. This is for instance the mission of the International Framework for Nuclear Energy Cooperation (IFNEC).

Licensing and regulation

This roadmap recommends the following actions:	*Proposed timeline*
Governments must ensure that regulators are strong, independent and staffed with enough skilled, competent and adequately remunerated personnel to carry out their missions.	Ongoing
International co-operation should continue to be promoted, whether among industry (e.g. WANO or the World Nuclear Association [WNA]) or regulators (IAEA, the Western European Nuclear Regulators Association [WENRA], the Multinational Design Evaluation Programme [MDEP], NEA Committee on Nuclear Regulatory Activities [CNRA]) or technical organisations.	Ongoing
Licensing frameworks for advanced reactors, including SMRs and Gen IV reactors need to be developed.	2015-30
Site analysis including Environmental Impact Assessments and stakeholder consultations to be carried out thoroughly prior to the development of new nuclear projects, taking into account lessons learnt from the Fukushima Daiichi accident and the possible effect of Climate Change in the long term, so as to ensure a high level of public support for the projects.	Ongoing

Regulators, whether in newcomer countries or established nuclear countries, should be strong and independent. They need to have sufficient, well-qualified and resourced staff to carry out their missions (NEA, 2014a). There is an important role for international organisations to promote efficient regulation, harmonise requirements and share experience (see Box 11). In particular, peer review processes, whether among operators or among regulators, is seen as an effective process to improve the overall level of nuclear safety.

The nuclear industry is sometimes concerned about the risk of over-regulation, through the multiplication or duplication of regulatory requirements. Better co-ordination and harmonisation of these requirements is needed in order to have an efficient regulation of the industry.

Finally, to accelerate the deployment of new technologies, licensing frameworks should be flexible enough to regulate such technologies in a risk-informed manner. The United States is addressing this challenge for SMRs through the DOE's Licensing Technical Support programme, which supports the development of certification and licensing requirements for US-based SMR projects. Similar initiatives should be launched in other countries, for SMR and advanced technologies such as Gen IV designs, so as to facilitate the deployment of these technologies once they have been demonstrated. It should be noted, however, that there are examples of regulatory regimes around the world (United Kingdom and Canada) whose frameworks already contain this flexibility and are prepared to address SMRs and Gen IV technologies. In general, greater international collaboration is needed so that a design approved in one major nuclear-competent country can be built elsewhere with a minimum of duplicated effort and time.

Box 11: International collaboration among regulators: The Multinational Design Evaluation Programme (MDEP) (Case study 9)

MDEP was established in 2006 as a multinational initiative to develop innovative approaches to leverage the resources and knowledge of the national regulatory authorities that are currently or will be tasked with the review of new reactor designs. MDEP has evolved from primarily a design evaluation programme for two new reactor designs (EPR and AP1000) to a multinational co-operation programme involving several new reactor designs and issues related to new reactor challenges.

MDEP gathers the nuclear regulatory authorities of 14 countries. It has five design-specific working groups (EPR, AP1000, APR1400, ABWR and VVER) and three issue-specific working groups (digital instrumentation and control, mechanical codes and standards and vendor inspection co-operation). MDEP produces common positions and technical reports for public use. Design-specific common positions describe common conclusions reached by the working group members during design reviews. MDEP has also encouraged international organisations to work together on the harmonisation of standards. MDEP has been a decisive trigger for their co-operation and will continue to encourage such initiatives, including the standard development organisations' code convergence board and WNA/CORDEL's working groups ("World Nuclear Association's working group on Cooperation in Reactor Design Evaluation and Licensing").

Siting and planning

Siting of nuclear facilities is an essential part of a nuclear programme, and it is one which requires thorough analysis, as well as interactions with local communities well ahead of any decision. The analyses supporting site suitability, although established at the onset of a project, need to be revisited periodically throughout the lifecycle of the facility to confirm that the design continues to be adequate in the face of changing site characteristics. Characteristics may also change as a result of new analysis techniques. There are many guidelines on how to carry out siting activities (IAEA, 2012). Criteria for assessment and selection of suitable sites for the construction of NPPs include:

- health, safety and security factors
- seismicity of the site, and vulnerability to extreme natural or man-made events
- engineering and cost factors (for instance, availability of cooling water, electricity infrastructure, distance to load centres)
- socio-economic factors
- environmental considerations.

For the siting and analyses, environmental impact assessment (EIA) processes should be carried out (see Box 12). It should also be mentioned that when an operator wants to operate a facility beyond the original design lifetime, or when the design conditions change (for instance, due to power uprates), an EIA should be performed again to take into account the new operating and environment conditions. At all stages of siting, stakeholder involvement in the decision-making process is necessary.

Following the Fukushima Daiichi accident, renewed attention has been paid to the vulnerability of existing (and future) sites with respect to the possibility of major earthquakes and flooding, whether from tsunamis or other causes (dam breaks, extreme precipitation events). This may reduce the number of possible new sites that a country can select for its nuclear programme. Another aspect that has received more attention is the particular case of multi-unit sites, i.e. sites that accommodate several nuclear reactors.

Building several hundreds of GW of new capacity by 2050 will require the extension of existing sites to accommodate additional units, if the sites are suitable, as well as the assessment and selection of new sites. For countries that already have nuclear power plants (NPPs), it is often easier to consider building nuclear facilities on existing sites as local communities are already informed about the risks and benefits of nuclear energy.

Box 12: Environmental impacts assessments in Finland (Case study 10)

In Finland, EIAs are an integral part of the licensing process for nuclear facilities. An EIA is a procedure that ensures that the environmental implications of decisions are taken into account before the decisions are made.

In Finland, EIAs cover the whole lifetime of the nuclear facility, as well as the front and back ends of the nuclear fuel cycle. Of particular importance are aspects related to the use of cooling water (large quantities of water are needed to cool NPPs and thermal releases can be significant), impact on fauna, flora and biodiversity, and nuclear accidents and their consequences. An EIA typically lasts for about a year. An essential part of the EIA process is the consultations with civil society through public hearings.

In 2008, the Finnish company TVO performed an EIA related to the expansion of the Olkiluoto NPP (two units in operation, one unit under construction), adding fourth unit, OL-4. The report addresses the impacts during construction, operation (including impact on land use, air quality, water system and fishing industry) of exceptional situations such as accidents or phenomena related to climate change.

Nuclear safety

This roadmap recommends the following actions:	***Proposed timeline***
Operators of NPPs to implement post-Fukushima safety upgrades in a timely manner.	2015-25
Safety culture needs to be enhanced and monitored across the nuclear sector (operators and industry, including the supply chain, and regulators) and at all levels of staff.	Ongoing
Governments should support efforts in safety research, and ensure that results are communicated to a wide audience.	2015-25

In parallel to the safety upgrades that were requested after the Fukushima Daiichi accident, enhanced safety requirements were put in place by regulators to ensure that nuclear plants operate to even higher safety standards. Japan in particular reviewed and reorganised its regulatory system, establishing its independence and setting out new safety requirements (see Box 13). The country's 48 reactors will now be assessed against these new standards before they can be allowed to restart. At the end of 2014, four units had been approved for restart by the Japanese regulator. In the European Union, the Nuclear Safety Directive was amended in July 2014 based on the lessons learnt from the Fukushima Daiichi accident, the EU "stress tests" and the safety requirements of the Western European Nuclear Regulators Agency and the IAEA.

In the Russian Federation, the regulatory framework is now being updated to take into account the "stress test" results and lessons learnt from Fukushima Daiichi accident, in particular with regard to requirements for special procedures beyond-design-basis accidents and severe accidents management. Requirements accounting for external, natural and human-induced impacts at NPP designing and siting, (as well as combination of such impacts) and requirements for the contents of safety analysis reports are also considered.

Safety assessment methodologies, such as probabilistic safety assessment (PSA) methods, are also being improved and further developed. Recommendations for level two and three PSAs of external events or fire and flooding have been revised and their use encouraged as a tool to improve on-site and off-site emergency planning. In general, governments should devote more efforts to safety research, including severe accident research, and the results communicated to a wider audience.

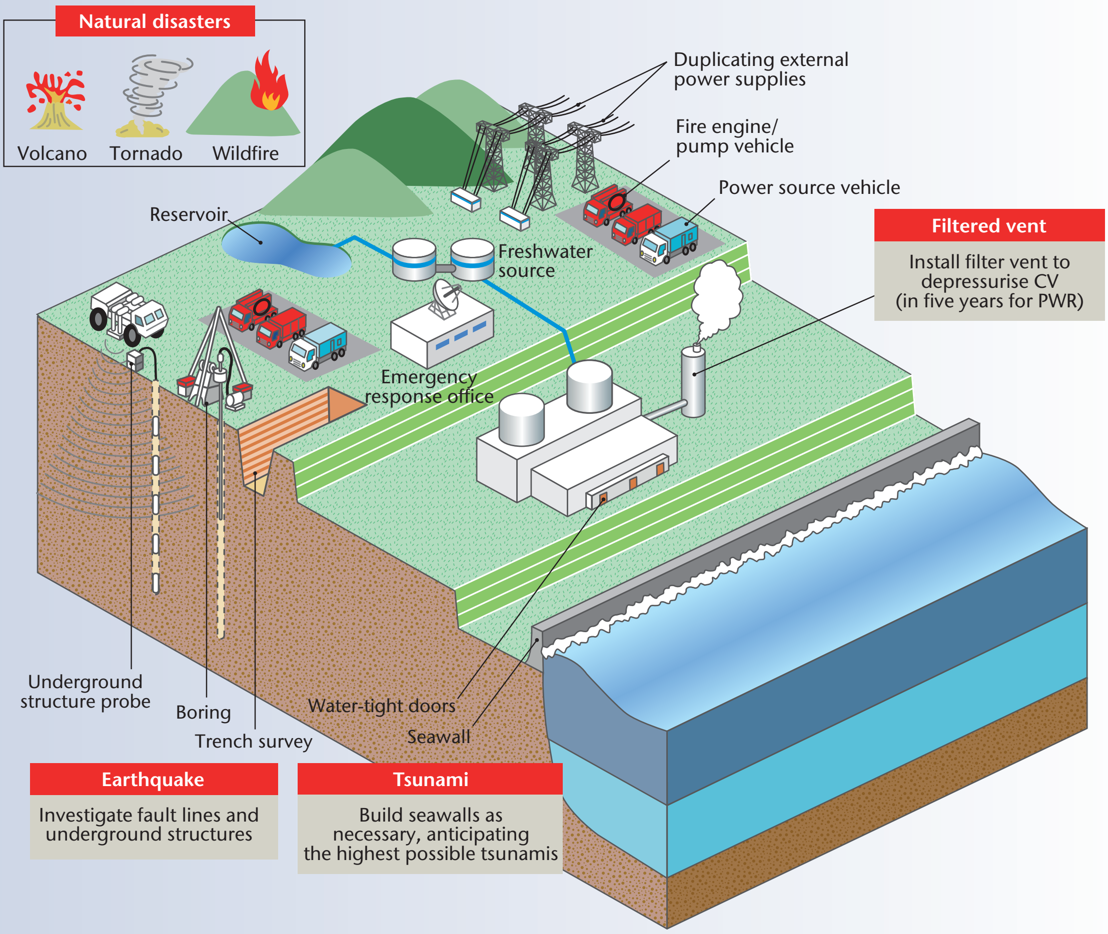
The Fukushima Daiichi NPP accident emphasised the importance of promoting safety culture across organisations. Safety culture can be defined as a set of characteristics and attitudes in organisations and individuals. that ensures that nuclear safety issues receive appropriate attention as an overriding priority over other considerations.

Safety culture needs to be enhanced across the whole nuclear sector (operators and industry, including the supply chain, and regulators) and at all levels of staff.

Box 13: New enhanced safety standards in Japan (Case study 11)

Following the Fukushima Daiichi NPP accident, Japan undertook a review of its nuclear regulatory structure and implemented significant reforms aimed at improving the nuclear industry's oversight and tightening safety requirements. The nuclear regulatory body was separated from nuclear promotion and the Nuclear Regulation Authority (NRA) was established as an independent commission. In addition to the administrative reform of Japan's nuclear regulatory institutions, new safety standards were introduced to prevent accidents with significant radioactive releases (Figure 9). Of the 48 NPP units in Japan, 17 are currently undergoing review by the NRA in accordance with these new enhanced safety standards. It is expected that a few of them could complete the review and could be considered ready to restart at the beginning of 2015. The restart of Japan's NPPs will help the country to significantly reduce CO_2 emissions from the power sector.

Figure 9: New enhanced safety requirements in Japan



Source: FEPC (Federation of Electric Power Companies of Japan) (2014), *Electricity Review Japan*, FEPC, www.fepc.or.jp/english/library/electricity_review_japan/_icsFiles/afieldfile/2014/07/11/2014ERJ_full.pdf.

Financing nuclear development

This roadmap recommends the following actions:	*Proposed timeline*
Governments favouring nuclear power to provide clear policies and a stable long-term strategy for nuclear development.	2015-25 and beyond
Governments should ensure price transparency and the stable policies required for investment in large capital-intensive and long-lived base-load power. Policies should support a level playing field for all sources of low-carbon power projects.	2015-20 and beyond
Loan guarantees by both vendor governments and host governments may be needed to reduce financing costs.	Ongoing
Governments to enable investment in low-carbon electricity sources through carbon trading schemes, carbon taxes or mandates for low-carbon electricity.	2015-35
Industry needs to develop communication strategies targeted at educating institutional investors and other financial institutions on the economic benefits of investment in NPPs.	2015-25
A refinancing strategy should be developed as part of a project financing plan and implemented once the plant is operational and construction risks are no longer applicable. Other strategies could include widening the source of financing to longer-term sources of financing such as pension funds and other institutional investors.	Ongoing
Industry needs to improve on its capacity to deliver "on time and to budget", thereby reducing the investment risks associated with construction and the need for government guarantees.	2015-20

An estimated USD 4.4 trillion would need to be invested in nuclear energy between 2011 and 2050 to reach the 930 GW of installed capacity under the 2DS. With an average NPP taking five to seven years to build and costing approximately USD 3.5 billion to 5.5 billion per plant, the financing of nuclear projects presents its own unique challenges. The risks associated with construction delays and cost-overruns are particularly important considerations in financing NPPs. Most plants under construction today have strong government involvement through state-owned enterprises or through loan guarantees, and are often government sponsored or financed projects. Few utilities today have the ability to develop new plants solely on their balance sheet without some sort of government guarantee or long-term power purchase agreement at predictable prices.

A clear commitment and long-term strategy for nuclear development at the national level is critical in raising financing for nuclear projects. Governments have a critical role to play in streamlining electricity market regulations to ensure that they work effectively and efficiently in order to limit the impact of associated risks on financing costs. The high investment cost of a nuclear plant means that its overall economics, and the feasibility of its financing, depend greatly on the cost of capital. This cost will be determined by the evaluation of various risk factors, and hence the key to successful financing is first to minimise the financial risks and then to structure projects using appropriate ownership and contracting models so that the remaining risks are appropriately shared among the parties involved.

The roles and responsibilities of different stakeholders such as the vendor, utility, host country, international contractors, local supply chain participants and regulators, as well as investors and financing institutions, need to be clearly defined. This will help to better allocate risks across relevant stakeholders. The main risks associated with nuclear plants are construction risks (cost and duration), electricity price risks and regulatory risks which can impact planning and construction times (nuclear safety regulation), as well as load factors (electricity market regulation).

In addition, country (political stability) and currency risks are also important but manageable via different hedging or insurance mechanisms or through government guarantees.

Electricity markets

Governments have a key role in providing sufficient confidence to investors in new generation projects. Clear and predictable long-term electricity prices that enable adequate return on investment are central to developing bankable projects. In regulated electricity markets, investor confidence can be gained via the regulated electricity price. Provided clear litigation clauses are included within contracts, investors are generally confident that utilities operating in regulated markets will be able to repay debts through electricity tariffs. These tariffs, which are fixed by the energy market regulator, on average cover the cost of fuel, operating and maintenance costs, waste management and decommissioning, depreciation, debt repayment and a return on capital. Regulated electricity markets effectively protect against construction and market risks, thereby facilitating the financing of large capital-intensive projects (see Box 14).

In liberalised markets, financing of nuclear energy can be significantly more difficult due to uncertainties in long-term electricity prices and hence higher interest costs. This is reflected in an increase in the cost of capital that makes most projects unattractive. To overcome these uncertainties, a long-term power purchase agreement such as the UK contract for difference (CfD) pricing model can provide the needed investor confidence to finance nuclear projects. The UK CfD fixes the price of energy from the plant, the "strike" price, and consumers are committed through legislation to pay or receive the difference between a market reference price and the strike price, depending on which one is higher. CfDs are designed to shield investors from power market volatility, particularly when there are expected to be high levels of intermittent

Box 14: Financing of new units at the Vogtle Power Plant in Georgia, USA (Case study 12)

The Southern Nuclear Operating Company is developing two new nuclear units at the Vogtle plant in Georgia, which already has two operating Westinghouse PWRs. This is the first nuclear reactor construction in the United States in 30 years and will consist of two AP 1 000 units of 1 200 MW each. Vogtle is operated by Southern Nuclear Operating Company and is owned by four companies: Georgia Power (45.7%), Oglethorpe Power (30%), MEAG Power (22.7%) and Dalton Utilities (1.6%). To facilitate the development of new advanced nuclear facilities, the United States government has established, under the 2005 Energy Policy Act, two forms of incentives. First, a production tax credit of USD 18 per megawatt hour is granted for the first eight years of operation of NPPs. Second, a system of loan guarantees is proposed that could cover up to 80% of the construction costs of a new advanced nuclear facility.

Market and regulatory conditions in Georgia also played an important role in the successful development of the nuclear new build at Vogtle. Georgia is a regulated electricity market, with a limited number of players and an overall limited level of competition. The particular structure of Georgia's electricity market, which ensures the stability of the demand and a low-risk environment for electricity generating companies, is favourable to the development of nuclear projects that are highly capital-intensive but can provide a lower and stable electricity generation cost in the long term. During the construction of Vogtle, Georgia Power was allowed to charge a construction work in progress (CWIP) tariff to customers, increasing electricity tariffs by about 7%. Under the CWIP, Georgia Power can more effectively meet the financial needs of a new nuclear build, which in turn will result in reducing long-term electricity cost for the customers. The two other main shareholders of Plant Vogtle have a similar company structure and electricity price arrangements that protect them effectively from construction and market risks.

renewables, which can drive electricity prices to zero or below in some extreme cases. This arrangement also helps offset future political risks or changes in government policies on nuclear energy. In the risk allocation, the developer of the nuclear project retains all project risk while vendors often carry most of the construction risk.

Carbon pricing remains the central pillar of any low-carbon policy. Whether as a carbon trading scheme, carbon tax or as a mandate on utilities to use low-carbon sources, incentives for investing in low-carbon energy are needed to help accelerate the deployment of nuclear energy. In the absence of a sufficiently high carbon price that reflects the externalities of fossil-fuelled generation, governments will have to continue providing policy solutions that improve the net present value of low-carbon investments and mitigate the market risks for project developers and financial investors.

Financing schemes supporting nuclear power development

Since the 2010 IEA/NEA *Technology Roadmap*: *Nuclear Energy*, two events have further added to the challenges of financing nuclear energy by commercial banks. The first is the adoption of Basel III regulations in the banking sector, which set limits to the amount that banks can lend and effectively reduced the availability of long-term debt. The second is the Fukushima Daiichi NPP accident, which led many banks to re-evaluate lending policies for nuclear projects. However, some of the banks that were financing nuclear projects before the accident appear to be considering financing nuclear projects again. Unfortunately, in many of the markets that have an interest in developing nuclear, the wholesale prices are extremely low, which for these capital-intensive projects, creates greater challenges for financing.

Governments and operators will need to review methodologies for estimating damages associated with nuclear accidents and for assessing their costs, and consider the implication for existing liability regimes. Sharing of lessons learnt that assist stakeholders in assessing improvements in technical areas, organisation management, planning and budgeting can result in risk profiles that are more acceptable to investors. Reputational risk considerations, environmental responsibility and commitment to international regimes and standards also need to be considered with respect to financing nuclear projects. The Fukushima Daiichi accident has led many banks to develop lending policies specific to nuclear energy, and some have adopted environmental and social guidelines, with projects classified according to their environmental and social impacts.

Government involvement in financing through Export Credit Agencies and in the form of government loan guarantees will remain critical for the nuclear industry as it will help to lower overall financing costs by hedging a number of risks including geopolitical, regulatory and construction risks.

Box 15: The Akkuyu build, own and operate model (Case study 13)

The Akkuyu NPP project will be Turkey's first NPP and also the first project to be built under a BOO financing model. Rosatom, Russia's state-owned nuclear company, is responsible for engineering, construction, operation and maintenance of the plant and will also initially hold 100% ownership. Akkuyu will have a total installed capacity of 4.8 GW comprised of four VVER1200 units (AES 2006 design), Gen III design with advanced safety requirements, and passive and active safety systems.

Initial funding for the project will be provided by Rosatom and up to 49% of the project may be sold to investors at a later stage. The total cost of the project is estimated at USD 20 billion and is backed by a 15-year power purchase agreement for 70% of the electricity generated by the first two units and 30% of the last two units at an average price of US cents 12.35/kWh.

Akkuyu has benefited from the strong support of both the Russian and Turkish governments, highlighting the importance of government-to-government relationships in the development of large nuclear projects. The Rosatom BOO model is an extremely attractive full-service model for new nuclear countries with limited expertise and resources. Under the BOO model, Rosatom will provide engineering, construction, operation and decommissioning services for NPPs.

Given the impact of recent events, vendor financing in the form of equity, for example, could increase as the utilities have become less effective at raising large amounts of long-term debt, or it has become uneconomical. Rosatom's "build, own and operate" (BOO) model is one example of this potential financing option (see Box 15). Most vendors are reluctant to engage in financing of nuclear projects, but current financing conditions could make it difficult to finance projects without such support. Vendor financing can address shorter-term financing constraints, but in the longer term a more sustainable model will be needed that allows utilities to finance these projects in the market. In certain regions, Islamic bonds could also be a potential financing instrument to support investments in nuclear projects.

The "Mankala" principle (co-operative model between shareholders) used in Finland is an original approach that brings together a consortium of electricity consumers (typically, energy-intensive industries such as pulp and paper, as well as municipalities) who have shares in the electricity generation plant, which can be a hydro-electric or an NPP. These shareholders receive the corresponding shares of electricity produced by the plant at full cost. Thus a Mankala-type project is not subject to electricity price risk, and its shareholders benefit from the equivalent of a long-term supply contract and stable electricity rates.

