Nuclear Decommissioning

SUBSEA ENGINEERING OPPORTUNITY
International Market Insights Report Series

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Scottish Enterprise

Contents

1. Summary

This report is part of a series of reports considering the opportunities for the Scottish oil and gas (O&G) subsea supply chain in other subsea and related markets. The report is a desk review considering the international activity of each of the sectors including where there is current activity and where there is the potential for activity based on published targets and available resource and opportunity. The report also considers the particular synergies of the given sector and the subsea oil and gas supply chain. These opportunities cover areas where there is a direct cross over and also where there are opportunities for collaboration to provide innovative solutions.

Although not a subsea industry in its own right, nuclear decommissioning provides interesting opportunities for the subsea O&G supply chain, due to the nature of the work including dismantling operations in hazardous and underwater environments. Areas of greatest crossover include inspection, repair and maintenance (IRM), monitoring, remotely operated and autonomous vehicles, project management and HR, HSE.

With over 400 civil nuclear reactors in operation globally, 75 percent of which are at least 25 years old, the worldwide nuclear decommissioning market is expected to be worth £250 billion in the decade to 2025.[1]

Table 1 below shows a summary of countries with current or imminent decommissioning of nuclear power plant (NPP) activity. The table includes the status of nuclear plants in the listed countries and type of reactors and overall capacity as well as year that the first NPP entered commercial operation. The inclusion of the operating year is to give an idea of when decommissioning may start in a given country, assuming a lifetime of 30-40 years with potential extension by 20 years or more through a Plant Life Management (PLiM) programme. Further columns in the table show the percentage of electricity that NPP produces as a percentage of the country's electricity demand, showing the importance of nuclear power to a country. This does not include the import/export of nuclear power generated electricity, where export may be an important part of the value of the nuclear industry to a country. The final column regards any ongoing or imminent decommissioning activity that may be happening in the country, including, where available the cost of decommissioning for that country. Section 4 expands on the activities in the listed countries.

Table 1: Table summarising global nuclear power plant decommissioning activity, current or imminent. Source: World Nuclear Association

Country	Number of nuclear reactors and stage of lifecycle	Type of reactor / nuclear capacity	Year of first commercially operating NPP	Percentage of electricity from NPP	Decommissioning activity / status
Armenia	1 shut down 1 operational 1 to be constructed by 2020.	VVER440 – V270 392 MWe	1976	31%	One unit in decommissioning (shut down in 1989)

[1] Department for International Trade, 2015

Bulgaria	4 shut down 2 operating 1 planned	1.9 GWe VVER1000-V320 (operating)	1974	~30%	4 VVER440 were shut down in 2002 (x2) and 2006 (x2)
France	13 shut down 58 operating	63.1 GWe	1956 / 1977 (for currently operating)	<75%	13 experimental and power reactors are being decommissioned in France
Germany	8 shut down in 2011. 9 operating	20.3 GWe 6x BWR 11x PWR	1971	Up until March 2011 <25% Now 14%	The remaining operational NPPs will shutdown in the coming decade
Italy	4 shut down (last two following Chernobyl) Some interest in restarting a NPP programme	GCR, BWR and PWR facilities	1963	0%	Shut down between 1987-1990 Decommissioning due to be complete 2024
Japan	17 Shut down 42 Operable 5 of which restarted 21 in the process of restart approval	44 GWe Mostly PWR / BWR	1966	1.7%	17 in permanent shutdown (research and commercial)
Kazakhstan	1 shut down in 1999 Plans for small cogeneration units (heat and desalinated water)	Fast reactor	1972	Looking to generate 4.5% by 2030	Shut down in 1999, co located with 3 gas fired power plants.
Lithuania	1 shut down in 2009 Proposals to return to nuclear, but on hold from 2012	RBMK	1983	When operating <70%	First RBMK plant to be decommissioned
Pakistan	5 operational 2 under construction 1 planned	1.3 GWe 1 PHWR, 4 PWRs	1972	5.5%	1 due to be shut down 2019
Russia	36 operational 6 under construction 26 planned 22 proposed	27.9 GWe	1973	~18%	Shut downs expected from 2019
Slovakia	3 shut down 4 operating	1.8 GWe VVER440-	1972	50%	3 reactors shut down