The role of development banks in the financing of nuclear plants is at present unclear. While they have financed past projects, development banks are not currently financing NPPs, but could potentially play a role in assisting developing countries interested in developing nuclear energy. For multilateral development banks, political factors and capital availability to fund such large projects will likely make it difficult for these institutions to fund entire projects. However, they could play an important role in catalysing higher levels of private finance by providing insurance against political risks.

Incentives for investment in low-carbon energy sources, such as carbon markets, carbon taxes and targets or mandates for carbon-free electricity supply could also encourage nuclear investments. Nuclear energy should be treated on an equal footing with other low-carbon technologies.

Finally, to help reduce the overall financing costs of an NPP, a refinancing strategy should be developed and implemented once the construction is completed and the plant is operational. With the construction risk no longer a factor, and the plant generating large cash flows, the risks associated with the project are significantly lowered and financing costs reduced. Refinancing could also free up much needed capital by the vendor or utility to invest in other projects.

Training and capacity development

This roadmap recommends the following actions:	***Proposed timeline***
Countries undertake a national skills evaluation to quantify the need for a skilled nuclear workforce to maintain the operation of existing fleets and for future decommissioning needs, as well as for nuclear new build, where relevant. Evaluation should also include requirements for nuclear regulators and researchers, as well as for the need to replace those due to retire.	2020-25
Newcomer countries should evaluate the need for skilled nuclear workers during the construction and operation phases, including for those who will be employed by nuclear regulators.	2015-25
Newcomer countries to develop local training programmes aimed at developing a nuclear-aware and nuclear-competent workforce.	2015-25
In countries with mature nuclear industries, companies and governments will need to implement programmes aimed at knowledge preservation of those workers who will be retiring in the next decades. Mentoring programmes could be implemented to ensure a transfer of knowledge; lessons learnt and best practice among operators, regulators, waste management and decommissioning experts.	2015-30

This roadmap recommends the following actions:	Proposed timeline
International co-operation is needed to help transfer nuclear training programmes from existing nuclear countries to newcomer countries. Opportunities will be needed for newly trained/educated workers to gain practical experience and develop and maintain skills while waiting for their countries nuclear fleet to begin operations.	2015-30
Existing nuclear countries with post-graduate nuclear training programmes should develop student exchange programmes aimed at newcomer countries. Where possible, these programmes should include a period of practical work experience at a nuclear facility and potentially the creation of equivalent training programmes in the newcomer country.	2015-30
Implement policies to attract and maintain highly skilled regulators.	Ongoing
International collaboration is needed to harmonise training programmes so as to develop mutual recognition of qualifications at an international level.	Ongoing

The distinctive characteristics of nuclear energy and its fuel cycle give rise to special requirements for education and training. In all countries with nuclear programmes, there exists a substantial nuclear fleet to be safely operated, maintained and eventually decommissioned. An essential element in the implementation and safe operation of all nuclear facilities, in addition to nuclear technology research and development (R&D), is a knowledgeable and skilled workforce. The importance of education and training in maintaining safety must be a priority for all nuclear countries. Although seen as two separate processes, education and training are intertwined in the preparation and maintenance of a competent nuclear workforce.

The future demand for global employment in nuclear-related activities is in the tens to hundreds of thousands of skilled workers (NEA, 2012c). The demand for nuclear skills are generally set against an ageing workforce, which highlights the urgency for targeted programmes to maintain an adequately skilled and competent workforce and attract a flow of new recruits for long-term sustainability. Policy decisions need to be made today to ensure that an adequate nuclear education and training infrastructure is available in the decades to come.

In 2012, the NEA published *Nuclear Education and Training: From Concern to Capability,* which assesses the current state of nuclear education and

Figure 10: An illustrative taxonomy: Sectors and functions

Nuclear power plant New build	▪ Design ▪ Supply	▪ Construction ▪ Commission
Nuclear power plant Operation	▪ Operation ▪ Maintenance	▪ Waste management ▪ Safety and environment
Nuclear power plant Decommissioning	▪ Decommissioning operation ▪ Maintenance	▪ Waste management ▪ Safety and environment
Nuclear research reactors	▪ Design and engineering ▪ Utilisation	▪ Operation and control
Nuclear regulation	▪ Assessment and review ▪ Authorisation	▪ Inspection and enforcement ▪ Regulation and guidance

Source: NEA (2012c), Nuclear Education and Training: From Concern to Capability, OECD/NEA, Paris.

training and identifies remaining gaps and actions that are required to address skills development needs in NEA member countries. Part of that work included the development of a classification system for nuclear job profiles or "job taxonomy". This taxonomy encompasses the full lifecycle of a nuclear reactor from new build to operation and decommissioning, as well as research and nuclear regulation, and classifies them according to functions (Figure 10). Each function of each sector contains a job specification which defines the occupational levels and competencies required, as well as sets of initial qualifications, advisory training and continuous professional development to support them. As only a few countries are active in the entire nuclear fuel cycle, the taxonomy did not cover fuel cycle issues.

Human resource assessments

Since a large number of workers in the nuclear energy sector will retire in the coming decades, policies must be put in place to ensure trained and qualified personnel and workers are available to support the development of nuclear programmes and the required regulatory function. In some countries, maintaining and attracting highly skilled regulators will need to be a priority. A number of countries have recognised this need and are promoting education and training programmes to increase human resources for the nuclear sector. Countries such as France, Japan, the Republic of Korea and the United Kingdom have implemented national assessments for nuclear human resource needs to maintain existing nuclear operations, as well as to staff new build construction and operation (see Box 16).

Box 16: Nuclear skills assessment in the United Kingdom (Case study 14)

The UK government recognised nuclear skills development as a key component in developing new nuclear build and set up the Nuclear Energy Skills Alliance to address current and future nuclear skill needs for the UK nuclear programme. The alliance brings together government, skills bodies, higher education and R&D communities to develop labour market intelligence for nuclear and to develop interventions and mitigation options that will ensure that the UK nuclear industry has the required skills to support current and future programmes. Based on scenario analysis for 16 GW of new build by 2025, the alliance estimated that 110 000 to 140 000 person years (excluding manufacturing) would be required to complete the programme and a peak annual employment of 14 000 in the period 2020-22.

A risk register was established to provide ongoing assessment that would be used to inform the evolving skills landscape. Of the 34 skill areas identified by the risk register, 13 were given a high priority rating. *Nuclear Labour Market Intelligence* was published in December 2012 and outlined a common skills delivery plan. The plan sets out 22 priority skill areas for the delivery of the UK nuclear programme and identified over 100 key actions. A combination of qualitative and quantitative assessments can be used to support national skill assessments, which should be regularly monitored and updated as a country's programme evolves.

In newcomer countries, training of personnel in preparation of the launch of a nuclear programme is a significant investment, which requires incentives to be put in place to attract young talent, train them and ensure they are available when the programme starts. Given the long lead times to develop and implement a nuclear energy programme and the need to gain practical operational experience, these programmes should include practical training and operational experience in a foreign country. Once educated and trained, these nuclear-skilled workers from newcomer countries will need sufficient incentives to return or remain in their countries. R&D activities, possibly linked to the use of a research reactor are seen as an effective way to develop and maintain skills and competence.

Internationalisation of nuclear training and education

In parallel to an increased globalisation of the nuclear industry, there has been an increase in the internationalisation of R&D. This is to a large extent due to decreasing R&D budgets at national levels, which encourages research organisations to pool resources, share experimental facilities and carry out projects at the international level. There are a number of international and bilateral initiatives focused on collaborative research, education, training and knowledge management, including the Sustainable Nuclear Energy Technology Platform in the European Union, which gathers industry, research and academia, or the Generation IV International Forum, which provides a framework for international R&D on Gen IV systems. The NEA itself provides support to international projects such as code validation benchmarks or safety-related experiments.

The global nuclear industry is acutely aware of the need to ensure a high level of nuclear skills development in existing and newcomer countries and has well-developed training programmes that are shared across countries, providing an important source of nuclear training. In addition, global partnerships such as the World Nuclear University (WNU) and the European Nuclear Education Network (ENEN) have been developed to enhance international education and training for the development of nuclear energy.

WNU was created in 2003 with the support of the IAEA, OECD/NEA, WANO and WNA to provide global guidance on preparing the future generation of nuclear industry leaders and to enhance nuclear education worldwide. WNU activities include the Summer Institute (a six-week intensive course for future nuclear leaders), the Radiation Technologies School (a two-week course for future leaders in the radiation and radioisotope field) and a one-week course focused on key issues in the nuclear industry today. These courses are offered in host countries where significant interest exists for the development of nuclear energy[8]. Training events are held in partnership with other organisations and trainers come from industry, government and academia. The WNA provides administrative support to the WNU. To date, almost 900 professionals have attended the Summer Institute, while 200 have attended the Radiation Technologies School and approximately 6 000 have benefited from the one-week training courses.

Mobility of nuclear literate workers across borders will be particularly important both in terms of providing sufficient specialised nuclear workers (such as nuclear engineers and welders) as well as facilitating a transfer of expertise to newcomer countries. The UK skills passport and French ticketing system provide a good basis for developing mutual recognition of qualifications from one country to another and help to support workforce mobility.

8. Additional information on WNU courses can be found at www.world-nuclear-university.org.

Codes and standards, supply chain development and localisation issues

This roadmap recommends the following actions:	***Proposed timeline***
Industry to continue to work towards harmonisation of codes and standards to improve the integration of a global supply chain.	Ongoing
Newcomer countries' legitimate demands for localisation in nuclear projects should be appropriately balanced by the need to have an overall cost efficient and qualified supply chain. Guidance on how to reach the balance between global and local supply chains should be elaborated.	2025

There are currently 70 reactors under construction in 15 countries, and several newcomer countries are either in various stages of planning a nuclear programme (for example Indonesia, Jordan, Malaysia, Poland, Turkey, Saudi Arabia, Viet Nam) or sometimes already constructing NPPs (Belarus and the United Arab Emirates). To reach 930 GW of nuclear capacity by 2050, many more construction projects will need to be launched, and the nuclear industry will need to address two particular challenges if it is to achieve this long-term objective in a cost-effective way: (i) improve the standardisation of reactor designs through a harmonisation of codes and standards and (ii) ensure that nuclear supply chains, both local and global, are qualified, and that there are no bottlenecks that could delay projects.

Improved standardisation and harmonisation of codes and standards are seen as effective ways to improve new build performance and to reduce costs. However, given the number of different designs and national regulatory frameworks, it would be unrealistic to imagine that, in the short term, there might be an international licensing process or reciprocal acceptance of approvals between countries. Information exchange and lessons learnt during licensing and safety reviews can ease regulatory processes and align regulatory requirements (this is the objective of the MDEP initiative). On the industry side, work is being done to advance reactor design standardisation – this is the main focus of the WNA's CORDEL initiative.

In terms of supply chain issues, the availability of large heavy forgings, once identified as a potential barrier, is no longer a problem as a number of facilities in China, France, Japan and the Republic of Korea, for instance, are able to manufacture these large components, and their industrial capacity meets the demand in the short to medium term. The main issue facing nuclear project developers is the qualification of the supply chain that is required for the project, as well as reaching the appropriate balance between localisation demands in countries that do not necessarily have a nuclear industry and a proven and qualified global supply chain.

Localisation can be challenging when a new nuclear project is established in a newcomer country, particularly if the contract to build a new plant stipulates a high local content requirement. For countries that have a large nuclear programme, localisation can be successful and help drive down the costs of future plants (see Box 17).

Box 17: Setting up and qualifying a supply chain for Generation II and Generation III reactor technology: The case of heavy component manufacturing in China (Case study 15)

With 26 reactors under construction (at end 2014), China's new build programme represents about 40% of the world's nuclear reactor construction projects. Half of these reactors are Gen II+ CPR-1000 reactors derived from the Daya Bay and Ling Ao 900 MW reactor technology from vendor Framatome (now AREVA), with localisation rates that now reach more than 80%. The equipment localisation programme that AREVA initiated with China General Nuclear Power Corporation (CGN) started with the Ling Ao phase I project in 1995, but really developed with the acceleration of the Chinese nuclear programme ten years later to initiate a supply chain localisation programme, while minimising project risks in terms of schedule and cost, CGN defined a realistic localisation plan with AREVA, and this plan was included in the supply contract. During the project implementation, CGN and AREVA set up strict monitoring to follow and secure the components' delivery according to the project's schedule.

The successful experience gained in China will help to address localisation targets in countries planning new build with partial localisation of the supply chain, such as Brazil, India, the Republic of South Africa, Saudi Arabia, and the United Kingdom.

Table 5: Progression in terms of localisation

Equipment	***Ling Ao phase 1, 900 MW reactor (1994)***	***Ling Ao phase 2, CPR-1 000 (2004)***	***Taishan 2nd unit, EPR 1 600 MW (2009)***
Steam generators	1 (out of 3)	3 (out of 3)	4 (out of 4)
Reactor pressure vessel	0	1	1
Pressuriser	1	1	1

There needs to be a good balance between supply chain localisation and globalisation, which depends on the extent of the past and future nuclear programme in the country of localisation. Guidance on how to reach this balance would be beneficial. Qualification of a new supply chain remains a challenge. Establishing a nuclear supply chain in a country that had a nuclear industry in the past can also be difficult. The absence of activity over one or two decades is sufficient to lose precious know-how and manufacturing capabilities. Italy, which recently reconsidered the nuclear option, organised a comprehensive survey of its industry with the objective of identifying companies that could participate in a new build programme (see Box 18). The United Kingdom, whose new build programme is now moving ahead dynamically, has been promoting the development of a British nuclear supply chain with the publication of the "Supply Chain Action Plan" in 2012 and a Nuclear Industrial Strategy document in 2013. In parallel, industry has set up a supply chain portal through the Nuclear Industry Association. Initiatives taken by Enel in Italy, and by government and industry in the United Kingdom, are good examples of action to promote a solid industrial base for nuclear projects.

Box 18: Preparing for a new build programme in an industrial country: Supply chain survey (Case study 16)

In preparation for a future new build programme, in 2009 the Italian government asked Enel to develop a nuclear awareness and qualification process for Italian companies. The government's goal was to make it possible for the Italian industry to have a large role in the new build programme (i.e. 70% target localisation for the last units to be built). In October 2009, Enel and EDF, supported by the Italian Industries Association, started a market survey aimed at screening the Italian industry. Unfortunately, this initiative was abandoned after the Fukushima Daiichi accident when a moratorium on nuclear activities was decided.

However, the preparatory work allowed Enel to conclude that in order to increase localisation content, a series of measures were needed, such as government incentive programmes, partnerships with qualified nuclear international suppliers and national experts' support for industry. Critical points found during the market survey were related to nuclear steam supply system equipment and to aspects related to quality management for nuclear work. In particular, the need to implement programmes for nuclear equipment qualification and the need to intensify the knowledge of nuclear codes and standards and of documentation configuration management processes were identified. Sixty Italian companies were identified as currently active in the nuclear field, with qualifications by nuclear technology vendors. An additional 60 to 70 companies had nuclear experience in the past, and these had dormant nuclear skills that could be recovered within a reasonable timeframe with relatively minor efforts in view of the new opportunities. From a qualitative point of view, the survey gave a wide and detailed picture of the Italian industry's present capabilities and future potential and made the industry aware of its strengths and areas that would need improvement.

Communication and public acceptance

This roadmap recommends the following actions:	***Proposed timeline***
Development of education and information centres to support effective, transparent communication and public knowledge about the facts related to the nuclear industry. In newcomer countries, it will be particularly important to ensure broader public awareness of nuclear power development.	2015-30 and beyond
In many countries, the operator of the nuclear facility plays a front-line role in communicating with stakeholders in real-time during an event. In this case, the regulatory authorisation for activities involving a nuclear facility should include a review and acceptance of the operator's strategy and programme. Performance of the programme should also be assessed by the regulator on a periodic basis.	Ongoing
Targeted communication programmes with influential stakeholder groups such as politicians, media, teachers and local leaders need to be implemented to improve understanding about the benefits and risks of nuclear energy. Communication should be transparent and occur at regular intervals and via a range of personal, print and online sources.	Ongoing
Measures to be implemented to share information in a timely manner on any safety events proposed by national regulatory organisations.	Ongoing
National regulatory organisations need to implement communication mechanisms and tools for discussion between interested parties and the regulator.	Ongoing
Clear and regular communication with host municipalities in the identification and development of deep geological disposal sites. A process based on voluntary participation with clarified withdrawal conditions is recommended and should include alternative sites from the beginning.	2015-30 and beyond

Introducing nuclear energy or expanding its role requires the support of all stakeholders, including the public, and should be based on an assessment of risks and benefits. The benefits of nuclear in terms of energy security and threats of climate change are often overshadowed by concerns over nuclear safety, risks of an accident, radioactive waste management and disposal and potential proliferation of nuclear weapons.

A successful strategy for nuclear communication will vary depending on the local situation. Understanding and responding to the concerns and needs of the local community will be key in devising a successful communication strategy. Project developers need to be sensitive and responsive to stakeholder concerns. Communication strategies aimed at improving public acceptance of nuclear energy should be transparent and achieved via fact-based information. Education should be the focus of communication. Public education programmes clearly explaining the risks and benefits of nuclear energy need to be developed as part of a country's decision to develop nuclear energy. Nuclear safety and radiological protection needs to be explained simply, with easy to understand language, and the positive aspects of nuclear energy (e.g. the creation of jobs and boosting of local and regional economies) need to be highlighted in nuclear public acceptance programmes.

In 2009, the European Commission conducted a Eurobarometer survey in the 27 member states on public perception of nuclear safety (EC, 2010). Results of this survey found that, overall, European public opinion accepts the value of nuclear energy to some extent as a means of reducing energy dependence, and opposition to nuclear development is mostly related to the perception of risks associated with nuclear energy. The study found that most Europeans considered themselves ill-informed about nuclear safety, obtaining most of their information from mass media, which they considered insufficient. Respondents who felt they were well informed about issues linked to nuclear safety were clearly more supportive of the value of nuclear energy and hence had higher acceptance.

Finland and France have been identified as two examples where communication and public acceptance for nuclear has been successful. In Finland, significant time and resources were invested in educating local communities with respect to the local benefits and risks for nuclear facilities such as waste repositories or new reactors. In France, LCIs (Local Commissions of Information) have been operating for several decades around nuclear facilities. They provide an efficient framework for all stakeholders to meet, and for the public to have access to information.

Transparent communication and information from regulatory organisations is particularly important to build confidence and trust in their ability to regulate operations of nuclear facilities. Lack of consistency in messages from one national authority could affect confidence in regulators elsewhere. Close contact should be maintained by national regulatory organisations and information about safety events shared in a timely manner.

Finally, governments, and intergovernmental organisations, in particular bodies working on climate change, have a role to play in communicating to the public about the positive contributions that nuclear energy makes and will make in the future in the reduction of greenhouse gas emissions from the power sector. This *Roadmap* and the underlying 2D Scenario highlight the significant role that nuclear energy has to play in the decarbonisation of the world's energy system.

Conclusion:
Near-term actions for stakeholders

This *Roadmap* has been designed with milestones that the international community can use to measure progress and assess efforts to ensure that nuclear energy development is on track in achieving the emissions reductions required by 2050.

Below is a summary of the near-term actions required by nuclear energy stakeholders, presented to indicate who should take the lead in specific efforts. In most cases, a broad range of actors will need to participate in each action. The IEA and NEA, together with government, industry and non-governmental organisation stakeholders, will report on this progress and recommend adjustments to the *Roadmap* as needed.

Lead stakeholder	Actions
Governments	• Provide a clear commitment and long-term strategy for nuclear development. • Recognise the importance of long-term operation to maintain low-carbon generation capacity and security of energy supply; provide clear prospects to encourage operators to invest in refurbishments. • Support efforts in safety research, and ensure that results are communicated to a wide audience. • Continue to co-operate to discuss international fuel services as a means to secure the development of nuclear power. Ensure that policies are in place for long-term storage, including DGD of high-level waste. • Continue to support R&D in advanced recycling technologies to reduce the volume and toxicity of high-level waste. • Ensure that dedicated funds are set aside for decommissioning activities and that operators provide sufficient funding to these funds during operation of NPPs by regularly reviewing the adequacy of accrued funds. • Work with industry to open up the market for small modular reactors by accelerating the deployment of SMR prototypes that can demonstrate the benefits of modular design and construction. • Support R&D and prototype development for Gen IV systems to ensure technologies are ready for deployment in 2030-40. • Ensure regulators are strong, independent and staffed with enough skilled and competent personnel to carry out their missions. • Encourage the development of licensing frameworks for advanced reactors, including SMRs and Gen IV reactors. • Expand public-private partnerships with industry to develop demonstration projects for nuclear cogeneration, in the areas of desalination or hydrogen production. Develop education centres to support effective communication and public knowledge about the facts of nuclear.
Industry	• Implementation of Post-Fukushima safety upgrades by operators of NPPs in a timely manner. • Optimisation of Gen III designs to improve constructability and reduce costs. • Lessons learnt from current FOAK projects should be used to ensure that NOAK plants are built on time and to budget. • Investments are needed in environmentally sustainable mining to address expected long-term demand. • Nuclear facilities that have been shut down should be decommissioned in a timely, safe and cost-effective manner. • Enhance safety culture across the nuclear sector and at all levels of staff. • Improved communication with institutional investors and other financial institutions to better educate investors on the economic benefits of investment in NPPs. • Continued harmonisation of codes and standards to improve the integration of a global supply chain.

Lead stakeholder	*Actions*
Universities and other research institutions	• R&D in ageing and improved safety is needed to support long-term operation of existing NPPs for 60 years of operation or more. • Studies should be carried out to ensure extended (dry) storage of spent nuclear fuel satisfies the highest safety and security requirements. • Devote more effort to safety research and communicate results to a wide audience. • A national skills evaluation should be undertaken to quantify the need for a skilled nuclear workforce. • International co-operation is needed to help transfer nuclear training programmes from existing nuclear countries to newcomer countries. • Student exchange programmes aimed at newcomer countries should be developed and where possible include a period of practical work experience at a nuclear facility.
Financial institutions	• Export credit agencies should continue to support nuclear financing by providing loan guarantees. • Pension funds and other institutional investors should consider investments in NPPs. • Development banks could support nuclear training and capacity development needs in new comer countries.