	2 under construction	V213			(2xVVER440-V230) due to accession into the EU
South Korea	1 shut down 24 operating 3 under construction 2 planned	23 GWe PWR/PHWR/OPR	1978	33%	First reactor shut down in 2017. Plans to phase out over 45 years.
Spain	2 shut down 8 operating	7.1 GWe PWR and one BWR	1968	20%	In Feb 2011, the Spanish government removed a rule limiting NPP life to 40 years, thus allowing for PLiM
Sweden	5 shut down 8 operating	8.4 GWe PWR / BWR	1975	35%	6 reactors currently in decommissioning
Ukraine	4 shut down 15 operating 2 under construction 11 planned	13.1 GWe VVER1000	1981	50%	Original shut down dates start at 2017, now likely extended to 2030s
UK	15 operational 11 planned 2 proposed		1956	21%	Around half the capacity is due to be shut down by 2025
USA	24 shutdown 99 operating 2 under construction 2 large 12 small planned 21 large 7 small proposed	98.7 GWe Largely PWR and BWR	1960	19%	24 reactors have been shut down, 11 in SAFSTOR and 4 in DECON.

Technology synergies from the subsea O&G supply chain to the nuclear decommissioning sector exist particularly around the need to investigate, monitor, manipulate and dismantle equipment underwater and in a hazardous environment. The move to a greater use of robotics, including remotely operated (ROVs) and autonomous (AUVs) vehicles is welcomed by the industry along with a range of tooling requirements. The nuclear decommissioning supply chain is particularly looking for products or innovations that will increase safety and reduce costs.

2. Subsector overview

2.1. Types of nuclear decommissioning

There are a number of strategies for the decommissioning of NPPs, the International Atomic Energy Agency (IAEA) defines decommissioning as the "administration and technical actions taken to allow the removal of some or all of the regulatory controls from a facility."[2] This definition therefore suggests that the act of decommissioning starts in the design phase of the facility. It's assumed completion is when the facility is no longer under 'regulatory control'. At this point the facility is able to be reused for another purpose or the site is returned to a greenfield state.

Since 1996, the IAEA have endorsed three decommissioning strategies, which are described below. Countries have used these strategies along with a further couple, also described below, or modifications to the endorsed strategies, to facilitate their decommissioning plans. National policy and regulations will determine what can be used for specific sites.[2,3]

IAEA endorsed strategies:

- **Immediate dismantling** ('early release' or DECON (in the US))
  This option is implemented as soon as possible after a NPP is permanently shutdown. It involves the prompt removal and processing of the radioactive material from the plant which is then transferred to a storage or disposal site. This strategy often ensures that personnel who have worked on the site are part of the decommissioning team. Whilst this retention of the working knowledge of the facility is an asset in the decommissioning process, the disadvantage of this strategy is that the radioactivity levels of the site are still high, meaning there is a greater risk with carrying out the decommissioning work.
- **Deferred dismantling** (sometimes called safe storage 'SAFSTOR' or safe enclosure)
  This option allows for time to pass from the completed shutdown of the facility to allow for residual radioactive decay to occur, often 40-60 years. This lowers the worker radiation doses during the dismantling phase. There is a risk that operational knowledge of the site and skilled personnel are lost as well as difficulty in dismantling due to corrosion and breakdown of the equipment, pipes, etc. inside the facility. There is also a risk of regulatory changes that could put more onerous requirements on the clean-up process. An additional benefit is that the deferral allows a longer period for decommissioning funds to accumulate (see section 2.3) to pay for the work, the requirement for decontamination may also be reduced in this strategy. This is often employed where a reactor has been shutdown in a site where there are still operational reactors, thereby monitoring costs, etc. are not an added cost.
- **Entombment** (Entomb)
  This strategy involves the fixing of any radioactive material within part of the original structure of the facility and fully sealing this modified section, allowing the contaminated parts to remain on the site. This essentially turns the old NPP into a near surface waste disposal site. Requirements for the regulation and safety of the entombed material will have

[2] International Atomic Energy Association, Status of the Decommissioning of Nuclear Facilities around the World, 2004
[3] World Nuclear Association, Decommissioning Nuclear Facilities, 2018

to be met. This allows for some of the site to be repurposed, and removes the need for finding a storage or disposal site and the transfer of the contaminated waste there.