Annex

Nuclear energy case studies

www.iea.org/publications/freepublications/publication/technology-roadmap-nuclear-energy.html

Case studies have also been developed together with various nuclear energy stakeholders to help illustrate lessons learnt and good practices in the development of nuclear energy. The inclusion of these cases within the roadmap are aimed at providing additional insights and practical support for the recommendations and proposed actions in this roadmap.

Topic	***Case study description***
Nuclear new build	Lessons learnt from Gen III construction projects: Experience in Japan on construction of Gen III reactors.
	IAEA milestone approach for national nuclear infrastructure: UAE's experience.
	Environmental impact assessments: Lessons learnt from Finland.
	Setting up a supply chain in China.
	Preparing for new build in Italy.
Decommissioning	Decommissioning in Germany: E.ON's experience with decommissioning of Stade NPP and Würgassen NPP.
Waste management	Recycling of spent fuel: Experience with nuclear fuel recycling in France.
	Deep geological disposal in Sweden: Lessons learnt on implementation of a DGD facility.
Operations	WANO peer review process: The World Association of Nuclear Operators brings together operators from every country in the world with the objective of achieving the highest levels of operational safety and reliability.
	Integrated architect-engineer model: France's experience with implementing a model to increase safety and performance of plants by maximising the use of experience feedback.
	Research for extended operation of NPP: US research focused on life time extensions of up to 80 years or beyond.
	International collaboration amongst regulators: Multinational Design Evaluation Programme is an initiative to develop innovative approaches to leverage resources and knowledge of national regulators.
	Enhanced safety standards in Japan: Summary of new measures implemented after the Fukushima Daiichi accident.
Financing	Financing of new units at the Vogtle plant: Measures used in the United States to facilitate financing.
	Akkuyu build, own and operate model: Rosatom's model to facilitate deployment of nuclear projects.
Education and training	Nuclear skills assessment in the United Kingdom.

Abbreviations, acronyms and units of measure

Abbreviations and acronyms

2DS	2 degress Celsius Scenario in *Energy Technology Perspectives 2014*
6DS	6 degrees Celsius Scenario in *Energy Technology Perspectives 2014*
ADS	accelerator-driven systems
ASEAN	Association of Southeast Asian Nations
ASTRID	advanced sodium technological reactor for industrial demonstration
BOO	"build, own and operate" model
BWR	Boiling water reactor
CANDU technology	CANada Deuterium Uranium
CEFR	China experimental fast reactor
CGN	China General Nuclear Power Corporation
CNRA	Committee on Nuclear Regulatory Activities
DGD	Deep geological disposal
EDF	Électricité de France
ENEN	European Nuclear Education Network
FANR	Federal Authority for Nuclear Regulation
FBR	fast breeder reactor
FNR	fast neutron reactors
FOAK	first-of-a-kind
GCR	gas-cooled reactor
Gen II	Generation II
Gen III	Generation III
GFR	gas-cooled fast reactor
GHG	greenhouse gas
GIF	Generation IV International Forum
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IFNEC	International Framework for Nuclear Energy Cooperation
IFNEC	International Framework for Nuclear Energy Cooperation
INES	International Nuclear Event Scale
INIR	Integrated Nuclear Infrastructure Review
ITER	International Thermonuclear Experimental Reactor
LFR	lead-cooled fast reactor
LWR	Light water reactor
MDEP	Multinational Design Evaluation Programme
MOX	mixed oxides of plutonium and uranium
MSR	molten salt reactor
NEA	Nuclear Energy Agency
NOAK	Nth-of-a-kind
NPP	Nuclear power plant
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NRA	Nuclear Regulation Authority
NSREG	European Nuclear Safety Regulators Group
NUGENIA	NUclear GENeration II and III Association
OECD	Organisation for Economic Co-operation and Development
PFBR	prototype fast breeder reactor
PHWR	pressurised heavy water reactor
PSA	probabilistic safety assessment
PV	photovoltaics
PWR	Pressurised water reactor
R&D	Research and development
RBMK	Reactor Bolshoy Moshchnosti Kanalnyy (High-power channel-type reactor – graphite-moderated boiling reactor)
RU	recycled uranium
SCWR	supercritical water-cooled reactor
SFR	Sodium-cooled fast reactor
SMR	Small modular reactor
SNF	Spent nuclear fuel
UAE	United Arab Emirates
VHTR	very-high-temperature reactor
VHTR	Very-high-temperature reactor
VVER	Water-moderated water-cooled power reactor
WANO	World Association of Nuclear Operators
WENRA	Western European Nuclear Regulators Association
WNA	World Nuclear Association
WNA	World Nuclear Association
WNU	World Nuclear University

Units of measure

°C	degree Celsius
Gt	gigatonnes
GW	gigawatt
GWel	gigawatt electrical capacity
GWh	gigawatt-hour (109 watt hour)
kW	kilowatts
kWh	kilowatt-hour (103 watt hour)
MW	megawatt (106 watt)
MWh	megawatt-hour (106 watt hour)
tHM	tonnes of heavy metal
TWh	terawatt hours

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INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its mandate is two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply and to advise member countries on sound energy policy.

The IEA carries out a comprehensive programme of energy co-operation among 29 advanced economies, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports.

The Agency aims to:

- Secure member countries' access to reliable and ample supplies of all forms of energy; in particular, through maintaining effective emergency response capabilities in case of oil supply disruptions.
- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
- Find solutions to global energy challenges through engagement and dialogue with non-member countries, industry, international organisations and other stakeholders.

IEA member countries are: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea (Republic of), Luxembourg, the Netherlands, New Zealand, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission also participates in the work of the IEA.

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 31 countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, the Republic of Korea, the Russian Federation, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission also takes part in the work of the Agency.

The mission of the NEA is:

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

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information.

The NEA Data Bank provides nuclear data and computer program services for participating countries. In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD is a unique forum where the governments of 34 democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

The OECD member countries are: Australia, Austria, Belgium, Canada, Chile, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Republic of Korea, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission takes part in the work of the OECD.

OECD Publishing disseminates widely the results of the Organisation's statistics gathering and research on economic, social and environmental issues, as well as the conventions, guidelines and standards agreed by its members.

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2015

2020

2025

2030

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Annex: Nuclear Energy Case Studies

Case studies have also been developed together with various nuclear energy stakeholders to help illustrate lessons learnt and good practices in the development of nuclear energy. The inclusion of these cases as an Annex to the *Roadmap* are aimed at providing additional insights and practical support for the recommendations and proposed actions in this roadmap. These case studies cover lessons learnt from new build projects, decommissioning and waste management best practices, setting up of a geological repository for high level waste, innovative financing, education & training skills programmes, and benefits of peer reviewing processes amongst operators or regulators to share knowledge and improve safety.

Case study 1: Peer review process amongst nuclear operators - WANO

The World Association of Nuclear Operators (WANO) brings together operators from every country in the world that has an operating commercial nuclear power plant with the objective of achieving the highest possible standards of nuclear safety.

WANO was created in 1989, when the world's operators set aside their regional and competitive differences to form a safety-focused association as a response to the Chernobyl accident in 1986. Based in London with regional centres in Moscow, Atlanta, Tokyo and Paris, WANO continues to cut across political barriers and interests. It exists purely to help its 130 members accomplish the highest levels of operational safety and reliability. WANO is a non-profit organisation and does not advocate for, or on behalf of, the nuclear industry. It is not a regulatory body and does not advise companies on issues such as initial reactor design selection. With safety as its only goal, WANO helps operators communicate effectively and share information openly to raise the performance of all operators to that of the best.

For the past 25 years, WANO has been helping operators through four core programmes:

Peer Reviews: Since 1992, WANO has conducted more than 500 operating station peer reviews in 31 countries/areas, including at least one at every WANO member station. These reviews help members compare their operational performance against standards of excellence through an in-depth, objective analysis of their operations by an independent team from outside their organisation. The result is a frank report that highlights strengths and areas for improvement in nuclear safety and plant reliability. After the Fukushima Daiichi accident in 2011, WANO moved toward a four-year frequency for peer reviews, with a follow-up at the two-year point. In addition, WANO provides all new units with a pre-startup review before initial criticality. In 2012, a pre-startup peer review team office opened in Hong Kong to better meet member needs in the Asian region.

Operating Experience (OE): This programme alerts members to mistakes or events that have occurred at other nuclear power plants and enables them to take corrective actions to prevent similar occurrences at their own plant. Fundamental to OE's success is the willingness of WANO members to openly share their operating experience for the benefit of other nuclear operators throughout the world. An event is defined as any significant deviation from the normal expected functioning of a plant. When an event occurs, the affected plant management and staff analyse it and complete a WANO Event Report (WER), which is then sent to their WANO regional centre and posted on the members' website. Recognition of the importance of this activity is growing and the total number of events reported by WANO members continues to increase.

Technical Support and Exchange: This programme has many facets, including: Technical Support Missions, which are carried out at the request of a plant or utility and let WANO members help each other fix identified issues or problems. A team of peers is selected on the basis of their expertise to review technical issues identified during peer reviews; Performance Indicators help members assess their plant's performance against an international benchmark. Worldwide reference targets have been established to promote long-term improvement in areas such as capability factor, forced loss rate, collective radiation exposure, fuel reliability, chemistry performance and industrial safety accident rates; Principles and Guidelines help members review existing programmes and monitor the adequacy of corporate policies and plant practices. They also help members develop new programmes and corrective actions to tackle identified weaknesses. There are now almost 30 WANO principles and guidelines and over 100 good practices available on the WANO members' website; Operator Exchanges refer to any information shared directly between operators with the purpose of increasing safety and reliability. These include operator exchange visits, communication through the WANO website, exchange of documentation, personnel and any other exchange and/or co-operation between operating organisations.

Professional and Technical Development: This programme provides a forum for WANO members to enhance their professional knowledge and skills so they can deal with potential safety issues before they become problems. Specific activities include workshops, conferences, seminars, expert meetings and training courses. These activities let members from all regions compare their operations and emulate best practices. Importantly, they also provide an ideal opportunity to establish relationships with colleagues from around the world. Each activity focuses on improving plant performance in areas such as operations, maintenance and engineering. Specific topics are chosen on the basis of members' requests, specific gaps or needs identified by WANO staff and/or industry trends.

Case study 2: Lessons learnt from Gen III construction projects

Vendors of Generation III reactors are aware of the need to deliver nuclear power plants on time and to budget, and are taking full benefit of the experience gained during "First Of A Kind" (FOAK) projects to optimise the designs, the supply chain, and to manage the construction projects more effectively. For many vendors and equipment suppliers, especially in Europe and in the United States, Gen III projects represent the first nuclear new build projects for more than ten years, with much of the experience gained during the peak construction times of the 1970s and 1980s to be regained.

AREVA has quoted the following improvements between the Olkiluoto 3 EPR "FOAK" project in Finland (first concrete poured in 2005, and start up expected in 2016 at the earliest), and the Taishan 1&2 EPR projects in China launched (first concrete in 2009): 40% fewer engineering hours; reactor building construction from first concrete to dome lifting reduced by 23 months; steam generators delivery time reduced by two years; and corium spreading area protection layer delivery reduced by nearly 77%.

Westinghouse, which is currently supporting the construction of 8 AP1000 reactors over 4 sites, two in China (in Haiyang and Sanmen) and two in the United States (V.C Summer and Vogtle sites), is also taking full benefit from lessons learnt during construction. The vendor is seeking improvements along four directions: optimisation of the construction project and schedule; design optimisation to eliminate FOAK issues; improvement of processes and procedures; strengthening the operation of the supply chain, in particular with respect to localisation aspects.

A 4 to 5 year construction span is a realistic target for N^{th} Of A Kind (NOAK) reactors, in line with the proven construction spans of mature Gen II designs. This target has already been surpassed by Hitachi with the ABWR design, constructed in less than 4 years at the Kashiwazaki-Kariwa, Hamaoka and Shika nuclear power plants in Japan. Unit 6 of Kashiwazaki-Kariwa was the first ABWR built, and it was completed in less than 37 months and began operation in 1996. Unit 7 was built in less than 39 months. The next ABWRs, Hamaoka-5 and Shika-2 were completed respectively in 42 and 43 months. Reasons for these extremely impressive construction spans include: use of modularisation with a very heavy lift crane; open-top and parallel construction floor packaging; front-loaded construction engineering detailed schedule management; and integrated construction management system. According to Hitachi, modularisation gives a streamlined and effective on-site approach, open-top construction and use of a heavy lift crane allow large-scale modules to be placed directly into place. The company's fully integrated design, engineering and management allows a cohesive approach to plant construction and deployment. Advanced technologies are also used to streamline construction activities. Lessons learnt during construction are also consolidated in an advanced integrated CAE system which relies on a plant engineering database and on accumulated experience and management know how. Finally, a quality assurance system that extends to design, manufacture, inspection, installation, and preventative maintenance after delivery contributes to better overall performance.

Figure A.1: Example of modular construction using a heavy lift crane for the ABWR

Source: GE Hitachi

Case study 3: The integrated architect-engineer model, a proven industrial model to optimise design, construction and operation of NPPs

EDF has developed an industrial model, the integrated architect-engineer model which is the basis of the success of the French nuclear programme, 19 nuclear power plants with a total of 58 reactors in operation and one under construction, providing 75% of the country's electricity. In this model, thanks to the strong interactions between design, procurement and operation, the operator increases the safety and the performance of the plants by maximising the use of experience feedback. This approach is particularly useful when planning the life-time extension programme of the operating plants.

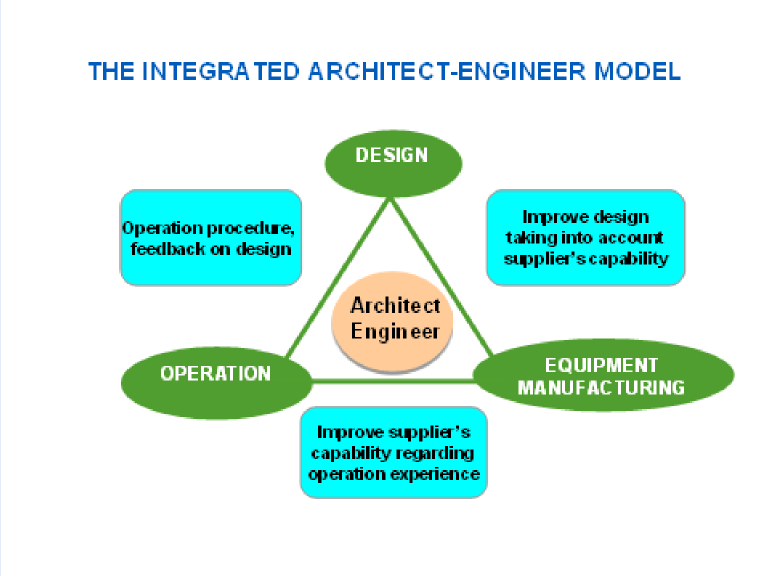
For a country at the beginning of its nuclear development, a strong partnership with an established operator working under this model can also help reduce the industrial risks of the new projects and thus make it easier to attract financial partners. Developing a nuclear project can be a long and challenging task which brings no revenue until the start of commercial operations. The pay-back period is quite long (usually over 20 years) and measures the exposure of the project to operational and market risks. So to convince industrial and financial partners, harnessing the industrial challenges is a must. This also has an impact on financing: on one hand, delays in construction mean extra financing to be found, but on the other hand, being ahead of the learning curve reassures lenders for the following units. For newcomers, having an experienced nuclear utility on board the project is an advantage, either as a main project sponsor or as a strategic partner. A nuclear programme spans 100 years with different operational phases: a robust and long-term cooperation with an experienced nuclear utility can thus bring many benefits.

The operator of a nuclear plant is responsible for ensuring its safety, and may have to deal with unplanned situations. When this happens, the operator has to ensure that both its facility and its organisation can adapt quickly to manage the situation, and prevent the recurrence of a similar event. To do so, it must collect the widest possible feedback both from daily events and exceptional situations, in its country and abroad, for similar or different types of plants (the World Association of Nuclear Operators, WANO, provides its members with this kind of information). Then, its engineering teams process this feedback and implement the measures to continuously improve the safety and performance of its facilities. Through the application of these principles to the nuclear generation, the plants under operation, construction and design evolve at the same time. This amounts to a progressive standardisation process, according to which all the plants of the operator offer the same safety standards, whatever their age and technology. There is no "old" plant: every plant complies with the present safety standards. This of course requires the operator to be able to permanently and directly discuss improvements with the safety authorities.

The higher the interactions, the higher the impact on the industrial developments, because the architect-engineer model promotes the owner and operator interests and optimises the design within the technical limits of the original nuclear power plant design. The alternative model, which is actually the most common approach used by nuclear operators, especially in newcomer countries, is the turn-key contract model. In this model, the owner may find it difficult to integrate operational feedback and optimise the performance of the plant, and this may lead to increased generation costs.

The architect-engineer model also offers advantages in terms of enhancing the safety levels of the nuclear power plants, whether they are Generation II or Generation III/III+ designs. Beyond the design features that a reactor may have, for instance a core catcher, an in-vessel retention system, or the numbers of safety trains, what is important is the level of safety that it offers, for instance a probability of core melt less than 10^{-6} per reactor per year for internal events and less than 10^{-5} for all events; or protection against hazards, especially external hazards. However, no design is fully safe by itself. It is the way it is operated that makes a plant safe, not the accumulation of technologies and equipment. And integrating feedback experience and lessons learnt is essential. Immediately after the Fukushima Daiichi accident, EDF immediately mobilised 300 engineers who analysed for 4 months each of the 19 EDF sites. A report of 7000 pages was issued to the French Nuclear Safety Authority on 15 September 2011, as part of the post-Fukushima "stress tests" evaluations. The analysis went beyond the current safety referential, checking in particular the efficiency of protections, and for extreme events, on a deterministic basis. Very few companies in the world, and of course no manufacturer or operator of turn-key plants, would be able to implement this level of analysis, as quickly and on such a scale. EDF was able to integrate in its life time extension programme the lessons learnt from the Fukushima Daiichi accident and is currently investing to prepare its fleet to operate for up to sixty years. Continuous investments and improvements through integration of operational experience have meant that the cost of the Fukushima safety upgrades is less than 20% of the cost of the life-time extension programme.

Figure A.2: Integrated architect-engineer model



Source: EDF

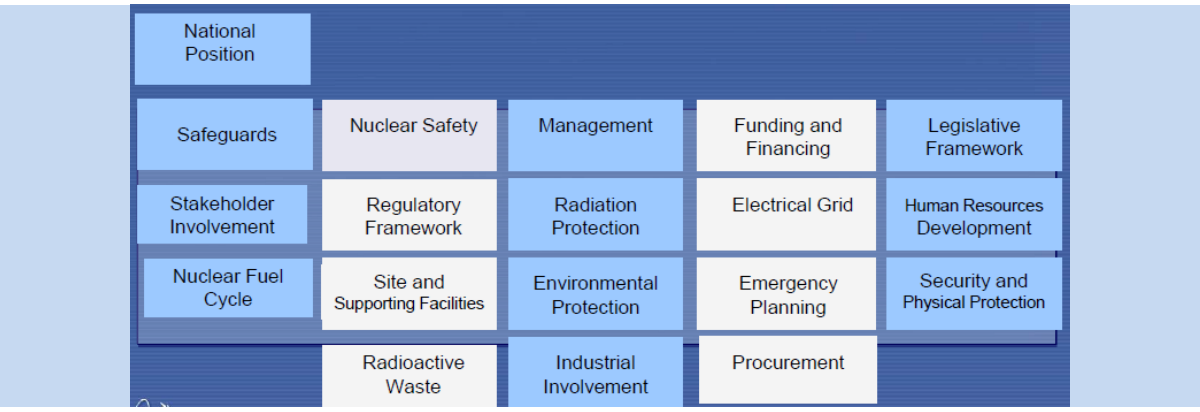
Case study 4: IAEA Milestone approach for national nuclear infrastructure – UAE experience

To help guide member states in the development of a nuclear energy programme, the IAEA released in 2007 a publication outlining the major milestones to be achieved in establishing the required infrastructure for the development of nuclear energy[1]. This guideline known as the IAEA Milestone approach, consists of 19 elements which are central to the development of a nuclear programme (Figure A.3). Each element contains detailed conditions which should be met over 3 milestone phases. The 1st milestone indicates a country is "ready to make a knowledgeable commitment to a nuclear programme", the 2nd milestone "ready to invite bids for the first nuclear power plant" and the 3rd milestone "ready to commission and operate the first nuclear power plant" (IAEA 2007).

With electricity demand expected to exceed 40GW by 2020, nearly doubling 2010 levels, the United Arab Emirates (UAE) has identified nuclear as an important source of future electricity supply, which is currently almost exclusively supplied by natural gas. As a proven, cost-competitive and low carbon source of electricity, nuclear power could provide a significant source of base-load electricity for the UAE. With domestic natural gas supplies limited to about 20 GW of capacity, nuclear is also seen to improve future energy security in the country.

[1] Details of the IAEA Milestones is available from http://www-pub.iaea.org/MTCD/publications/PDF/Pub1305_web.pdf

Figure A.3: 19 elements central to development of national nuclear infrastructure



Source: IAEA

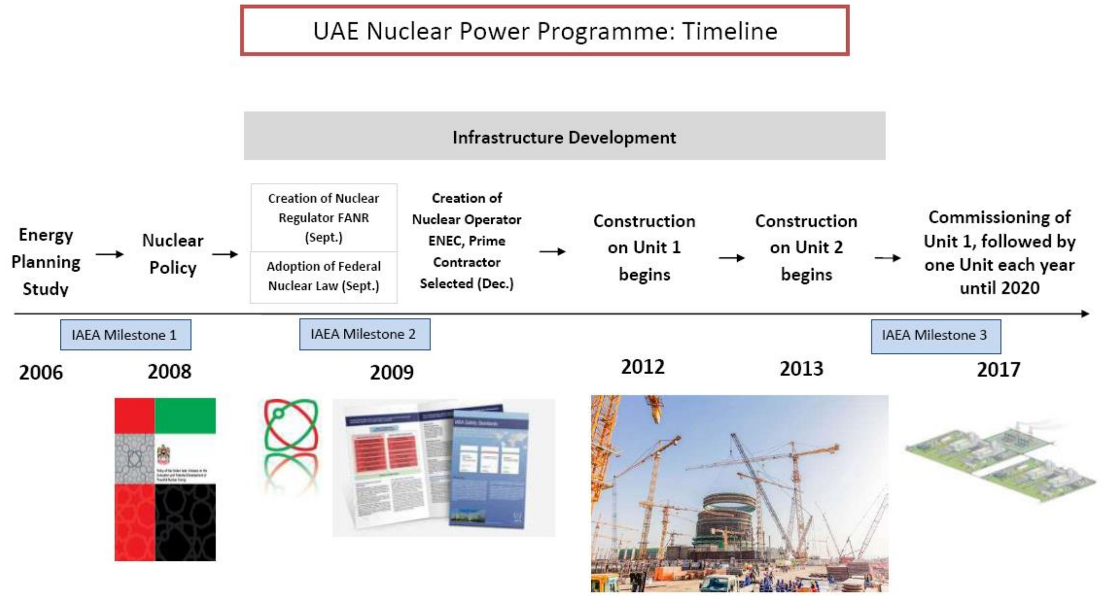
In April 2008, the UAE published its Nuclear Policy and shortly afterwards, on the recommendation of the IAEA, a Nuclear Energy Program Implementation Organisation (NEPIO) was housed within the Executive Affairs Authority (EAA) of Abu Dhabi[2]. The NEPIO team developed an integral strategy document or "Roadmap to Success" to translate the IAEA milestones into an implementation plan customised to meet the needs of the UAE. This roadmap formed the basis of UAE's early nuclear development programme (Figure A.4).