Other strategies:

- Phased decommissioning
  This is variation on either immediate dismantling or deferred dismantling, where the process has to be temporarily halted due to e.g. the resolution of a technical issue, or to make provisions for where the contaminated waste will be stored or disposed of. This strategy potentially carries the same risk in terms of loss of knowledge and skills depending on the length of the decommissioning hiatus.
- Abandonment
  This case is where a facility is simply left in the condition it was when operations ceased, although some clean-up may occur in the final stages of operation. There is very little financial obligation with this strategy, at least in the short term, however, it is not an internationally accepted practice due to the risk of harm to the public and the environment. This strategy can result in a larger cost overall for decommissioning than if a strategy were adopted from the start.

2.2. Decommissioning process

There are three main stages to decommissioning a nuclear power plant, once there has been a decision to shutdown the reactor, this can be because the NPP has reached the end of its useful life, either through reaching the end of the licence period (and any extension); through a known fault with a reactor that is uneconomic to fix (e.g. the VVER-440 reactor at the Greifswald plant in Germany); or because of political decisions, such as the EU decision to phase out RMBK reactors post-Chernobyl, or the German decision to shut down all NPPs in the wake of the Fukushima disaster in 2011. Once shutdown the timeline for the decommissioning stages will vary based on the strategy being followed, as described in section 2.1. The process will largely remain similar between immediate and delayed dismantling, even over a different timeline, with firstly the removal of the spent nuclear fuel (SNF) from wet storage and its transfer to dry storage, and finally the dismantling and decontamination of the site. These stages are outlined in more detail below.

- Removal of High-Level Waste (HLW)
  On shut down or shortly after the spent nuclear fuel (SNF) and other HLW e.g. fuel element debris (FED) is removed from the reactor and transported to its dry storage location. Where this is not removed immediately, the reactor's pressure vessel is flooded with water, as it is a good absorber of emitted radiation. For most reactors, 99 percent of radioactive material is associated with the fuel.[3]
- Initial dismantling and removal of contaminated parts/management to a point to allow residual radioactive decay.
- Dismantling, demolition and remediation.
  Dismantling of the facility, demolition of the structure, and remediation of land and water to meet an agreed end-state for future use. This would be either a green or brown field site, but in either case, available for re-use.

2.3. Financing of nuclear decommissioning

All nuclear power plants (NPP) must have a system for paying for their decommissioning, as in most countries it is the operator or owner that is responsible for the cost of decommissioning. Decommissioning costs vary based on type of reactor; complexity of the site; decommissioning strategy; changes in regulation and knowledge of the plant during operation. As there are few completed decommissioning projects internationally, and these are largely experimental reactors, accurate cost estimates are difficult. A range of cost is often cited as between €0.5 (£0.44bn) and €1bn (£0.89bn)[4], although some estimates go as low as ~€300m (£266m). It is however a small fraction of the electricity generation costs. Deferring costs, through e.g. the use of a delayed decommissioning strategy, can reduce costs due to the reduction in residual radioactivity, it also allows for technical innovation and development as well as experience that could lead to cost saving practices. Deferral does have an associated cost through the monitoring and surveillance of the site during the care and maintenance (C&M) phase.

Financing methods depend on the country, but include strategies such as[3]:

- **Prepayment**
  Money is deposited into a decommissioning fund (a separate account) on a regular basis from an early stage in the project (likely to even pre-date operation of the plant). This money can only be used for decommissioning. This is an often-used strategy, and in most cases, works well. Deferred decommissioning allows a further build-up of the fund during the C&M phase. The risk is where a plant closes early due to an uneconomically repairable fault or political will and the fund has not had time to gather sufficient funds. This is the European Commission's recommended strategy.[5]
- **External-sinking fund** (Nuclear power levy)
  A decommissioning fund is created and paid into from a levy charged on the sale of electricity to consumers. This fund is out of the control of the owner/operator, but contributions are only made based during the operating lifetime of the plant. This is the main system used in the USA, where utilities are collecting 0.1-0.2 cents/kWh. It has the same risk as with prepayment in terms of insufficient funds being collected if the facility stops operating prematurely.
- **Surety fund, letter of credit, or insurance**
  This is where the utility purchases a guarantee that decommissioning costs will be covered even in the event of the utility defaulting.

There are also specific assistance packages that assist with financing decommissioning in specific circumstances, such as the European Union Nuclear Decommissioning Assistance Programme. This EU programme provides support to the Bulgarian, Lithuanian and the Slovak Republic governments, for the commitment made when they joined the EU to close their Soviet designed reactors, namely VVER 440-230 and RBMKs[6]

[4] Nuclear Energy Agency, Financing the Decommissioning of Nuclear Facilities, 2016
[5] Official Journal of the European Union, Commission Recommendation, on the management of financial resources for the decommissioning of nuclear installations, spent fuel and radioactive waste, 2006
[6] Nuclear Energy Agency, Costs of Decommissioning Nuclear Power Plants, 2016

Table 2: Some examples of cost estimates for nuclear decommissioning. Source World Nuclear Association

Country	Size of plant	Cost estimate
USA	>1100 MWe	\$0.46m – \$0.73m /MWe (£0.33m - £0.52m /MWe)
	~500 MWe	\$1.07m - \$1.22m /MWe (£0.77m - £0.88 /MWe)
Finland	2x 502 MWe	€326m (£289m)
Switzerland	1000 MWe	CHF 663m (£504m)
Slovakia	2 x 440 MWe	€1.14bn (£1.01bn)

3. Subsea engineering needs

3.1. Decommissioning process

As outlined in section 2.2 there are three main stages to decommissioning:

- Removing of spent nuclear fuel (SNF) and other radioactive material, such as contaminated waste.
- Initial dismantling and removal of contaminated parts for an immediate dismantling strategy. For a delayed dismantling strategy, this includes removal items such as non-safety related equipment and then management to a point to allow residual radioactive decay
- Dismantling, demolition and remediation to a point where a site can be released for other use.

There are technology synergies through the removal of SNF to the decontamination and dismantling of the plant with subsea engineering, which are discussed in section 3.3 below.

Many of the oldest NPPs were designed, built and operated with no or little consideration given to decommissioning. There are therefore numerous instances of areas where radioactive waste which needs to be removed is not accessible, or hazardous to get to, and where the use of robotics, automation and bespoke solutions is therefore essential.

Examples of preliminary decommissioning plans for some of the Canadian reactors can be found on the Ontario Power Generation website, under Nuclear Decommissioning. These PDPs provide an overview of the activities to be carried out, projected costings and environmental and safety considerations. They are specific for the NPPs they refer to, and to Canadian regulations on decommissioning, but can provide an overview that may be useful.[7]