In September 2009, the Federal Authority for Nuclear Regulation (FANR) was established as an independent nuclear regulatory body responsible for licensing and regulation, nuclear safety and security, radiation protection and safeguards and to ensure the fulfilment of national obligations under international treaties and conventions. This was followed in December 2009, with the creation of the Emirates Nuclear Energy Corporation (ENEC) to implement the UAE's nuclear programme. In late December 2009, ENEC announced that it had awarded the construction of 4 APR1400 units to a consortium led by the Korean Electric Power Company. The project when completed in 2020 would have a total installed capacity of 5.6 GW and represents one of the fastest deployment schedules in the world.

The UAE has worked in close partnership with the IAEA in the development of its nuclear energy programme and the IAEA has provided support on legal and regulatory framework, licensing, infrastructure and capacity building, safeguards implementation and peer reviews. At the request of the UAE, the IAEA undertook an Integrated Nuclear Infrastructure Review (INIR) in January 2011. This peer review process was the first completed for a country which had reached Milestone 2 and consisted of a comprehensive review of phase 2 milestones for each of the 19 elements outlined in the IAEA milestone approach for the development of a national nuclear infrastructure.

[2] UAE nuclear policy document is available from http://www.enec.gov.ae/uploads/media/uae-peaceful-nuclear-energy-policy.pdf

Figure A.4: UAE timeline for nuclear energy development



Source: UAE

The review team concluded that the UAE had accomplished all of the conditions to meet Phase 2 conditions (and in general had progressed into Phase 3) in each of the 19 areas except for the adoption of an international instrument on civil liability for nuclear damage and promulgation of associated implementation legislation[3]. The team considered this a minor gap as UAE was expected to make significant progress on this issue. The review team recognised 14 good practices which other countries developing nuclear infrastructure should consider.

Highlights of the identified good practices include FANR's and ENEC's implementation of safety culture throughout their respective organisations; the UAE's approach to rapidly building national capabilities and national workforce through a mix of senior advisors, support companies and national staff focused on knowledge transfer; active coordination in human resource development across different organisations; and UAE's approach to public information and education programme which ensures all main sectors of the local community have access to basic information and the establishment of a detailed stakeholder tracking system to identify relevant parties, log contacts and identify future action.

The UAE has taken measures to ensure a robust nuclear safety regime including integrating lessons learned from Fukushima, establishment of a National Emergency, Crisis and Disasters Management Authority, and implementation of safety culture rules in ENEC. The IAEA, on request from UAE, also conducted an Integrated Regulatory Review Service IRRS) mission in December 2011.

UAE's experience with developing a national nuclear infrastructure and its establishment of a regulatory framework and system is impressive and the steps which the country has taken should be reviewed by other countries. However it should be noted that the UAE's success in implementing its nuclear programme in a relatively short timeframe (9 years from the publishing of its nuclear policy to commissioning of first unit versus IAEA's estimated 10 to 15 years) benefited from the ability to hire personnel with cumulative experience of over 100 years in FANR and ENEC. This was made possible by the availability of significant financial resources of the government. Few countries currently evaluating the development of nuclear have the financial resources to fast track their nuclear programmes by hiring a significant number of foreign experts and the availability of these experts, many of which will soon be retiring, is limited. New nuclear countries are advised to work closely with the IAEA and other relevant organisations and countries with extensive operating experience in the development of their programmes.

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[3] Full report of the INIR is available on http://www.iaea.org/NuclearPower/Downloads/Infrastructure/files/UAE-INIR-Mission-January-2011-Report.pdf

Case study 5: Research for extended operation (beyond 60 years) of NPPS

The current fleet of U.S. nuclear power plants was licensed initially to operate for 40 years. To date, 74 reactors have received 20-year license renewals and 17 applications are under review. 24 reactors have already passed the 40-year mark and are operating safety and reliably with renewed licenses in this extended period. By 2040, it is estimated that half the fleet will turn 60 (see Figure A.5), and if these reactors are retired, the country might face possible shortages of electricity. Hence, research is on-going to develop the technical and scientific knowledge needed to support nuclear plant operation beyond 60 years, up to 80 years or beyond. The Electric Power Research Institute (EPRI), the U.S. Department of Energy (DOE) which has an extensive network of national laboratories, and several universities are conducting research on management of ageing in nuclear power plants to understand and devise strategies to identify and mitigate the effects. The research is essentially dedicated to the long-lived components which are not replaced during regular refurbishments. These include the containment building, the reactor vessel, and can include piping and electric cables.

EPRI's Long-Term Operations Program, which has grown into a large research effort with broad collaborations across multiple countries and entities, includes:

- reviewing of each ageing management program element to determine if they are any ageing effects related specifically to plant operation beyond 60 years;

- performing concrete containment tests to evaluate novel approaches for assessing the condition of concrete containment structures, such as tendon load monitoring and surface strain monitoring;

- identifying the potential for cable failures as a result of ageing and environmental factors.

The DOE's Light Water Reactor Sustainability Program has two strategic goals, the first too develop the scientific basis for understanding and predicting long-term environmental degradation behaviour of materials in NPPs, the second to provide data and methods to assess the performance of systems, structures and components essential to safe and sustained nuclear power plant operations. The research on materials ageing and degradation covers:

- reactor metals: many types of metal alloys exist in nuclear plant systems, and some of these, particularly the reactor internals, are exposed to high temperatures, water and neutrons.

- concrete: assessing the long-term stability and performance of concrete structures within a nuclear plant is important because operational data or experience is limited and better assessments are needed to inform relicensing decisions.

- cables: degradation of cables is caused primarily by long-term exposures to high temperatures. Cables that are buried underground may be exposed to groundwater. Periodic cable inspections using non-destructive examination techniques are used to measure degradation and determine when replacement is needed.

- buried piping: although much of the buried piping in a NPP are related to non-safety systems, some serves a direct safety function. Maintaining the integrity and reliability of all of those systems is necessary for continued plant operation.

- welds: welding is used widely to repair components. Weld-repair techniques must also be resistant to the long-term effects of ageing, including corrosion, irradiation and other causes of degradation. New techniques for weldments, weld analysis and weld repair need to be developed.

The Nuclear Regulatory Commission (NRC) is also engaged in R&D to confirm the safety of U.S. NPPs during Long-Term Operation. Major NRC initiatives include:

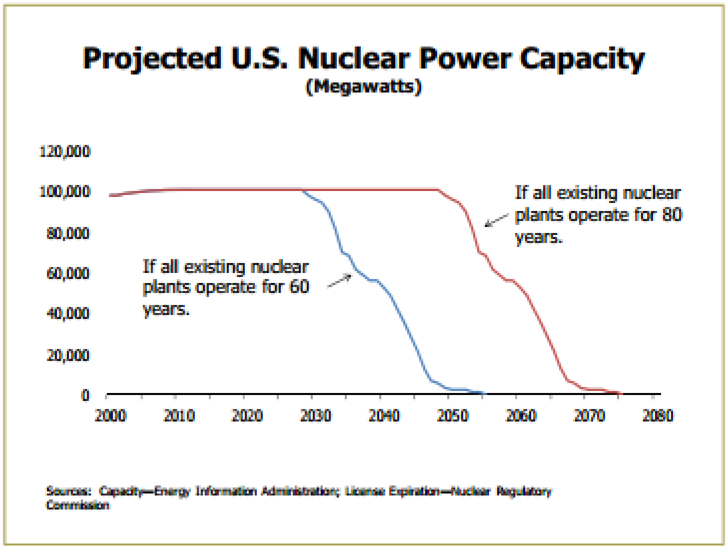
- revising its expert panel report on materials degradation to include longer time frames and passive long-lived structures and components;

- participating in the IAEA-sponsored International Generic Ageing Lessons Learned (IGALL) project to provide state-of-the-art guidelines for developing and implementing ageing management programs for different reactor designs around the world.

- evaluating the implementation of ageing management programs for plants that have continued operation in a second licensing period (beyond 40 years).

Other international initiatives include the Material Ageing Institute (MAI) set up by French utility EDF in 2008 and which now includes 11 members including EPRI, Japanese, Chinese and Russian utilities, as well as industry.

Figure A.5: Evolution of nuclear capacity in the U.S. depending on extended operation assumptions



Source: NEI White Paper, Subsequent License Renewal: Creating the Foundation for Nuclear Power Plant Operation Beyond 60 years, February 2013, http://www.nei.org/CorporateSite/media/filefolder/NEI-White-Paper-Subsequent-License-Renewal.pdf?ext=.pdf

Case study 6: Progress towards implementation of a Deep Geological Disposal site in Sweden

Sweden has for many decades been actively pursuing research activities for the development of a safe long term concept and technology for geologic final disposal of spent nuclear fuel from existing nuclear power reactors. A law enacted in the 1970s requires the nuclear industry to dispose of radioactive waste, as no burden should be put on future generations. This law led to the creation of the Swedish Nuclear Fuel and Waste Management Co (SKB). It is a private company jointly owned by the owners of the nuclear power reactors in Sweden. Today, SKB operates an interim storage facility for spent nuclear fuel, Clab, near Oskarshamn, and a final repository for short-lived radioactive waste, SFR, in Forsmark. Safe transportation of the radioactive waste from nuclear power plants to SKB's facilities is performed using a specially designed ship. The final repository (Deep Geological Disposal site) for spent nuclear fuel and the spent fuel encapsulation facility remain to be built.

SKB has been conducting RD&D activities with this objective for more than 30 years. The work has included technology development, drillings for knowledge-building (in the 1980s), feasibility studies (in the 1990s), safety analyses, site investigations and Environmental Impact Assessments (EIA) studies, consultations with local municipalities (between 2002 and 2008), and site selection processes. This has led to the KBS-3 system for final disposal (direct disposal) of spent nuclear fuel. A final repository is now planned in Forsmark (Östhammar municipality) as well as an encapsulation plant in Oskarshamn. Applications for a permit were made in 2011, and licensing procedures are expected to go on until 2019. The construction and testing of the DGD will take place between 2019 and 29, with operation to start around 2029 (with the transfer of spent fuel from Clab to the DGD facility) until 2075. The DGD is expected to hold about 12,000 tonnes of spent fuel at a depth of 500 metres (see Figure A.6), and is expected to be closed around 2100.

The characteristics of the KBS-3 Deep Geological Disposal (DGD) site are the following:

- Multiple barrier geologic final disposal system based on copper canister, buffer and bedrock.
- Deposition of canisters vertically in tunnels at a depth of around 470 metres below surface. Tunnels and shafts will be refilled with bentonite buffer, clay and rock spoil.

- No surveillance or monitoring should be needed for safety or security reasons after decommissioning and closure.
- Surface area will be restored and impact on land use will be limited during operation and afterwards. Containment/isolation is primary safety function, delayed transport secondary.

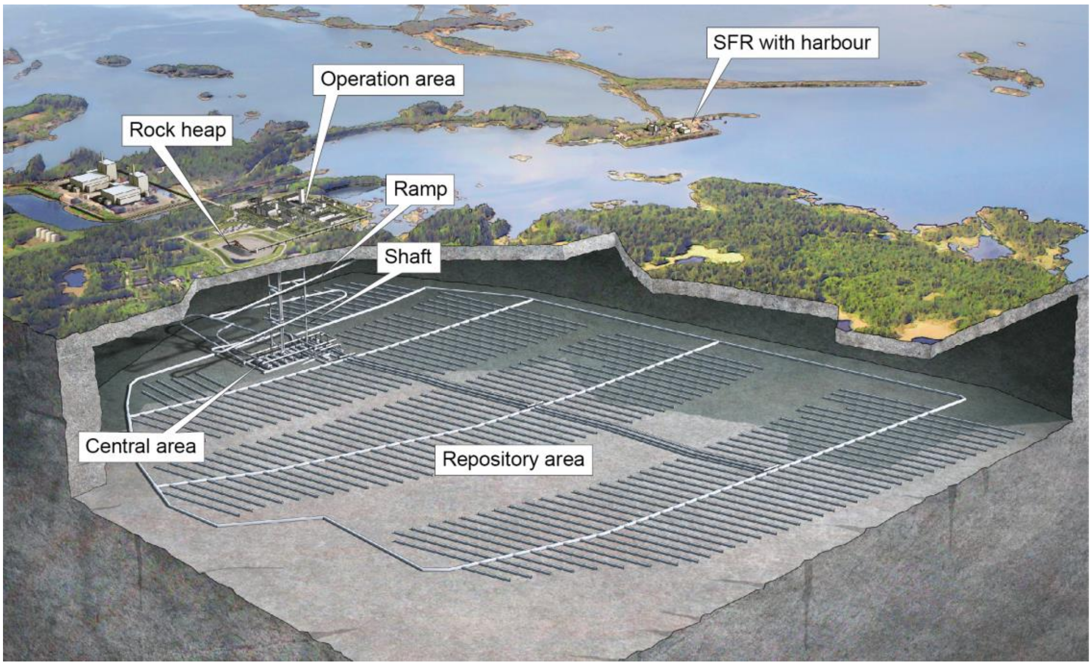
Funding for the DGD development has been ensured through payments from nuclear power producers to the "Swedish Nuclear Waste Fund" administrated by the Swedish Government and the regulator SSM.

Challenges that SKB faced included the extremely long term time span, the FOAK aspect of this kind of project (Finland is also developing a DGD for direct disposal of spent fuel with a similar technology, and both countries have had extensive collaboration), and achieving concept and site acceptance. For the latter, it was necessary to make the safety case understandable by the general public, and to describe extensively alternative concepts. Finally, in a project such as the development of a DGD for radioactive waste, there is always the risk of delays in political decision-making. Strong local support can help support national decision-making.

Key stakeholders in the development of the Swedish DGD and the spent fuel encapsulation facilities are SKB and its shareholders, the two concerned host municipalities, land owners and nearby residents, the two concerned regions, the regulator SSM, the land and Environment Court in Stockholm, the Swedish Government and their advisory board the Nuclear Waste Council, three NGOs (environmental organisations MKG, Milkas and SERO) which get support from the Nuclear Waste Fund to participate and a number of other more peripheral authorities and organisations. Getting local acceptance is a prime target. Annual opinion polls are carried through to measure opinions and acceptance (see Figure A.7). A joint decision about the approval of the DGD and its encapsulation facility is expected from the Government around 2018, following expected approvals from the host municipalities.

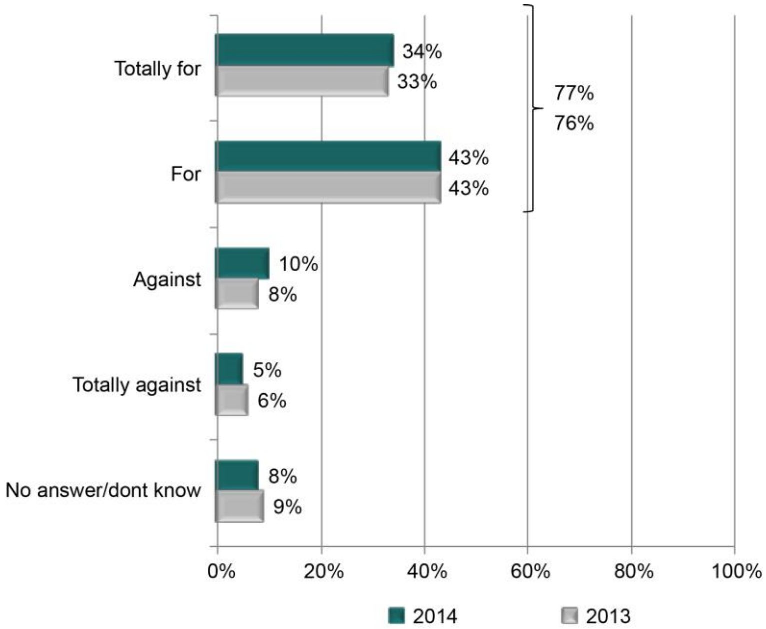
To achieve a successful implementation of a DGD project, a stepwise process with clear roles and responsibilities based on earmarked funding is necessary. Time, consistency, patience and a humble and listening approach are needed. Openness and transparency are essential to build and maintain trust and confidence. A process based on voluntary participation from host municipalities with clarified withdrawal possibilities/conditions is recommended. It is also very important to include and explain alternatives (disposal options, choice of sites) from the beginning.

Figure A.6: Swedish KBS-3 DGD concept in Forsmark



Source: SKB website, http://www.skb.se/

Figure A.7: Public attitude towards the Swedish DGD site in the Östhammar municipality



Source: SKB

Case study 7: Recycling of spent fuel

Used nuclear fuel recycling is today a fully industrial process with more than 45 years of experience, allowing reusing uranium and plutonium content to manufacture new nuclear fuel, while conditioning the non-reusable parts in a stable waste form. In France only, more than 30 000 tonnes of used fuel has been reprocessed to date, from which 20 000 tons come from French reactors. This has effectively reduced the amount of used fuel interim storage capacity by 2, while allowing up to 20% annual savings on natural uranium consumption.

The main steps of the process are the separation of reusable and non-reusable materials, conditioning of the non-reusable material and the fabrication of new fuel.

<u>Separation:</u>

After unloading from the reactor, nuclear fuel is typically left a few years in reactors pools, before being transported to the recycling plant, where it is unloaded and stored in pools before processing. First step of the separation process consists of a mechanical shearing followed by dissolution in nitric acid. Uranium and plutonium are then separated from the fission products using liquid-liquid extraction technology, and then converted for further reuse. Metallic parts from the fuel structure do not dissolve and are rinsed before being transferred to waste conditioning step.

<u>Waste conditioning:</u>

Fission products in liquid form are first concentrated and calcined before being incorporated into melted glass in an induction heated melter. Once the resulting glass has reached complete homogeneity, it is poured into standard stainless steel containers that are then welded and controlled for non-contamination. Metallic parts are compacted and inserted into standard stainless steel containers that are then welded and controlled. Both glass and compacted containers are then stored in a ventilated storage area until transportation to the geological repository or the customer site. Compared with direct used fuel disposal, the volume of conditioned waste is reduced by a factor of five, and the radiotoxicity by a factor of ten.

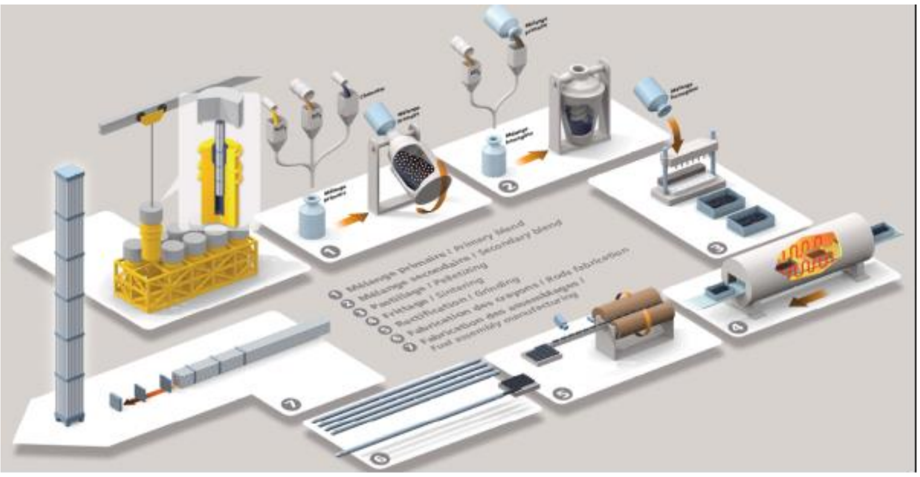
<u>Fuel fabrication:</u>

Recycled uranium is used to manufacture UOx fuel following similar steps as natural uranium. To manufacture MOX (see figure A.8), plutonium oxide is blended with depleted uranium oxide in a two steps process, before being pressed into pellets that are sintered, grinded and inserted into the rods. Rods are then closed, soldered and controlled before being assembled. The whole process is fully automated and takes place in glove boxes, to protect workers from contamination. To date, more than 2000 T of LWR MOX have been produced.

Advanced fuel cycles for the future:

In addition to allowing industrial recycling of current fuels, those technologies are key to prepare next generation fuel cycles, as most Gen IV fuel cycles depends on similar processes to recycle and manufacture fuel.