[7] Ontario Power Generation, Nuclear Decommissioning, Accessed February 2018

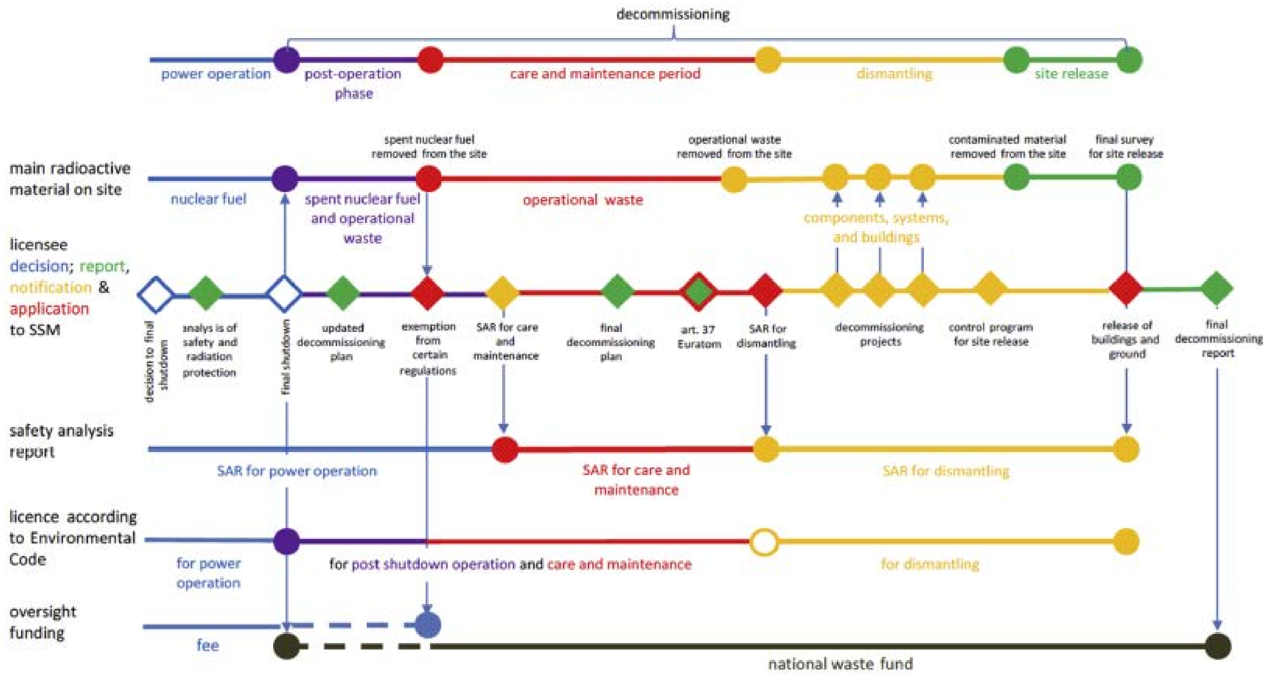

Figure 1: Example of the various timelines of a nuclear decommissioning project, based on the Swedish Radiation Authority Regulations and Environmental Code. Source. Amft Et al.

Figure 1 shows an example, from the Swedish Nuclear Regulatory Authority (SSM), of the type of activity timelines associated with the decommissioning of an NPP. Although the milestones (circles) and the required reports (diamonds) are specific to the Swedish regulations, the overall lifecycle across all decommissioning (allowing for different decommissioning strategies, e.g. DECON vs SAFSTOR) will be similar.[8]

3.2. Safety and environmental considerations

International consensus on safety procedures for the nuclear power, including mining, milling, NPPs, research reactors, etc. is documented by the IAEA into a series of safety fundamentals, requirements and guides, as shown in Figure 2.[9] These guides detail all aspects of civil, peaceful nuclear power and have a specific section on decommissioning and termination of facilities. Other aspects such as the transportation of radioactive material is covered in several parts.

[8] Amft, M., et al., Applying and adapting the Swedish regulatory system for decommissioning to nuclear power reactors - The regulator's perspective, Journal of Environmental Radioactivity, 2017.
[9] International Atomic Energy Agency, IAEA Safety Standards, 2016

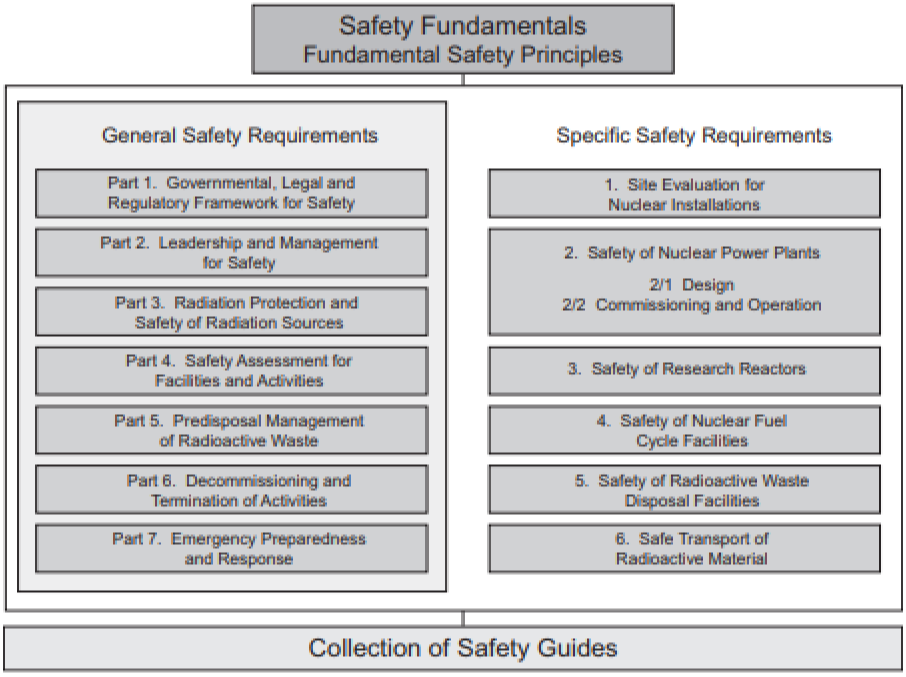

Figure 2: An overview of the long-term structure of the IAEA safety standards series. Source: IAEA

National governments may also have particular regulations that need to be complied with in addition to the requirements of the IAEA standards. This would include regulations such as the national implementation of the European Union Directive on Environmental Impact Assessments (EIA). For example, the UK requirements are set out in the Environmental Impact Assessment for Decommissioning Regulations (EIADR).[10]

3.3. Subsea Synergies

The biggest area for synergies between the subsea oil and gas sector and nuclear decommissioning is through the removal of radioactive and contaminated material. The synergies arise from the need, particularly in older NPPs, where decommissioning was not necessarily considered during the design phase, for work to be undertaken in a hazardous environment and also in difficult to access, often congested areas. The work includes the identification, classification, removal and management of contaminated materials. Given the NPPs that are currently being decommissioned were largely built in the 1970s and along with a lengthy operational life, these facilities may have been left in a 'care & maintenance' phase for a number of decades dealing with an ageing facilities also poses challenges and potential hazards. Conditions in some areas may also include dealing with gases that have been generated either by corrosion (e.g. hydrogen gas from Magnox swarf corrosion) or argon (which can be used for 'inerting' waste).[11]

- *Remotely operated equipment*

Many operations are already carried out through the use of remotely operated equipment, such as

[10] Office for Nuclear Regulation, Nuclear Reactors (Environmental Impact Assessment for Decommissioning) Regulations (EIADR), 2018
[11] Nuclear Decommissioning Authority, Research and Development, NDA Technical baseline, Issue 1, 2016

the 'uncanning' of spent nuclear fuel at reprocessing plants, and the removal of debris from cooling ponds and waste disposal sites. ROVs also provide the opportunity to remove workers for radiation exposure, therefore increasing safety and speed of work and reducing risk. Such activities include the cropping, cutting and grinding of underwater debris that would be undertaken by workers in protective clothing using long poles with equipment to carry out the tasks, in high radiation areas, the maximum work time for these workers would be two hours. An ROV can work on this in-situ, with workers piloting the tool from a safe distance. ROVs have also allowed for accurate inventory of storage ponds to be taken; radiation mapping of sites where previously only wall samples would have been able to be taken; and movement (slinging) of metal skips that had moved out of the reach of the skip handler (overhead gantry).[12]

Examples of tooling required on nuclear decommissioning ROVs includes[11]:

- Power manipulators
- Tools for sizing and handling waste items
- Grab and buckets
- Size reducing technology
- Dredging/suction tools for sludge removal
- High pressure water jets
- Video surveillance
- Clamshell grabber
- Sample retrievers
- Monitoring tools e.g. radiation sensors
- Lifting capabilities (A spent fuel rod weighs approx. 12kg)

Although some solutions are already in place, often, due to NPPs being non-standard in design, tools must be developed for a specific location and role. This can include grab and bucket tools being designed specifically for the vault that it is to be used in. Many of the storage pools are heavily congested with no complete inventory, ROVs must therefore have excellent manoeuvrability (e.g. vectored thrusters). Scaled down ROVs have been used at Sellafield, UK to penetrate blocked off areas through 6-inch holes to gain insight into what is within these redundant vaults.[12]

Other examples of ROVs used or proposed to be used at Sellafield include wall cleaner ROVs, and tracked ROVs for dismantling operations.[12]

The use of robotics, remote operation and autonomous equipment allows for activities in areas that would provide too high a radiation dose for manual tasks. Therefore, development and innovation in this area is still required to support ongoing and future decommissioning campaigns. From the experience of Sellafield Ltd[12] ROVs that have been used in the decommissioning process have not required any additional protection from the radiation exposure (e.g. 6 years operation) although the ROV does become contaminated. Protection however is required from the alkalinity of the storage pond water (commonly a pH of 11.4 to stop the fuel rods from breaking down). Protection is through coatings, particularly of aluminium parts, but also in materials choice. This is an area where the experience from NPP operations can assist the subsea industry in making equipment fit for purpose.