Figure A.8: MOX fuel fabrication



Source: AREVA

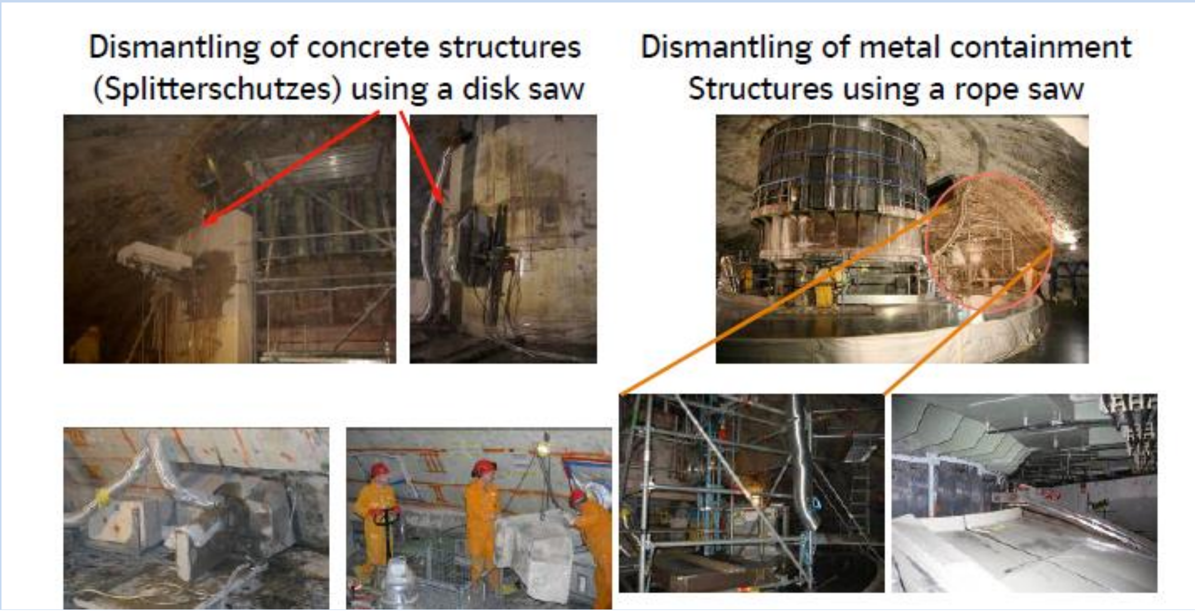
Case study 8: Decommissioning in Germany

German utility E.ON has gained substantial experience in the direct dismantling of Stade NPP (a 630 MWe PWR) and Würgassen NPP (a 640 MWe BWR) over the past 15 years. Given Germany's nuclear phase out policy – 8 out of Germany's 17 reactors have already been shut down and the remaining will be shut down by 2022, more E.ON plants will be decommissioned in the coming decades. E.ON's NPPs Isar 1 (878 MWe BWR) and Unterweser (1345 MWe PWR) reactors were both shut down in 2011 as a result of the phase out policy and the company has started the preparation for the decommissioning of these units. E.ON's expertise relies on a number of technologies that it has developed and mastered, as well as on qualified staff and established processes and practices, including radiation protection, surveillance, material and surface decontamination, and project and team management.

According to E.ON, a key aspect of any decommissioning project is the planning phase, starting from the back-end, in particular the disposal of the radioactive waste. Critical path analysis is required to avoid any bottlenecks (related to easy-to-use technology, interference between parallel work packages, licensing or staffing aspects) in the project, and ensure that all phases run smoothly. In terms of managing radioactive waste, the availability of repositories for high level waste on one hand, and in particular low and medium level waste on the other, is crucial. If these are not available in the timeframe of the decommissioning planning, intermediate storage facilities need to be available, and licensed to receive the waste from the decommissioning activities, otherwise the decommissioning activity may be delayed. The purchase and delivery of containers and casks licensed for the storage and transport of waste has to be planned and controlled carefully too.

In addition to planning, challenges exist in managing financial and human resources: as funds are based on current decommissioning cost estimates, project management is crucial to ensure that the work is performed within the expected budget. From a human resource point of view, the challenge is to motivate staff who have worked part of their professional lives to maintain the existing asset. However, as decommissioning is the final end in the lifetime of the plant, the company has to develop career paths to keep staff motivated so that they will participate in the decommissioning project and remain within the company once the plant has been dismantled.

Figure A.9: Dismantling of the containment of Würgassen NPP



Source: E.ON

Case study 9: International collaboration amongst regulators: Multinational Design Evaluation Programme

The Multinational Design Evaluation Programme (MDEP) was established in 2006 as a multinational initiative to develop innovative approaches to leverage the resources and knowledge of the national regulatory authorities which are currently or will be tasked with the review of new reactor designs. MDEP has evolved from primarily a design evaluation programme for two new reactor designs (EPR and AP1000) to a multinational cooperation programme involving several new reactor designs and issues related to new reactor challenges.

MDEP gathers the nuclear regulatory authorities of 14 countries: Canada, China, Finland, France, India, Japan, Korea, Russia, South Africa, Sweden, the United Kingdom and the United States as full members, and Turkey and the United Arab Emirates as associate members. It is structured in five design-specific working groups (EPR, AP1000, APR1400, ABWR and VVER) and three issue-specific working groups (digital instrumentation and control, mechanical codes and standards and vendor inspection cooperation). The MDEP Policy Group and the Steering Technical Committee oversee the programme (see figure A.10).

MDEP's main objectives are:

- to enhance multilateral cooperation within existing regulatory frameworks (a key concept throughout the work of the MDEP is that national regulators retain sovereign authority for all licensing and regulatory decisions);
- to encourage multinational convergence of codes, standards and safety goals;
- to implement the MDEP common positions in order to facilitate the licensing of new reactors.

To carry out the work, two main lines of activity have been implemented:

- the exploration of opportunities for harmonisation of regulatory practices;
- the cooperation on the safety reviews of specific reactor designs.

In addition, the IAEA takes part in the work of MDEP so as not to duplicate any work already conducted in the field of harmonisation and to consider MDEP's positions in its standards development programme.

Working groups have programme plans with specific activities and goals, and have established the necessary interfaces both within and outside of the MDEP members, with other international organisations, industry (applicants, licensees, vendors) and standards development organisations.

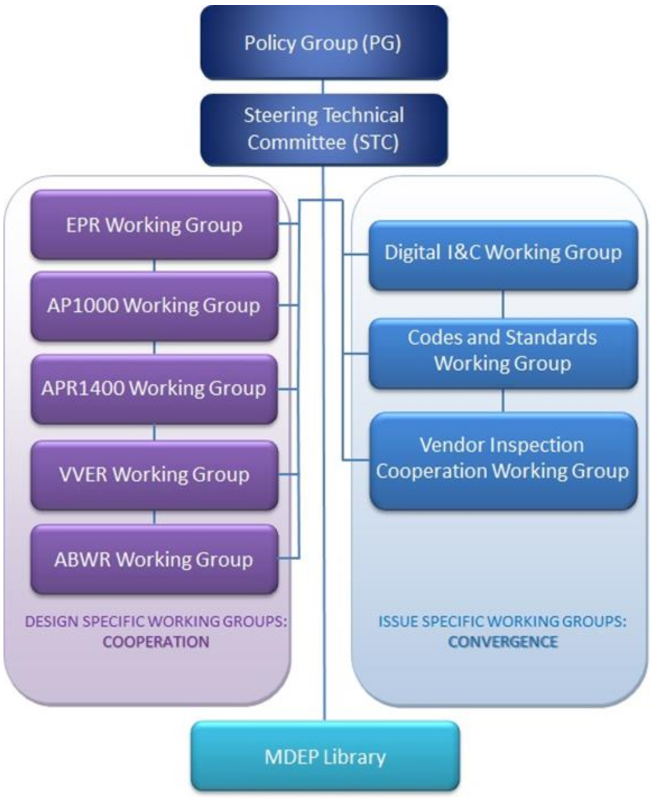
MDEP releases for public use common positions and technical reports, available on the MDEP website: http://www.oecd-nea.org/mdep/. Design-specific common positions describe common conclusions reached by the working group members during design reviews. Three of them have been released so far. One of them specifically addresses Fukushima-related issues (external hazards, combinations of events, loss of off-site and emergency power, core melt, hydrogen release and explosion, steam explosion, etc) for the EPR design, and will be followed by common positions on the same issues for the other designs considered within MDEP. This illustrates the value of gathering together regulators concerned with one specific design to discuss recent safety concerns and also the benefit of having a structure which can ask groups working on different new designs to produce common position papers on issues that are relevant for all designs.

Generic common positions apply to more than one reactor design. They document practices and positions that each of the working group members find acceptable. The common positions are intended to provide guidance to the regulators in reviewing new or unique areas, and are shared with IAEA, and other standards organisations, for consideration in standards development programmes. Ten have been released: nine on digital I&C and one on codes and standards. The digital I&C working group's numerous common positions highlight on one hand the difficulty of the regulation of this new issue to new reactors and the necessity to set up an expert group, but also on the other hand the success of coming up with shared approaches to deal with this challenge. Technical reports document the progress of working groups and provide deep insight and lessons learned in the various areas of topics addressed. Ten have been released: two on vendor inspections related topics and three on codes and standards harmonisation.

MDEP has also encouraged international organisations to work together on the harmonisation of standards. MDEP has been a decisive trigger for their cooperation and will continue to encourage such initiatives, such as the standard development organisations' code convergence board and WNA/CORDEL's working groups.

Future work of MDEP will include a discussion of commissioning activities.

Figure A.10: MDEP organisational structure



Source: MDEP, http://www.oecd-nea.org/mdep/

Case study 10: Environmental Impact Assessments in Finland

In Finland, EIAs are an integral part of the licensing process concerning nuclear facilities, as required by Finnish laws (EIA law of 1994, updated in 1999, Nuclear Energy Act of 1987, updated in 2012), EU directives such as the 1985 EIA Directive (amended since), and international conventions such as the Espoo (a neighbourhood of Helsinki) Convention adopted in 1991 and which entered into force in 1997. EIAs are carried out prior to the government's and Parliament's Decision in Principle (DIP) on the nuclear project.

An EIA is a procedure that ensures that the environmental implications of decisions are taken into account before the decisions are made. In Finland, EIAs cover the whole lifetime of the nuclear facility, as well as the front and back ends of the nuclear fuel cycle. Of particular importance are aspects related to the use of cooling water (large quantities of water are needed to cool nuclear power plants and thermal releases can be significant), impact on fauna, flora and biodiversity, and nuclear accidents and their consequences.

Under the Espoo convention States are also under the obligation to notify and consult each other on all major projects under consideration that are likely to have a significant adverse environmental impact across boundaries.

In Finland, the applicant prepares a so-called EIA Programme which is a plan for the required analysis and the implementation of the assessment procedure, and then an EIA report which describes the project and its options, as well as the environmental report itself, which includes proposals for actions required to prevent and reduce adverse environmental effects. An EIA typically lasts for about a year. An essential part of the EIA process is the consultation of civil society, through public hearings.

In 2008, the Finnish company TVO performed an EIA related to the extension of the Olkiluoto nuclear power plant (2 units in operation, 1 unit under construction) by a fourth unit, OL-4. The report, available on the TVO site at http://www.tvo.fi/Environmental%20impact, is a comprehensive document addressing impacts during construction, operation (including impact on land use, air quality, water system and fishing industry), exceptional situations such as accidents or phenomena related to climate change.

As part of the Espoo convention process, an international EIA was also organised, involving all Baltic countries Estonia, Germany, Lithuania, Sweden, Poland as well as Norway and Austria, and documents were translated in nine different languages.

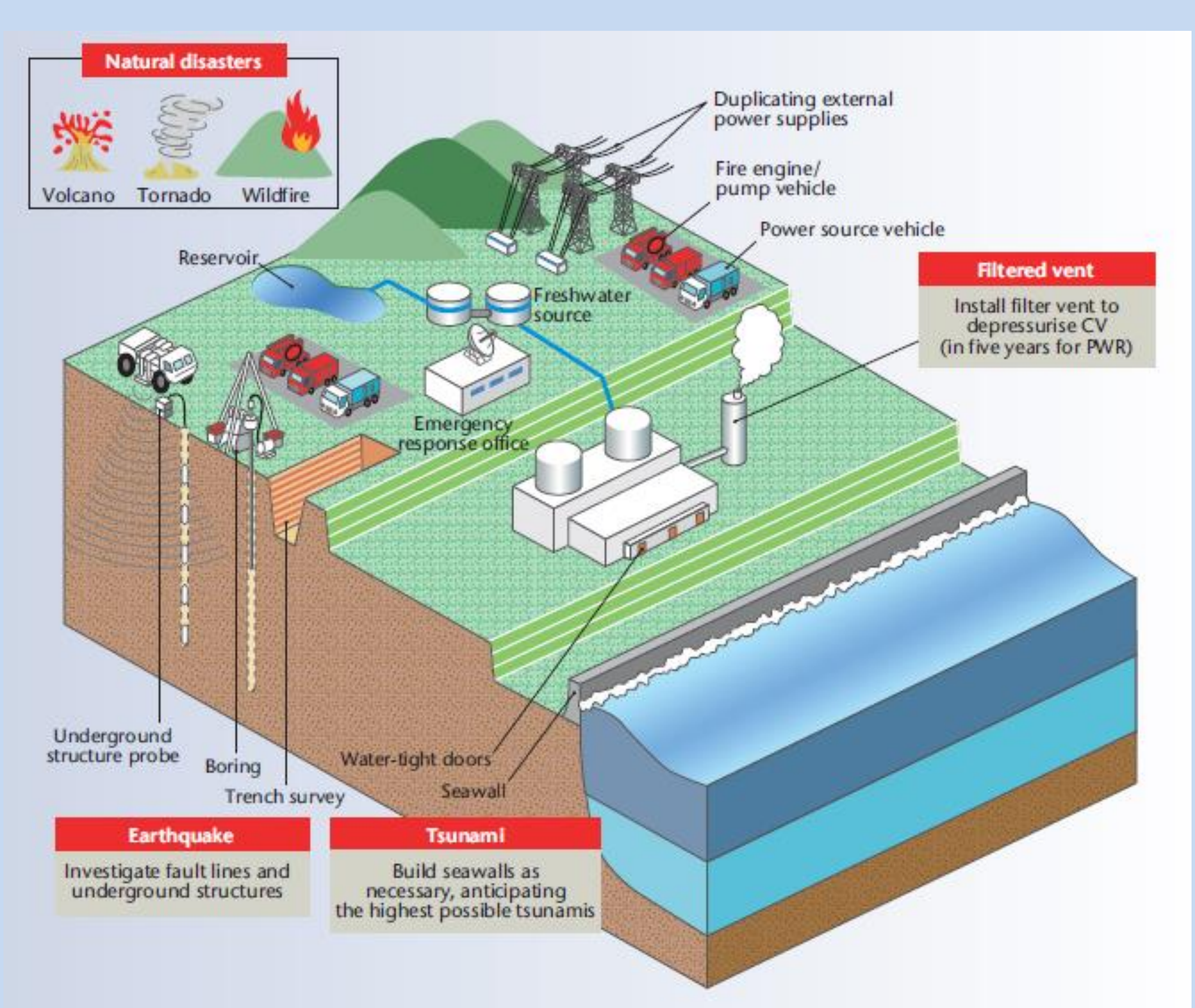
Case study 11: New enhanced safety standards in Japan

Following the Fukushima Daiichi accident, Japan undertook a review of its nuclear regulatory structure and implemented significant reforms aimed at improving the nuclear industry's oversight and tightening safety requirements. The nuclear regulatory body was separated from nuclear promotion and the Nuclear Regulation Authority (NRA) was established as an independent commission. The Chairman and four Commissioners are appointed by the Prime Minister and supported by a Secretariat with the Japan Nuclear Energy Safety Organisation (JNES) – the technical safety organisation - merged into the NRA. The NRA is responsible for nuclear safety, security, safeguards, radiation monitoring and radioisotope regulation.

In addition to the administrative reform of Japan's nuclear regulatory institutions, new safety standards were introduced to prevent accidents with significant radioactive releases (Figure A.11). The measures can be divided into those which are aimed at strengthening the design and performance of the reactors and those addressing situations of severe accidents.

These changes are aimed at ensuring the highest levels of safety and include reinforcing existing measures covering seismic/tsunami resistance, natural phenomena, fire, reliability of the reactor, reliability of power supply, and cooling functions. They also include four new measures covering suppression of release of radioactive materials, intentional aircraft crashes, prevention of containment failure and prevention of core damage or multiple failures. Previous safety measures covered only single failure without damage to the reactor core. Of the 48 nuclear power plant units in Japan, 17 are currently undergoing review by NRA in accordance with these new enhanced safety standards. It is expected that a few of them could complete the review and could be considered ready to restart at the beginning of 2015. The restart of Japan's NPPs will help the country to significantly reduce CO_2 emissions from the power sector.

Figure A.11: New enhanced safety requirements in Japan



Source: Federation of Electric Power Companies of Japan, 2014

In addition to the changes implemented by the government, Japan's nuclear industry also set up a Working Group on Voluntary Efforts and Continuous Improvement of Nuclear Safety to examine internal working procedures and reporting on safety and risk assessment of accidents. Although nuclear safety requirements are determined by the NRA, it is the operators' responsibility to ensure safety and the new Working Group has defined that they must pursue safety levels which exceed the regulatory standards and continuously seek to improve the safety of nuclear facilities. This is an important change from operations prior to 2011 when Japan believed plants posed no risk as long as they met regulations.

Japan will contribute to global nuclear safety, non-proliferation and nuclear security by providing nuclear technology with enhanced safety based on lessons learnt from the Fukushima accident and strengthen human resource and institutional development in nuclear newcomer countries.

Case study 12: Financing of new units at the Vogtle Power Plant in Georgia, USA

In 2006, Southern Nuclear Operating Company started the permitting process with the NRC for the development of two new nuclear units at the plant Vogtle in Georgia. This is the first nuclear reactor construction in the United States in 30 years.

Plant Vogtle, located in the South-eastern part of Georgia sites two Westinghouse PWRs with a rated capacity of around 1150 MW that entered into operation in 1987 and 1989. The construction of two new AP1000 units of approximately 1200 MW at Plant Vogtle would make it the largest nuclear power plant in the United States with four reactors operating on the site and a total capacity of about 4700 MW.

Plant Vogtle is operated by Southern Nuclear Operating Company and is owned by 4 companies: Georgia Power (45.7%), Oglethorpe Power (30%), MEAG Power (22.7%) and Dalton Utilities (1.6%). Georgia Power, an investor-owned vertically-integrated utility, is the largest electricity generation and distribution company in Georgia, with a market share of over 60% of the total electricity. Oglethorpe Power is a non-profit electricity company co-owned by 38 local electricity retail companies to which it sells the electricity produced. MEAG Power provides electricity to 49 non-profit municipal electric utilities, which are co-owners of the company. Dalton Utilities is a small municipal electric utility company providing electricity to the city of Dalton.

In August 2006, Southern Nuclear submitted an application for Early Site Permit, which allows for preliminary construction at the site, and was approved by the NRC in August 2009. In March 2008 co-owners and operators of Plant Vogtle submitted to the NRC an application for a Construction and Operating License (COL), which authorises the construction and operation of a plant, , and received the license for Units 3 and 4 on February 2012. In April 2008, on behalf of the co-owners, Georgia Power entered into an Engineering, Procurement and Construction (EPC) agreement with Westinghouse and Stone & Webster for the development of the two AP1000 nuclear units. After that the first nuclear island concrete basement was poured at Unit 3 in March 2013, the construction has progressed with the placement of the containment bottom vessel and two other large modules in 2014. The schedule of Unit 4 is about 8-10 months behind that of Unit 3.

In 2009, the Commission of Georgia certified the overnight costs of the Vogtle project to be about 4.4 billion USD for Georgia Power and that the electricity production was expected by April 2016 for Unit 3 and April 2017 for Unit 4. In April 2013 Georgia Power reported that overnight costs have increased by about 10% to 4.8 billion USD and that the start of commercial operation would be delayed by about 18 months (it is expected in the last quarter of 2017 and 2018 for Units 3 and 4, respectively). Data is summarised in Table A.1[4].

Table A.1: Evolution of construction cost estimates for Plant Bogtle in the 2009-2013 period

	Cost estimates *[million USD]*		***Cost Increase*** *[%]*
	2009	***2013***	
EPC Base	6818	6829	0.2%
EPC Escalation	1490	1274	-14.5%
Owner's costs	1359	2400	76.6%
Total Overnight Costs	9667	10503	8.6%

The overnight costs of the project are higher than the original certification of 2009, rising from a total of USD 9.7 billion to USD 10.5 billion. Although offset by reductions in forecasted EPC cost escalations, owners' costs increase by more than a billion dollars. These owners' costs can be mainly attributed to the delays in the project's forecasted completion.

To facilitate the development of new advanced nuclear facilities, the federal Government of the United States has established, under the 2005 Energy Policy Act, two form of incentives. First, a production tax credit of 18 USD/MWh is granted for the first eight years of operation of nuclear power plants. However, the production tax credit is limited to the first 6000 MW of installed generation capacity build in the US. Second, a system of loan guarantees that could cover up to 80% of the construction costs of a new advanced nuclear facility. Under this scheme the US Government will reimburse the lender the principal and the interest in case of a default by the borrower. In exchange for providing a loan guarantee, DOE is authorised to charge sponsors a fee that is meant to recover the guarantee's estimated budgetary cost on a market basis. The DOE finalised

[4] The figures for Georgia power have been scaled to the whole plant, under the assumption that the co-owners have equally distributed shares of costs according to their ownership percentage)

the process to grant 3.46 and 3.07 billion USD as loan guarantees to Georgia Power and Oglethorpe Power, respectively, while the decision for a third loan guarantee of 1.8 billion USD to MAEG is in progress.

Market and regulatory conditions in Georgia also played an important role in the successful development of the nuclear new built at Plant Vogtle. Georgia is a regulated electricity market, with a limited numbers of players and an overall limited level of competition. The particular structure of Georgia's electricity market, which ensures the stability of the demand and a low-risk environment for electricity generating companies, is particularly favourable for the development of nuclear projects which are highly capital intensive but can provide a lower and stable electricity generation cost in the long term. For instance, electricity rates applied by Georgia Power are regulated by the Georgia Public Service Commission, which ensures a fair pricing for the customers. During the construction of Plant Vogtle, Georgia Power was allowed to charge a Construction Work in Progress (CWIP) tariff to the customers that increased electricity tariffs of about 7%. Under the CWIP, Georgia Power can meet more effectively the financial needs of a new nuclear build, which in turn will result in reducing long-term electricity cost for the customers.