[12] Phil Toomey, ROVs at Sellafield, Total Decom Webinar 13 March 2018.

- *Monitoring*

If a deferred dismantling strategy is used the NPP, once the HLW is removed, will be placed into a care and maintenance (C&M) or 'safstor' phase, often lasting 40-60 years. The buildings will be sealed for site security and environmental safety, but also for maintaining conditions internally. Access will be made into the building roughly every 5 years, depending on the schedule. Monitoring of these sites is therefore important to understand what is happening whilst it is sealed. Monitoring is also important in other temporary storage facilities, such as cooling ponds and vaults due to the changes that can occur to the material that is stored there and any by-products, such as the evolution of hydrogen gas. Monitoring also occurs for anything being discharged from the site, such as treated liquid effluent being discharged as water. Remote monitoring requirements therefore include sensors for long term monitoring strategies for:

- Corrosion
- Gas evolution
- Humidity
- Temperature

Other monitoring requirements would include

- Underwater video surveillance

- *Augmented and virtual reality*

The hazardous environment coupled with the bespoke nature of NPPs really drives an opportunity for developing new techniques through the use of augmented and virtual reality. The chance to develop strategies and simulate them allows for a reduction in risk and potentially reduced cost and time to actually carry out the work. Other digital opportunities, such as data visualization for decision making and the use of haptics – communication through touch – where technology can be developed to identify objects in contaminated water with low visibility, also have high potential.

- *Operational planning, HSE*

Risk assessment and risk management are key features in both the offshore oil and gas industry and nuclear decommissioning. Strategies, risk registers and in particular planning for high impact low probability events are common threads where learning could be shared.

- *Materials, containers, pipelines*

Materials for storing higher activity waste – there may be some crossover in technology in terms of engineered barrier systems; geosphere and geological knowledge; gas generation and migration through multi-barrier systems.[11]

- *Divers*

Divers are used in nuclear decommissioning in the clearing out of cooling ponds. They will be used where the radiation has decayed enough that the worker dose will not be too high. Understanding diving operations and diving experience, even though in shallower water than oil and gas operations, will be beneficial to nuclear decommissioning. The technology around diving equipment is also an area of crossover including air-fed diving suits.[11] Examples of diving activities include those from Dungeness A (2016) and Sizewell A (2018) where divers were used to dismantle intermediate level waste (ILW) including the metal skips used to house spent fuel rods in situ to allow for safer removal and transfer of the waste to its storage location. Innovation is helping to develop these activities, and experience from the O&G will be a valuable addition.[13]

[13] Nuclear Decommissioning Authority, News, Diving into innovation at Sizewell, 2018.

4. Global market with locations of interest

In this section, Tables 4, 5 and 6 show the operational/operable, under construction and planned nuclear power plants (NPPs) across the globe, by region. In 2018 there are 449 operational/operable NPPs globally, with 44 under construction and at least 88 planned.[14] For this report our interest lies in those that are operational/operable that are coming to the end of their active lives and those that have already been shut down due to end of economic working life or political decisions. Of the operational/operable NPPs many of these, particularly in Europe and the US are reaching the end of their operating lives, presenting a vast opportunity for the nuclear decommissioning supply chain.

The following sections look at the decommission activity happening or about to happen across the global regions.

4.1. Europe, Middle East and Africa

There are 28 countries in the EMEA region that have plans to operate, are operating, or have operated NPPs. The majority of these, e.g. two thirds of EU country's NPPs are at least 40 years old having been built largely in the 1970s, and as early as 1956 in France. Middle Eastern countries such as the United Arab Emirates (UAE) and Saudi Arabia have no currently installed capacity but have ambitions, four reactors under construction and 16 planned respectively. The decommissioning for these will therefore be many decades away as new build reactors have planned lifetimes in excess of 60 years, although shows that there will be a long-term pipeline of projects – these reactors at least will be built with decommissioning being considered from the design stage. Africa has two operational units in South Africa, which commenced operations in 1984, with three more proposed in the country and plans also for NPPs in Egypt. The main focus therefore is on the European countries, particularly those with the oldest fleet, and those whose political decisions have forced an early shut down, such as Germany.