The two other main shareholders of Plant Vogtle, have similar company structure and electricity price arrangements that protect them effectively from construction and market risks. Oglethorpe sells all the electricity produced via long-term contracts to the Electricity Membership Cooperatives that are co-owners of the company. The rates are determined as those sufficient to recover all cost of generation with a minor margin for the company. Oglethorpe has not reported any use of a Construction Work in Progress tariff, but given the closer relationship with its customers through its non-profit arrangement, they may have included such a financing provision in their rates with the understanding that it is directly beneficial to customers in the long term. MEAG Power supply electricity to municipal electric companies in Georgia, setting prices based on financial needs and customer interest. The municipalities are required to pay a sufficient share to cover the costs of generation plus any debt amortisation requirements

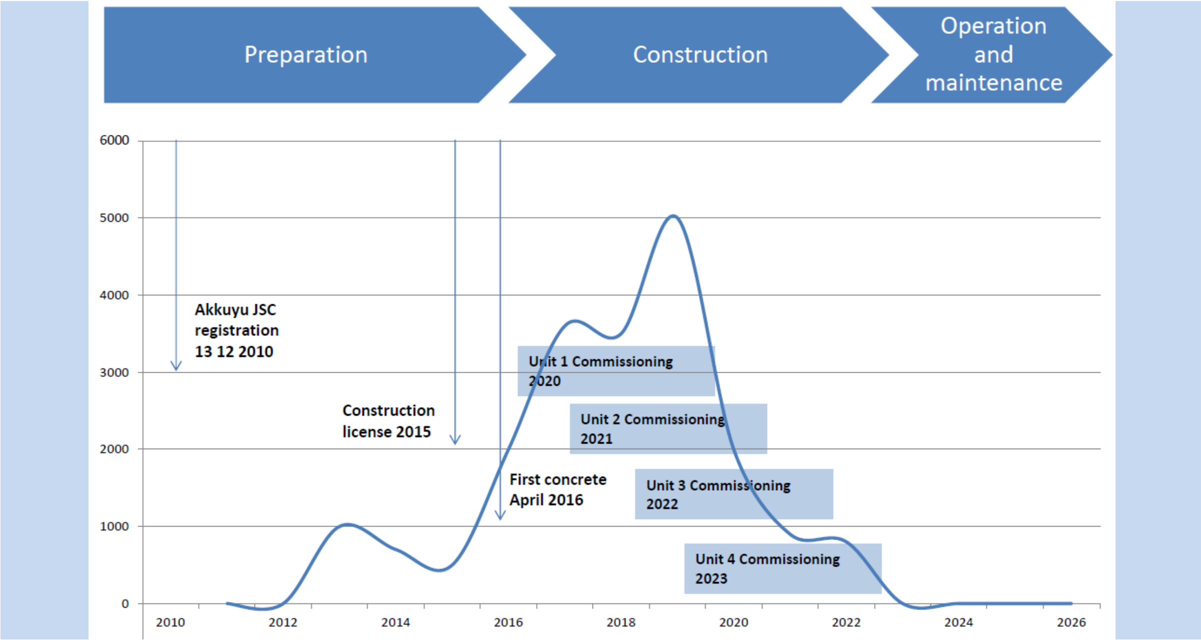
Case study 13: Akkuyu build, own and operate model

The Akkuyu nuclear power plant (NPP) project will be Turkey's first NPP and also the first project to be built under a build own and operate (BOO) financing model. In May 2010, an intergovernmental agreement between Russia and Turkey was signed for this project. Rosatom, Russia's state own nuclear company, is responsible for engineering, construction, operation and maintenance of the plant and will also initially hold 100% ownership. Located in southern Turkey, Akkuyu will have a total installed capacity of 4.8 GW comprised of four AES 2006 1200 units. The NPPs are of Gen III design with advanced safety requirements and passive and active safety systems. The designs meet all IAEA standards and post-Fukushima requirements.

Initial funding for the project will be provided by Rosatom and up to 49% of the project may be sold to investors, including equipment suppliers, off-takers and debt providers, at a later stage. The total cost of the project is estimated at USD 20 billion. Of this cost, 33% will be required for construction and assembly work, 28% for equipment and the remainder for commissioning, design and engineering, project management and other costs. The project is backed by a 15-year power purchase agreement for 70% of the electricity generated by the first two units and 30% of the last two units at an average price of US cents 12.35 / kWh. Financing for the project is currently underway and Rosatom is targeting a debt to equity ratio of 70%/30% with participation from Russian banks, investment funds and capital market participants.

Environmental assessment of the project will be completed after the adoption of EIA Report (evaluation of environmental impact), in Q4 2014. Obtaining the construction permit and pouring "the first concrete" according to the updated schedule, will be after receiving all licenses and permits, scheduled for September 2017. The start of operations for the 1st unit in accordance with the Intergovernmental Agreement, will take place 7 years after receiving all licenses and permits. Units 2, 3 and 4 will be put into operation with a one year internal.

Figure A.12: Akkuyu capital expenditure and project timeline



Source: Modified from Rosatom 2014

Cooperation between Russia and Turkey on the project covers a wide range of construction, operation and infrastructure issues with Russia responsible for engineering, design, construction management, fuel supply, operation, decommissioning and treatment of spent fuel and Turkey responsible for site allocation and infrastructure development and grid connection. The two countries are jointly responsible for nuclear energy regulation, construction and assembly works, emergency planning and public outreach. The project aims to maximise the involvement of Turkish personnel during construction and operation of the plant, with an estimated job creation potential of 10 000 during only the construction phase.

The project has highlighted a number of important lessons learned including the need to establish an effective system of consultations, government bodies and relevant agencies to support the development of a nuclear power industry. There is a need to work closely with local government bodies and consultants from the beginning of the project to understand local regulation and also to develop local expertise. Russia provided significant assistance to Turkey for the development of nuclear regulatory infrastructure, education and training as well as for public outreach and nuclear communication. Public acceptance and communication issues need to be addressed by the host country as part of the national nuclear program from the very beginning to address public concerns about nuclear. Two information centres have already been opened in Büyükeceli and Mersin and a third will be developed in Istanbul.

Akkuyu has benefitted from strong support by both the Russian and Turkish governments, highlighting the importance of government to government relationships in the development of large nuclear projects. The Rosatom BOO model is an attractive full service model for new nuclear countries with limited expertise and resources. This model is also being pursued in the implementation of Rosatom's project in Finland (Pyhäjoki), but under a smaller ownership stake of 34% which could be increased to 49%.

The Turkish and Finnish projects will serve as reference projects for Rosatom and the company plans to continue implementing its global projects under the BOO model. Rosatom believes that it could deliver an estimated 3-4 GW globally per year between 2020 and 2030. The company plans to take only minority shareholder positions in future projects. Under the BOO model Rosatom will provide engineering, construction, operation and decommissioning services for NPPs, which it hopes will create a universal reference model that can be replicated in other projects around the world, including new-comer countries striving to develop nuclear energy and related infrastructure.

Case study 14: Nuclear skills assessment in the United Kingdom

In 2008, the UK Government published a Nuclear White Paper confirming nuclear energy's role in the country's low carbon energy mix. Nuclear together with renewables and other new technologies would be needed to address the UK's energy security and climate change challenges. The paper also stated that the government should put in place measures to facilitate private investment in new nuclear plants and commit to enabling nuclear new build as soon as possible. The government recognised nuclear skills development as a key component in developing new nuclear and set up the Nuclear Energy Skills Alliance to address current and future nuclear skill needs for the UK Nuclear Programme. The Alliance brings together government, skills bodies and higher education and R&D communities to develop labour market intelligence (LMI) for nuclear and to develop interventions and mitigation options to ensure that the UK nuclear industry has the required skills to support current and future programmes.

An estimated 16 GW of new nuclear build by 2025 was initially identified by industry, then assumed to comprise 6 stations of 2 units each. The Nuclear Energy Skills Alliance published a report in 2010 outlining in detail the skills required for delivering the indicative 16 GW new build programme (Table A.2). The report showed an indicative scenario for skills need with new build construction starting in 2013 and 6 twin units being constructed with a staggered start date of 18 months between twin units. Based on this scenario a maximum of seven units would overlap between 2019 and 2021 with an estimated 110 000 to 140 000 person years (excluding manufacturing) required to complete the programme and a peak annual employment of 14 000 in the period 2020-2022. More recent work has developed the analysis of a programme, reflecting both the identification by the government of five suitable new build sites and an improved understanding of the future demands of the existing nuclear estate.

Table A.2: New nuclear workforce metrics

16 GW new nuclear	6 Twin-Unit Stations	Station (twin unit)	Construction* (twin unit)	Manufacture (twin unit)	Operation (twin unit)
Person years	110 000 – 140 000	21 200	13 000 (60%)	3 200 (15%)	5 000[b] (25%)
Timeframe of build	13 years	6 years	6 years	6 years	6 years
Employment – person years per GW	6 000	7 571[c]	4 643[c]	1 143[c]	1 786[c]
Employment – full time employment per annum	10 000	3 533[d]	2 167[d]	533[d]	833[d]
Skills levels			25% L2 60% L3 15%L4+	15-30% L2 30-40% L3 20-40% L4+	10% L2[e] 40% L3[e] 45% L4+[e]
Workforce split			40% civil 45% mechanical and electrical 15% management and supervision	10% civil 30% major nuclear 40% balance of nuclear island 20% balance of plant	60% nuclear operator 30% supply chain 10% utility HQ
Other	18 000 combined peak employment		12 000 peak employment 2021 UK supply (mostly)	1 000 [f] peak employment UK supply (mostly)	5 000 peak employment 2026 UK supply

Notes: a – Construction includes site preparation and electrical and mechanical jobs; b – thereafter 1000 fte pa for 60 years or 60 000 person years; c – uses a hypothetical EPR or AP1000 station; d – person years divided by timeframe; e – based on nuclear operator data; f – estimated contribution to peak from sector that is highly globalised- - Level 1: Elementary Occupations, Level 2: Intermediate Skills, Level 3: Skilled Technician Occupations and Associated Professional Occupations, Level 4: Professional Occupations, Level 5: Senior Managers

Source: Cogent (2010), http://www.cogent-ssc.com/research/Publications/Renaissance2.pdf

The analysis of the Nuclear Energy Skills Alliance was validated by a variety of companies and organisations that would be involved in the development of the new nuclear programme. Through this consultation process a number of emerging issues were identified that would affect the UK's capacity and capability to deliver on the programme. With respect to capacity, nuclear projects would compete with other large infrastructure projects for overlapping skills and in terms of capability the UK would need to accelerate nuclear education and training programmes to ensure that the health, safety and quality assurance needed for nuclear installations could be attainted. The lack of certainty with respect to the timing and awarding of contracts could make it difficult for small and medium enterprises to make the necessary investment in training and skills upgrades necessary. For larger firms this was not seen as an obstacle.

To address the concerns identified around supply of a sufficiently skilled workforce, a Risk Register was established to provide on-going assessment that would be used to inform the evolving skills landscape. The Risk Register divides the new build programme into five sections covering the four stages of new build activities: design and planning, equipment manufacture, engineering construction, commissioning and operation and a fifth cross cutting skills section. Each section is further divided into particular skill areas and a probability of significant skill deficit is evaluated. A score of high, medium or low is attributed to each skill category signalling the need and urgency for intervention. Of the 34 skill areas identified, 13 were given a high priority rating.

A Nuclear Labour Market Intelligence report was produced in December 2012 and defined a common Skills Delivery Plan. The plan sets out 22 priority skills areas for the delivery of the UK nuclear programme and identified over 100 key actions. Examples are: the launch of the Certificate of Nuclear Professionalism, the establishment of a Standards Advisory Group of licence holders and operators, and the development of the Supply Chain Apprentices for Nuclear (SCAN) model. The plan will be regularly updated as industry priorities evolve and will be monitored by the Skills Alliance board. To support the qualitative analysis used to identify skills priorities, the UK Department of Energy and Climate Change commissioned Cogent to develop a Nuclear Workforce Model (NWM), on behalf of the Nuclear Energy Skills Alliance, to enable dynamic modelling of the nuclear workforce supply to guide future interventions.

While the demand and, to a more limited extent, the supply of site based nuclear staff could be reasonably modelled, the project found that the pool of workers needed for construction had to be modelled separately due to the overlap in demand from other national infrastructure projects. The NWM is used as part of the collaborative reporting across the nuclear manufacture, construction, engineering construction and nuclear related workforces. It highlights potential nuclear skills pinch points, identifies opportunities for workforce transitioning and provides demand signals to training providers.

The various tools and measures taken by the UK to evaluate its nuclear skills requirements to meet its new build programme could be a model for other countries to evaluate. The implementation of the UK skills assessment required a high level of engagement and collaboration between employers and skills bodies, and also benefited from strong and continued support from government. A combination of qualitative and quantitative assessments can be used to support national skill assessments, which should be regularly monitored and updated as a country's programme evolves.

Case study 15: Setting up and qualifying a supply chain for Generation II and Generation III reactor technology: the case of heavy component manufacturing in China

With 28 reactors under construction, China's new build programme represents about 40% of the world's nuclear reactor construction projects. More than 2/3 of these reactors are Gen II+ CPR-1000 reactors derived from the Daya Bay and Ling Ao 900 MW reactor technology from vendor Framatome (now AREVA), with localisation rates that now reach more than 80%.

The equipment localisation programme that AREVA engaged with CGN started with the Ling Ao phase I project in 1995, but really developed massively with the acceleration of the Chinese nuclear programme ten years later. In 1995, there were few Chinese factories that had any experience in nuclear equipment manufacturing. To initiate a supply chain localisation programme while minimizing project risks in terms of schedule and cost, CGN defined a realistic localisation plan with AREVA and this plan was included in the supply contract. During the project implementation, CGN and AREVA set up a strict monitoring to follow and secure the components' delivery according to the project's schedule.

The localisation plan of Ling Ao phase I was successfully implemented and the project was on time and within the budget. In the later stages of cooperation between AREVA and CGN, whether the Ling Ao phase II project (contract signed in 2004) or the Taishan EPR project (contract signed in 2007, localisation for the 2nd unit), the same mechanisms were applied, in particular for the heavy components (Reactor Pressure Vessel, Steam Generators and Pressuriser) that are now manufactured in China as required by contracts.

According to these contracts, AREVA is responsible for the choice of its Chinese sub-suppliers, but also for the quality, schedule and cost of localised equipment. This requires a strong technical and quality support from the vendor to the different manufacturers in order to:

- help meet the required standard levels for nuclear components manufacturing

- keep the vendor's commitments towards its clients in terms of quality and delivery times.

At the beginning, there was a limited choice of possible industrial partners and AREVA viewed the localisation process as a phase of progressive qualification that would enable it to have the capacity to manufacture heavy components for the Chinese contracts.

For the 1st contract, Ling Ao Phase 1, signed in 1994, the customer required the localisation of one steam generator (out of 3, with AREVA responsible for complex operations such as the Inconel cladding and the deep drilling of the tubesheet), the pressuriser and some other auxiliary equipment. After a thorough technical and quality assessment, it was concluded that the two chosen suppliers could realise the localisation of these components provided AREVA invested heavily in the manufacturing capabilities and provided substantial technical assistance. There were several difficulties during the realisation due to the industrial set-up (several workshops, investments and modernisation in parallel to the manufacturing of the components, and learning of the nuclear safety culture), but components were delivered according to the planning and with the required quality standards.

For the 2nd contract, Ling Ao Phase 2, signed in 2004, corresponding to the construction of the CPR-1000 reactor derived from the 900 MW design of Ling Ao Phase 1, a greater share of localisation was requested, and comprised the manufacture in China of the 3 steam generator, the reactor pressure vessel and the pressuriser. The fabrication of these components started in a new industrial workshop in 2004 and was completed on time, with the last components delivered to the site in 2009. This second localisation phase showed the strong willingness of the Chinese partner to be autonomous, i.e. to be self-reliant in the area of heavy components for the many CPR-1000 projects to come, through the technology transfer from AREVA.

For the 3rd contract, the Generation III EPR Taishan project signed in 2009, AREVA agreed to the localisation of all the heavy components of Unit 2. This project is still ongoing: all the steam generators have been delivered, but the reactor pressure vessel and the closure head still have to be delivered. With this large localisation programme, the Chinese suppliers were able to be qualified for the manufacturing of all the heavy components of an EPR unit, with limited support from AREVA.

Table A.3: Progression in terms of localisation

Localisation	Ling Ao Phase 1, 900 MW reactor (1994)	Ling Ao Phase 2, CPR-1000 (2004)	Taishan 2nd unit, EPR 1600 MW (2009)
Steam Generators	1 (out of 3)	3 (out of 3)	4 (out of 4)
Reactor Pressure Vessel	0	1	1
Pressuriser	1	1	1

In order to ensure that the quality of the components manufactured by the local supply chain is at the same level as that of components manufactured in its own workshops, AREVA has implemented the following quality process:

1. Technical assessment of the suppliers' means and facilities, in order to verify that the manufacturer is able to realise the localisation scope subject to necessary investments (machines, equipment);

2. Quality system audit and improvement recommendations to ensure the components are manufactured in compliance with required standards;

3. Technical assistance programme on the basis of the partner's experience and capacity in manufacturing AREVA's components;

4. Implementation of a local team composed of a site manager to interface with the industrial partner, a technical coordinator dealing with all technical topic and a quality coordinator for all quality aspects (including treatments of non-conformity to the requirements);

5. Set-up of a project organisation within the partner's staff covering all aspects such as project management, scheduling, materials, workshop coordinator, non-destructive examination, welding, technology and quality;

6. Implementation of a back-office team in France to interface with the local team;

7. Implementation of a technical data package which includes all the necessary information to manufacture localised components.

The successful experience gained by AREVA in China will help it address localisation targets in countries planning new build with partial localisation of the supply chain, such as India, the United Kingdom, the Republic of South Africa, Saudi Arabia, or Brazil.

Figure A.13: Steam Generator for the Gen III EPR reactor

Source: AREVA

Case study 16: Preparing for a new build programme in an industrial country: supply chain survey

In 2009 the Italian Government decided to reconsider the nuclear option (abandoned after the Chernobyl accident). The Italian Utility Enel launched the Italian Nuclear Programme by signing a Memorandum of Understanding with the French Utility EDF to establish a 50/50 joint venture – Sviluppo Nucleare Italia – for developing the feasibility, conceptual, organization, regulatory, and economic studies for the engineering, procurement, construction, and operation of the Nuclear New Build Italian Units. The plan was to develop, construct and operate at least four Gen III EPR units (half of the capacity planned by the Italian government), with the first unit foreseen to start commercial operation in 2020.

The Italian Government (Enel major shareholder) asked Enel to develop a nuclear awareness and qualification process for Italian companies. The government's goal was to make it possible for the Italian industry to take a large participation in the new build programme (i.e. 70 % target localisation for the last unit). To do that, Enel and EDF set up the "supply chain development process" aimed at developing new nuclear skills or recovering the skills used in the past.

In October 2009, Enel and EDF supported by the Italian Industries Association started a market survey looking at the supply chain qualification process as a preliminary phase. This survey was aimed at screening the Italian industry as well as defining commodities or merchant categories to be used to optimise the future nuclear new build procurement plan, under strict nuclear safety and quality requirements, minimizing schedule and budget risks. Unfortunately, this initiative was stopped after the Fukushima Daiichi accident when a moratorium on nuclear activities was decided.

However, the preparatory work allowed Enel to conclude that in order to increase localisation content, a series of measures were needed:

- Government incentive programmes

- Partnerships with qualified nuclear international suppliers

- Sponsorship with national champions/universities/experts to assist in development of the industry.

The supply chain targeted was based on typical procurement plans for nuclear new build:

- Engineering companies, all engineering disciplines, civil, mechanical, electrical engineering,

- Manufacturing companies, such as forgings, systems and packages, turbine island, valves, piping, tanks and heat exchangers, pumps, cranes, HVAC, civil works, switchboards, cables, dry transformers, high tension transformers, diesel generators, electrical DC chargers and inverters, shielding and standard doors, field instrumentation, etc.

- Construction – Site Related - civil construction, structures, mechanical erection, electrical erection.

- Project Management companies.

The survey evaluated the following aspects:

- Technological needs: due to the high technological contents of some component/system;

- Market availability: to expand the base suppliers for high technology components/systems;

- Lead times: as the manufacturing of high technology components/systems under nuclear qualifications implied complex supply chains with long lead times, involving scheduling compliance risks;

- Purchasing / Procurement Strategy: as key decisional element for the Nuclear New Build

- Costs: because procurement of high technology components/systems under nuclear qualifications implied substantial costs, higher than conventional items, with considerable overrun risks

Information was collected on a portal set up by Enel, data was analysed and a more detailed questionnaire was sent to companies considered interesting because of their products or services. The questionnaire required a greater level of details with regard to: information on the company's equipment and machinery, supply chain system, composition and tools of the technical office, deeper economical and financial aspects, detailed references in both conventional and nuclear field, quality management system, environmental policy and safety policy. After the analysis of this second questionnaire, companies deemed to be particularly interesting were invited to schedule a meeting with Enel and EDF representatives at their factory, or at Enel offices. For each Company, an evaluation was performed, based on the following aspects: the factory shop (the machines, the tools and the processes used to carry on the production) and products/services provided by the Company. The process was completed with a final mark that classified the company according to four (4) colours (Red, Yellow, Light Green, Green). For companies with red and yellow marks, areas for improvement were highlighted, allowing them to develop a roadmap for improvement.

Critical points found during the market survey were related to nuclear steam supply system equipment, nuclear grade process equipment, very large forgings and castings, nuclear safety instrumentation & control. On the other hand, Italian industry was found to excel in areas related to nuclear plant conventional islands, including civil works, turbine, generator, large water cooling pumps, non-nuclear qualified electrical systems, high voltage transformers.

The survey showed strengths such as strong industrial know-how, long experience with Quality management system (ISO 9001:2008), leadership presence in high technological sector, strong manufacturing skills. But some critical issues were observed in relation to quality management for nuclear works, need to implement programmes for nuclear equipment qualification, need to intensify the knowledge of nuclear codes and standards, need of nuclear references, e.g. International Atomic Energy Agency, IAEA, nuclear engineering under design reviews or independent verifications usually required in nuclear, documentation configuration management, and material traceability as per stringent nuclear practices

In order to develop and/or re-establish the nuclear safety and quality culture, a series of initiatives were implemented. Technical seminars and workshops were held, and recommendations were issued on various topics, such as:

- Strengthen of the documentation management system;

- Internal self-assessment for improve Company management;

- Application of IAEA GS-R-3 “The Management System for Facilities and Activities” and associated standards;

- Organisation for nuclear safety and quality;

- Oriented Document management, configuration, and document control and

- Traceability Manufacturing processes approach, including material certification traceability and

- Qualification of special processes to nuclear standards;

- Implementation of Stakeholder satisfaction (IAEA) along with Customer satisfaction (ISO),

- Utilisation of feedback, and Lessons Learnt systems.

The survey results were highly satisfactory. More than 400 Italian companies signed up to the ENEL web procurement portal for the market survey, and responded to the questionnaires. More than 300 companies were interested in the Italian nuclear programme, especially in potential opportunities offered by new build or retrofits (abroad). During the survey, teams formed by Enel and EDF made about 130 visits to companies. 60 Italian companies were identified as currently active in the nuclear field, with qualifications by nuclear technology vendors. Some of them held especial nuclear accreditations such as the ASME (American Society of Mechanical Engineers) Nuclear Stamp. An additional 60 to 70 companies had nuclear experiences in the past, and these dormant nuclear skills that could be recovered within a reasonable timeframe with relatively minimum efforts in view of the new opportunities. More than a thousand specialised engineers, technicians, and economists from industry, universities, and government organisations, were involved.

From a qualitative point of view, the survey gave a wide and detailed picture of the Italian industry’s present capabilities and future potentialities and made the industry aware of its strengths and areas of improvement. It emphasised the need to:

- Develop a workforce with high nuclear safety culture and quality commitment;

- Develop and/or reinforce robust Quality Assurance organisation with strict quality plans and

- Increase the knowledge for ensuring high quality deliveries on time and budget.

In order to maximise the chance of a successful new build programme with high local content.

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2050 2045 2040 2035

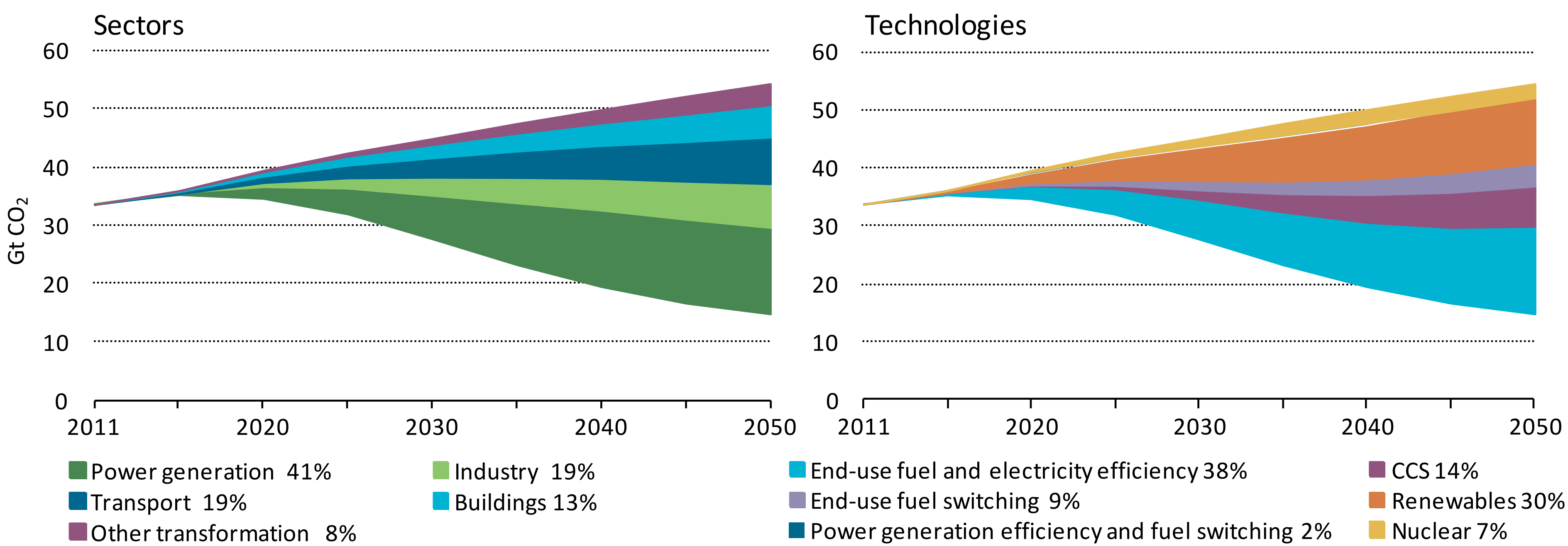
Energy Technology Perspectives

Technology Roadmap

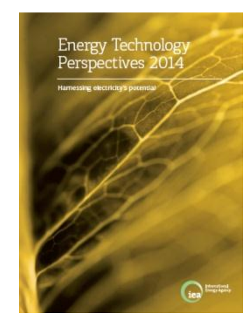
Nuclear Energy

2015 edition

IEA Flagship Publication, Energy Technology Perspectives



Source: Energy Technology Perspectives 2014



- **6° C Scenario – business-as-usual; no adoption of new energy and climate policies**
- **2° C Scenario - energy-related CO_2-emissions halved by 2050 through CO_2-price and strong policies**

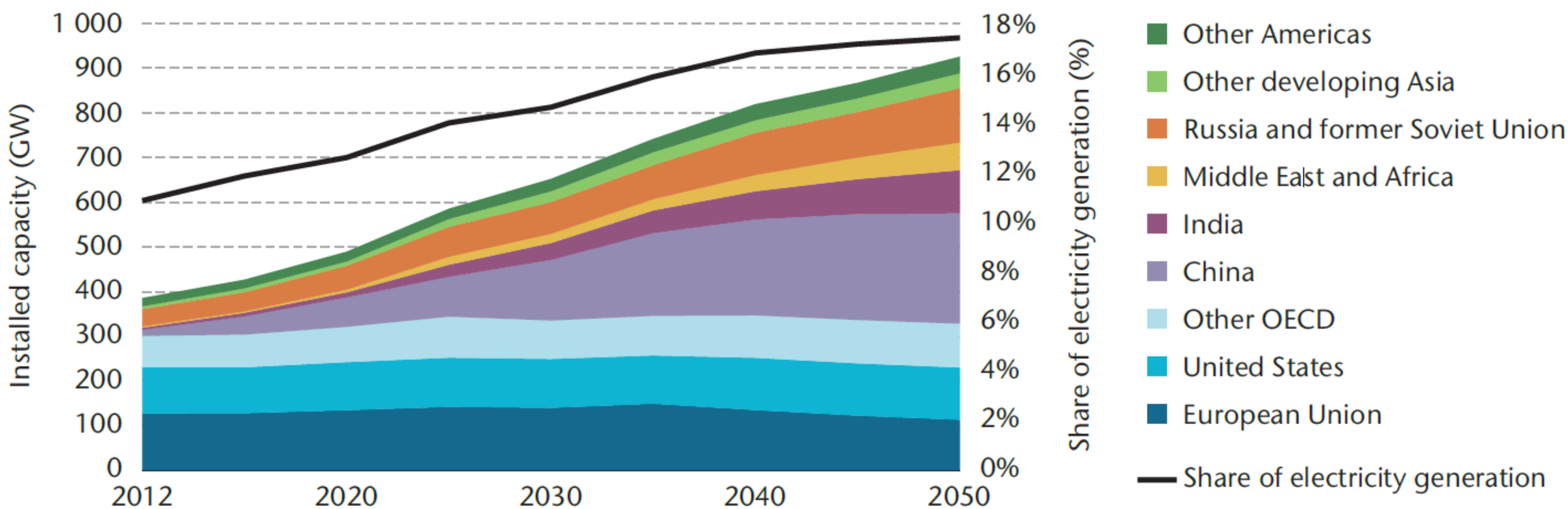
Nuclear since 2010, update of early roadmap

- Fukushima Daiichi accident (March 2011)
  - Impact on energy policies & public acceptance
  - Safety evaluations and upgrades
- Aftermath of financial crisis (2007-2008) and economic crisis
- Uranium market depreciation
- Shale gas revolution in the US (and US coal prices↘)
- Cost overruns and delays in some FOAK Gen III projects
- Lower than anticipated costs for onshore wind and solar PV

Objectives of the roadmap update

- Provide an overview of nuclear energy today, and areas of potential growth (regional analysis)
- Identify key technological milestones and innovations that can help support ambitious growth in nuclear energy
- Identify barriers to nuclear development
- Recommendations to policy-makers on how to reach milestones & address barriers
- Case studies developed with experts to support recommendations

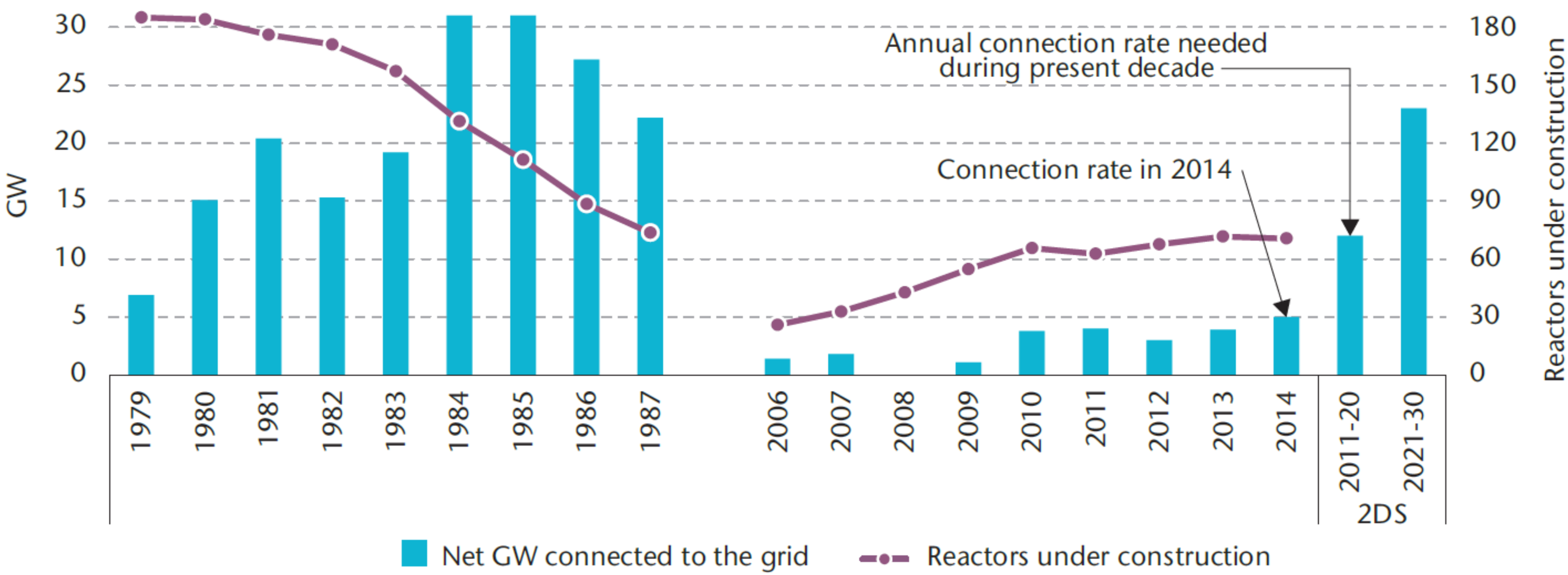
Nuclear in the 2°C Scenario (2DS)



(All capacities are gross capacities)

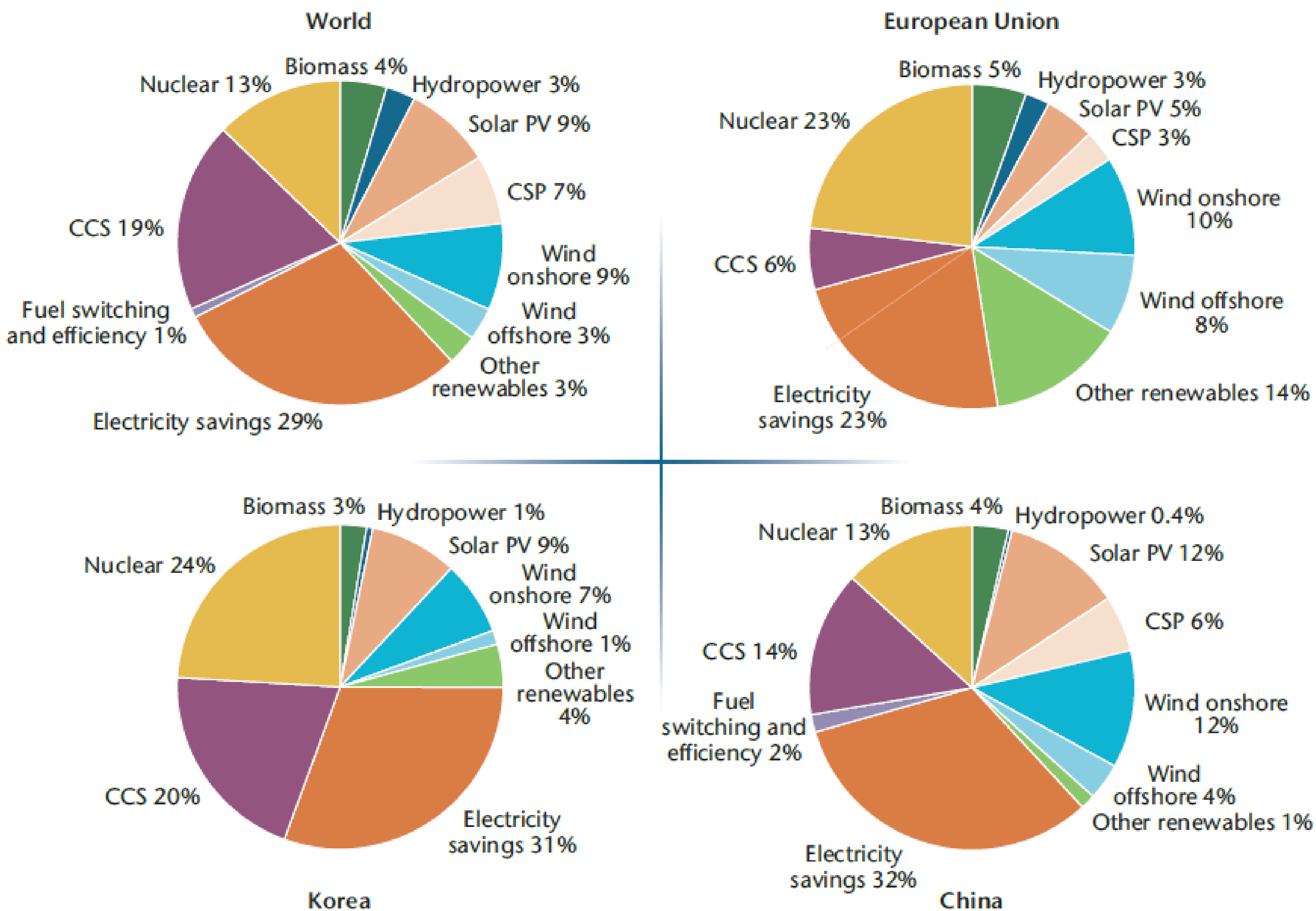
- **930 GW by 2050 (down from 1200 GW)**
- **17% share electricity (down from 24%)**
- **But still a formidable challenge (multiply current capacity by 2.3 in 35 years)**

Nuclear capacity additions

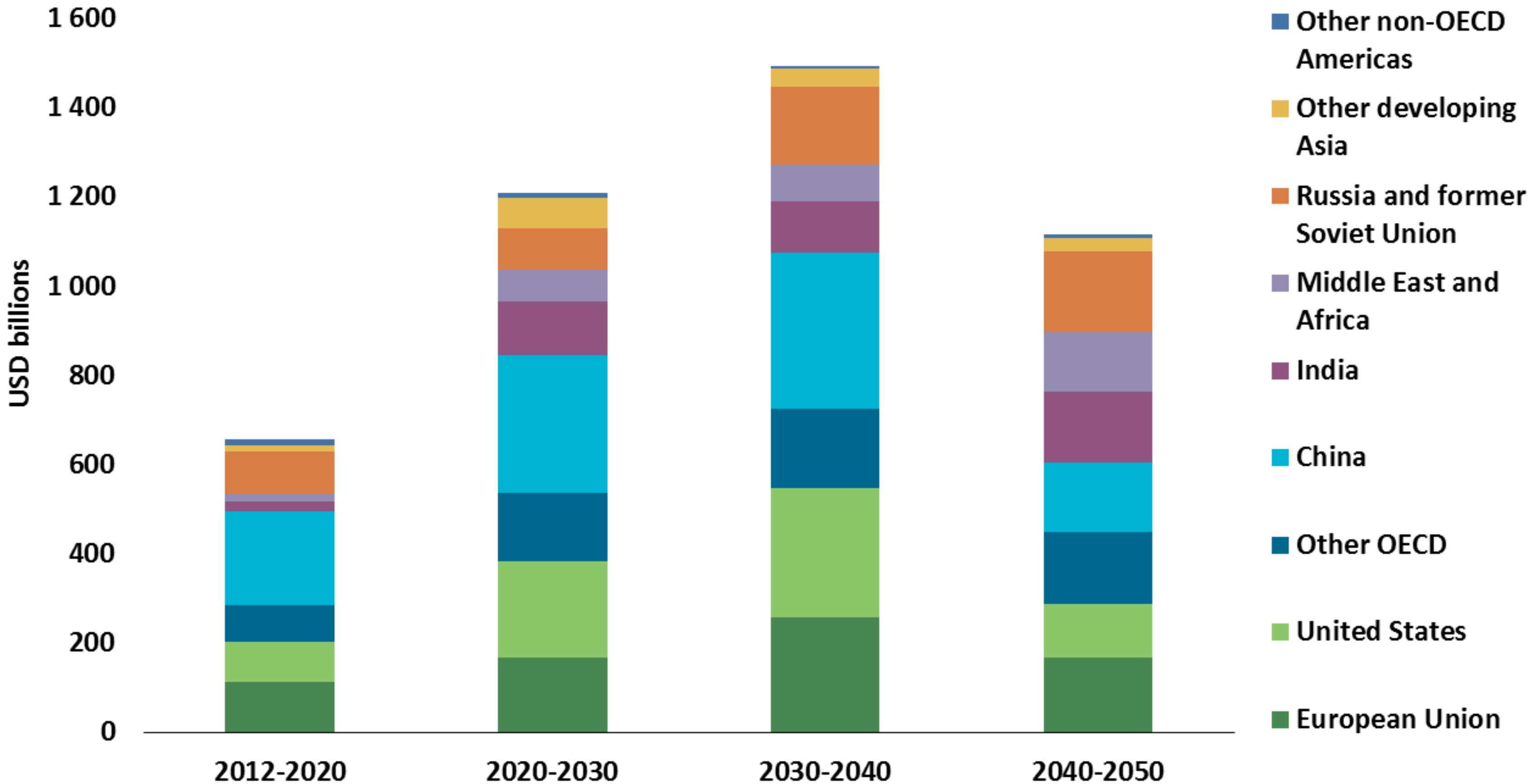


- **In 2014, 3 construction starts, 5 GW connected! (<< 12 GW/year needed this decade)**
- **Nuclear is not on track to meet 2DS targets**

Emissions reduction in the power sector in 2050



Nuclear investment requirements in 2DS, 2012-2050



Financing

- Government support key – long term strategy & policy stability (importance of technologically-neutral policies)
- Role of export credit agencies, part equity financing
- Refinancing strategies once construction completed
- Financing in liberalised markets challenging:
  - Cooperative model (Mankala principle), BOO model, …?
- Importance of de-risking nuclear projects:
  - "Build on time & to budget" requirement
  - long term power purchase agreements, CfD in UK
  - Importance of international nuclear liability conventions, clarify costs of nuclear accidents

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Roadmap actions and milestones

2015 | 2020 | 2030 | 2040

- Government
- Industry
- Academia/research
- Financial Institutions

Reactor technology

- Recognise the value of long-term operation to maintain low-carbon generation capacity and security of energy supply, provided safety requirements are met Clearer policies needed to encourage investment in both long-term operation and new build
- Optimise Gen III designs to improve constructability and reduce costs. The learning rate from FOAK construction needs to be accelerated to ensure that NOAK plants are built on time and to budget
- Accelerate the development of SMR prototypes and launch construction projects (at least 5 projects per design) that can demonstrate the benefits of modular design and factory assembly
- Recognise the long-term benefits of developing Gen IV systems in terms of resource utilisation and waste management, and support R&D and the development of at least one or two Fast Breeder Reactor prototypes to ensure technology is ready for deployment by 2030-2040
- Incorporate feed-back from operation of Gen IV prototypes to develop FOAK Gen IV commercial plants
- Put in place public-private partnerships to develop demonstration projects for nuclear cogeneration

Nuclear fuel cycle

- Invest in environmentally sustainable uranium mining to address expected long-term demand
- Ensure that policies are in place for long-term storage and disposal, including deep geological disposal of high level waste

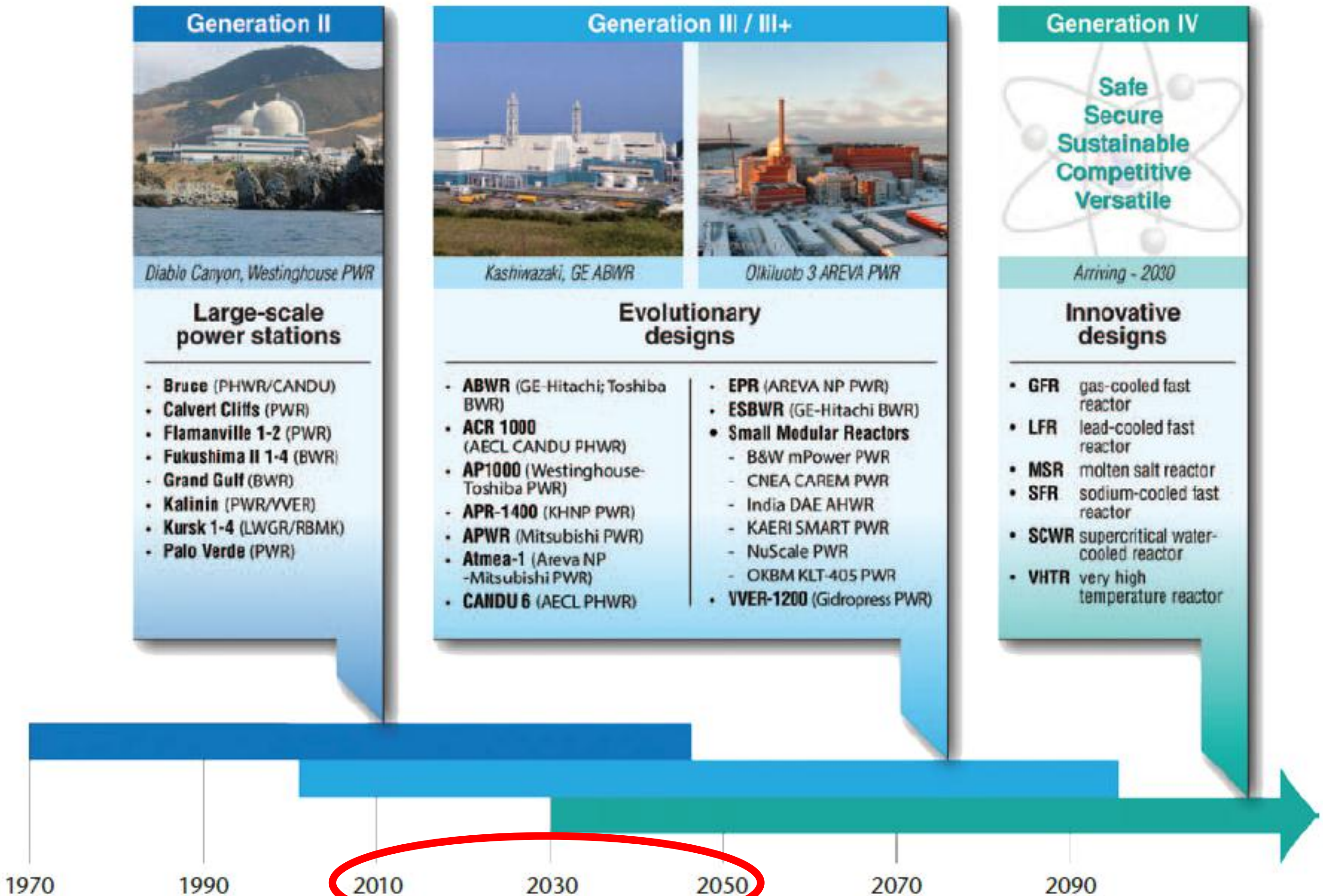
Licensing and regulation, nuclear safety

- Ensure that regulator are strong, independent and staffed with enough skilled, competent and adequately remunerated personnel to carry out their missions
- Continue to promote international co-operation through fora of regulators, industry and operators, and intergovernmental organisations and initiatives
- Develop licensing frameworks for advanced reactors, including SMRs and Gen IV reactors
- Implement post-Fukushima safety upgrades in existing reactors in a timely manner
- Enhance and monitor safety culture across the nuclear sector and at all levels of staff

Financing nuclear development

- Ensure a level playing field for all low-carbon power technologies, and provide clear policies (national but also within financial institutions, e.g. multilateral development banks) and stable lon
- Favour investment in low-carbon electricity sources through carbon-trading schemes, carbon taxes or mandates for low-carbon electricity

Reactor technology evolution



Source: Generation IV International Forum, www.gen-4.org.

Reactor technology evolution

- Safety upgrades & Long Term Operation of existing fleet
- Continuous evolution of Gen III/III+ designs:

Experience feedback from FOAK projects →

- Design simplification
- Standardisation
- Improved constructability
- Modularity
- Supply chain optimisation

→ Cost reduction; Build on time & to budget

- Small Modular Reactors
- Operational aspects
- Generation IV (Fast Neutron Reactors)
- Cogeneration / non-electric applications

Reactor technology

This Roadmap recommends the following actions:	*Proposed timeline*
Governments to recognise the value of long-term operation to maintain low-carbon generation capacity and security of energy supply, provided safety requirements are met. Clearer policies are needed to encourage operators to invest in both long-term operation and new build so as to replace retiring units.	2015-30
R&D in ageing of systems and materials is needed to support safe, long-term operation of existing nuclear power plants (NPPs) for 60 years operation or more.	Ongoing
Vendors to optimise Gen III designs to improve constructability and reduce costs. The learning rate from new build construction needs to be accelerated by rapidly integrating lessons learnt from FOAK projects (design optimisation, project management, supply chain, interactions with regulators) to ensure that NOAK plants are built on time and to budget.	Ongoing
To open up the market for small modular reactors (SMRs), governments and industry should work together to accelerate the development of SMR prototypes and the launch of construction projects (about 5 projects per design) needed to demonstrate the benefits of modular design and factory assembly.	2015-25
Governments to recognise the long-term benefits of developing Generation IV (Gen IV) systems in terms of resource utilisation and waste management, and support R&D and development of at least one or two Fast Breeder Reactor Gen IV prototypes.	2015-30
Public-private partnerships need to be put in place between governments and industry in order to develop demonstration projects for nuclear cogeneration in the area of desalination or hydrogen production.	2015-30
Incorporate feed-back form operation of Gen IV prototypes to develop FOAK Gen IV commercial plants.	2030-40

Nuclear fuel cycle

- **Uranium supply – more than adequate to meet high demand up to 2035 (Red Book)**
- **Potential for laser enrichment to reduce costs**
- **Accident Tolerant Fuel still decades away**
- **Deep Geological Disposal – recommended strategy for managing HLW, what ever the route (once-through or recycling). “Wait and See” not an option**
- **Extended storage needed, but NOT alternative to DGD**
- **Optimising waste management**
- **Importance of “fuel services” to support development**

Nuclear fuel cycle

This roadmap recommends the following actions:	***Proposed timeline***
Investments in environmentally sustainable uranium mining should be developed to address expected long-term demand.	2015-35
Governments to continue to co-operate to discuss international fuel services as a means to secure the development of nuclear power.	Ongoing
Governments should ensure that policies are in place for long-term storage and disposal, including deep geological disposal (DGD) of high-level waste, and should not defer nuclear waste planning – "wait and see" is not an option.	2015-50
Studies should be carried out to ensure that extended (dry) storage of spent nuclear fuel (SNF) satisfies the highest safety and security requirements.	Ongoing
Governments to continue to support R&D in advanced recycling technologies to reduce volume and toxicity of high-level waste.	Ongoing

Decommissioning

- **Perceived as an unresolved issue (~ waste)**
- **Issue of costs – and adequate funding**
- **Importance with respect to public acceptance**
- **Technology exists, and can be further developed to reduce decommissioning costs**
- **Also, newer designs take decommissioning into account**

This roadmap recommends the following actions:	*Proposed timeline*
Governments need to ensure that dedicated funds are set aside for decommissioning activities and that operators accumulate sufficient funding during the operation of NPPs to cover the future costs of decommissioning these facilities. Operators should regularly review the adequacy of the accrued funds.	Ongoing
Nuclear operators to ensure that shutdown nuclear facilities are decommissioned in a timely, safe and cost-effective manner.	Ongoing

Safety and regulation

- **R&D: Severe accidents, assessment methodologies (PSA)**
  - **Improved understanding, reduced conservatisms**
- **Enhanced safety requirements (impact LTO prospects?)**
- **Regulation:**
  - **Importance of strong & independent regulation stressed**
  - **Concern of 'over regulation' of nuclear industry (multiplication of regulatory requirements) $\rightarrow$ more coordination/harmonisation of requirements for more efficient regulation**
- **Safety culture needs to be enforced across the whole of the nuclear sector and at all level of staff**
- **Importance of peer-reviews (regulators, operators)**

Training-capacity building

- Perceived as one of the key barriers:
  - In nuclear countries: retirement of a significant share of current workforce in coming decades & in newcomer countries
- Many initiatives to identify needed skills, HR requirements – and set up E&T schemes
- Role of R&D to attract and train researchers/engineers

Public acceptance

- Remains a key issue
- Particularly sensitive in non-OECD / newcomer countries
- Need to provide adequate communication / targeted factual information on risks & benefits

Key actions for the next 10 years

- Offer same level playing field to all low C technologies (electricity markets)
- Industry to build on time and to budget, FOAK →NOAK
- Enhance standardisation, harmonise C&S and regulatory requirements
- Continue to share information & experience (among regulators and among operators) to improve safety
- Public acceptance must be strengthened (post F safety upgrades, fact-based information)
- Develop long-term strategy for radwaste management

DOWNLOAD THE ROADMAP AND ANNEX AT:

http://www.iea.org/publications/freepublications/publication/technology-roadmap-nuclear-energy.html

http://www.oecd-nea.org/pub/techroadmap/

FOR ADDITIONAL INFORMATION CONTACT:

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Questions?

Nuclear energy roadmap actions and milestones

2015 · 2020 · 2030 · 2040 · 2050

Legend: Government · Industry · Academia/research · Financial Institutions

Reactor technology

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- Develop licensing frameworks for advanced reactors, including SMRs and Gen IV reactors
- Implement post-Fukushima safety upgrades in existing reactors in a timely manner
- Enhance and monitor safety culture across the nuclear sector and at all levels of staff

Financing nuclear development

- Ensure a level playing field for all low-carbon power technologies, and provide clear policies (national but also within financial institutions, e.g. multilateral development banks) and stable long-term strategies for nuclear development
- Favour investment in low-carbon electricity sources through carbon-trading schemes, carbon taxes or mandates for low-carbon electricity

Training and capacity development

- In nuclear countries, undertake national skills evaluations to quantify the need for a skilled nuclear workforce to maintain the operation of existing fleets, for future decommissioning activities as well as for nuclear new build
- In newcomer countries, develop local training programmes aimed at developing a nuclear-aware and nuclear-competent workforce

Codes and standards

- Accelerate harmonisation of codes and standards to improve the integration of a global supply chain

Communication and public acceptance

- Develop targeted education and information programmes to improve the general public's understanding of the benefits and risks of nuclear energy

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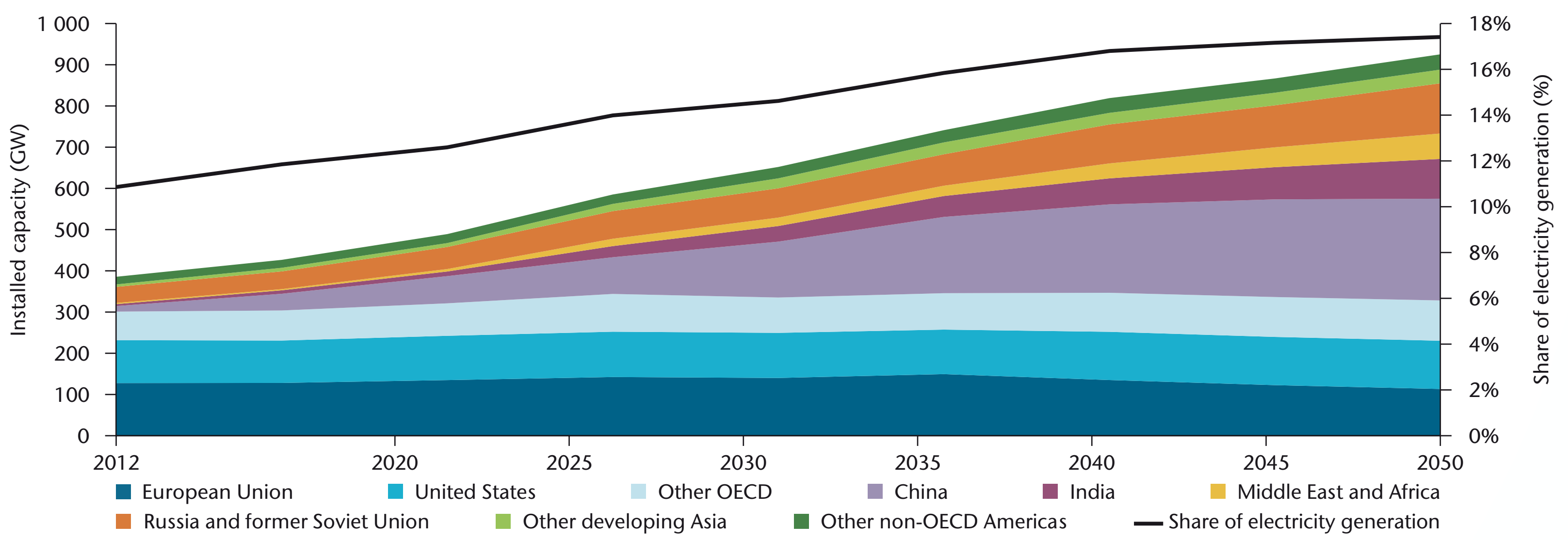
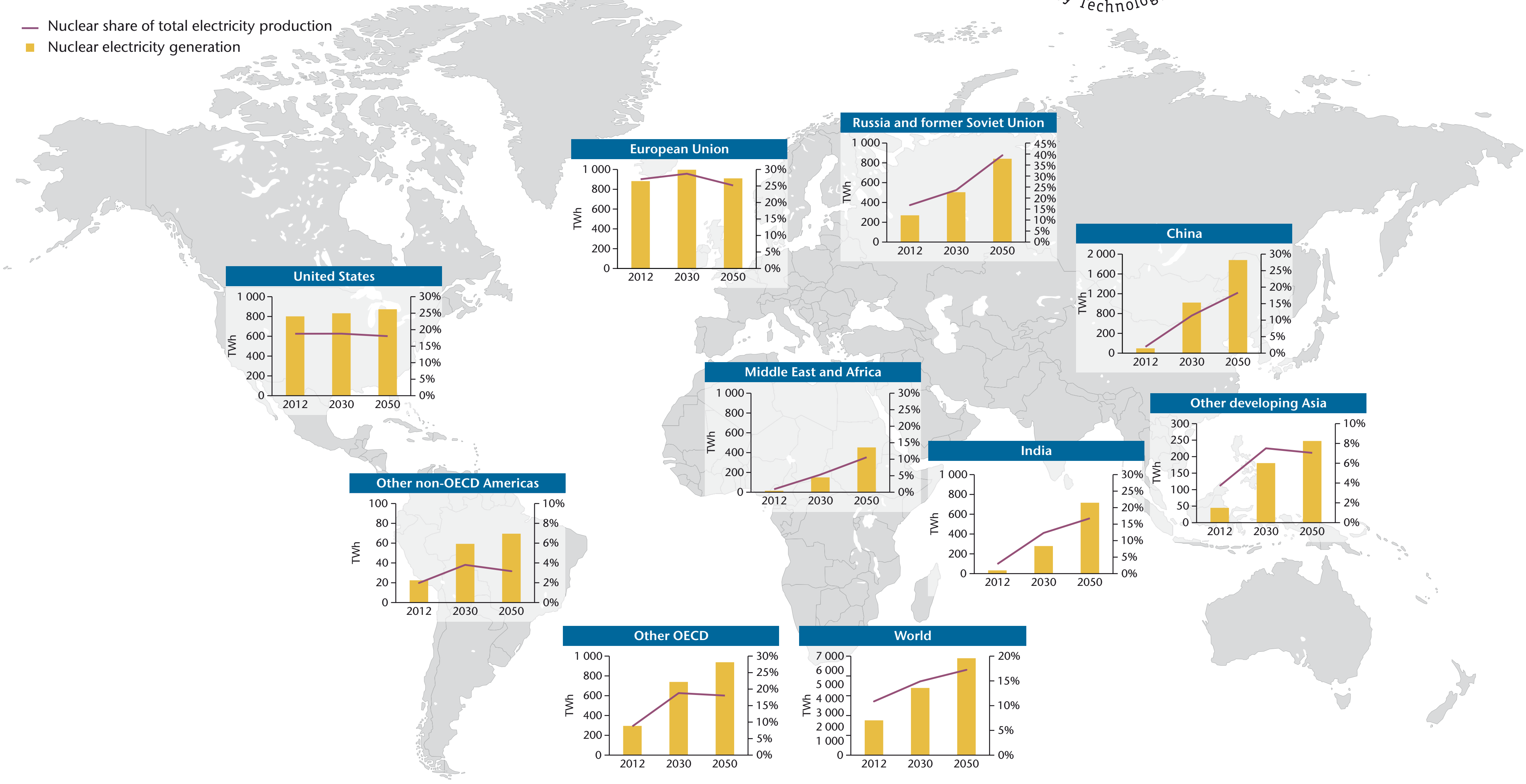
Nuclear generation capacity and share of electricity production 2012-50



Key findings

- Nuclear power is the largest source of low-carbon electricity in OECD countries and second at global level. Nuclear can play a key role in lowering emissions from the power sector, while improving security of energy supply, supporting fuel diversity and providing large-scale electricity at stable production costs.
- In the 2D scenario, global installed capacity would need to more than double from current levels of 396 GW to reach 930 GW in 2050, with nuclear power representing 17% of global electricity production.
- The near-term outlook for nuclear energy has been impacted in many countries by the Fukushima Daiichi nuclear power plant (NPP) accident. Although the accident caused no direct radiation-induced casualties, it raised concerns over the safety of NPPs and led to a drop in public acceptance, as well as changes in energy policies in some countries.
- However, in the medium to long term, prospects for nuclear energy remain positive. A total of 72 reactors were under construction at the beginning of 2014, the highest number in 25 years.
- Nuclear safety remains the highest priority for the nuclear sector. Regulators have a major role to play to ensure that all operations are carried out with the highest levels of safety. Safety culture must be promoted at all levels in the nuclear sector (operators and industry, including the supply chain, and regulators) and especially in newcomer countries.
- Governments have a role to play in ensuring a stable, long-term investment framework that allows capital-intensive projects to be developed and provides adequate electricity prices over the long term. Governments should also continue to support nuclear R&D, especially in the area of nuclear safety, advanced fuel cycles, waste management and innovative designs.
- Nuclear energy is a mature low-carbon technology, which has followed a trend towards increased safety levels and power output to benefit from economies of scale. This trajectory has come with an increased cost for Generation III reactors compared with previous generations.
- Small modular reactors (SMRs) could extend the market for nuclear energy by providing power to smaller grid systems or isolated markets where larger nuclear plants are not suitable. The modular nature of these designs may also help to address financing barriers.

Electricity generation (TWh) and share of electricity generation (%) in 2012, 2030 and 2050 in 2DS

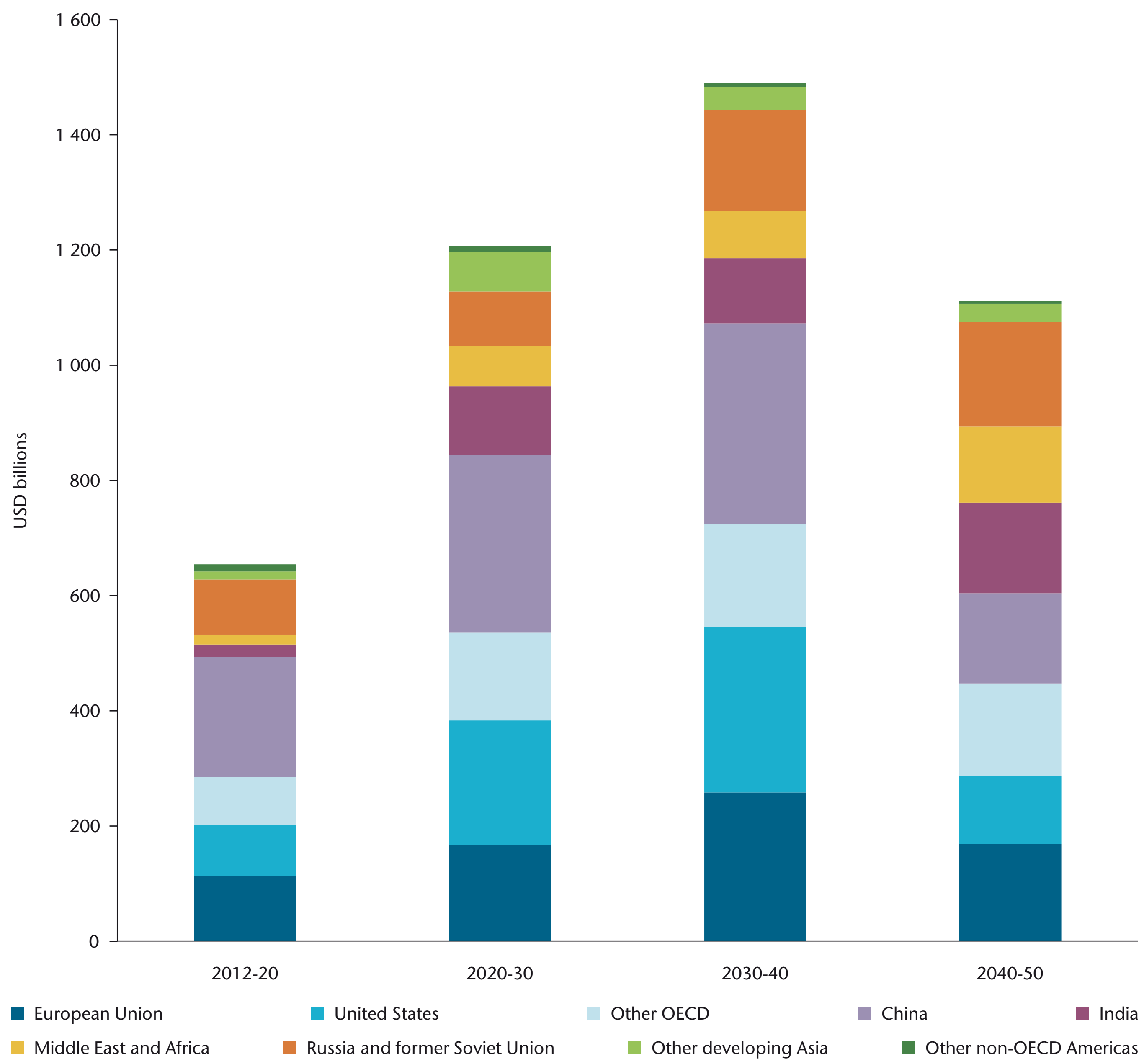


This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Key actions for the next 5 years

- Review arrangements in electricity market so as to ensure that they offer investment frameworks as favourable to new nuclear build as they are to other low-carbon technologies and allow nuclear power plants to operate effectively.
- Vendors must demonstrate the ability to build on time and to budget, and to reduce the costs of new designs.
- Enhanced standardisation, harmonisation of codes, standards and regulatory requirements, and the streamlining of regulatory licensing processes, are needed to reduce costs and to improve new build planning and performance. Industry must continue to improve quality assurance and control for nuclear structures, systems and components.
- Information exchange and experience sharing among regulators, and among operators of nuclear power plants, should be enhanced so as to improve overall safety and operational performance.
- Countries choosing to develop nuclear power for the first time must be prepared to set up the required infrastructures prior to the start of a nuclear programme. Building capacities in terms of trained, educated and competent staff for future operation and regulatory oversight is an absolute necessity and requires long-term planning.
- Actions to improve public acceptance must also be strengthened. These include implementing post-Fukushima safety upgrades in existing reactors and demonstrating that nuclear regulators are strong and independent.
- Governments that have not yet finalised their strategies for managing nuclear waste, should do so without delay. For high-level waste, deep geological disposal (DGD) is the recommended solution. Long-term planning, political commitment and strong engagement with local communities are central to this strategy.

Nuclear investment requirements in the 2DS from 2012 to 2050



Source: International Energy Agency.

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