Table 3: Countries with previous, current or planned activity in nuclear power in the EMEA region. Source: World Nuclear Association

Country	Number of nuclear reactors and stage of lifecycle	Type of reactor / nuclear capacity	Year of first commercially operating NPP	Percentage of electricity from NPP	Decommissioning activity / status
Armenia	1 shut down 1 operational 1 to be constructed by 2020.	VVER440 – V270 392 MWe	1976	31%	One unit in decommissioning (shut down in 1989)
Belarus	1 under construction	Expected 2400 MWe	Expected 2019		

[14] World Nuclear Association, Country profiles. Accessed February 2018

Belgium	7 operational	PWR 5.6 GWe	1974	~50%	Phase out by 2025
Bulgaria	4 shut down 2 operating 1 planned	1.9 GWe VVER1000-V320 (operating)	1974	~30%	4 VVER440 were shut down in 2002 (x2) and 2006 (x2)
Czech Republic	6 operating	VVER440/V213	1985	~33%	Indefinite licences on four reactors
Egypt	4 proposed reactors	Expected 4.2 GWe			
Finland	4 operating 1 under construction 1 in planning	2xBWR 2x VVER440/ V213 EPR in planning 2.7GWe	1977	30%	Shut downs from 2027 - 2038
France	13 shut down 58 operating	63.1 GWe	1956 / 1977 (for currently operating)	<75%	13 experimental and power reactors are being decommissioned in France
Germany	8 shut down in 2011. 9 operating	20.3 GWe 6x BWR 11x PWR	1971	Up until March 2011 <25% Now 14%	The remaining operational NPPs will shutdown in the coming decade €17bn[15]
Hungary	4 operating	1.9 GWe VVER440-V213	1982	>33%	Scheduled closing dates 2032-2037
Iran	1 operating 4 planned 7 proposed	915 MWe PWR	2013	Approx. 1.5%	No decommissioning at present as new sector
Italy	4 shut down (last two following Chernobyl) Some interest in restarting a NPP programme	GCR, BWR and PWR facilities	1963	0%	Shut down between 1987-1990 Decommissioning due to be complete 2024

[15] Steitz, C., Dismantling nuclear: German power firms sell new skills, Reuters, 2017

Jordan	1 in planning, to be constructed by 2025		Exp. 2025	Exp. 50%	
Kazakhstan	1 shut down in 1999 Plans for small cogeneration units (heat and desalinated water)	Fast reactor	1972	Looking to generate 4.5% by 2030	Shut down in 1999, co located with 3 gas fired power plants.
Lithuania	1 shut down in 2009 Proposals to return to nuclear, but on hold from 2012	RBMK	1983	When operating <70%	First RBMK plant to be decommissioned
Mongolia	Possible sites from 2021				
Netherlands	1 operating 1 research reactor 1 proposed	0.48 GWe PWR	1973	Research reactor produces 60% of Europe's medical isotopes.	The Dutch reactor is licensed to operate until 2034.
Poland	2 planned sites	6 GWe	Exp. 2029		
Romania	2 operational 2 planned	1.3 GWe Candu 6	1996	<20%	No published shut down dates
Russia	36 operational 6 under construction 26 planned 22 proposed	27.9 GWe	1973	~18%	Shut downs expected from 2019
Saudi Arabia	16 planned	Exp. 17 GWe by 2040		Exp. 15% by 2040	
Slovakia	3 shut down 4 operating 2 under	1.8 GWe VVER440-V213	1972	50%	3 reactors shut down (2xVVER440-

	construction				V230) due to accession into the EU
Slovenia	1 operating (shared with Croatia) 1 Under construction		1981		Expected close 2043
South Africa	2 operating 3 planned	1.8 GWe PWR	1984	5%	40 year operational life expectancy
Spain	2 shut down 8 operating	7.1 GWe PWR and one BWR	1968	20%	In Feb 2011, the Spanish government removed a rule limiting NPP life to 40 years, thus allowing for PLiM
Sweden	5 shut down 8 operating	8.4 GWe PWR / BWR	1975	35%	6 reactors currently in decommissioning
Switzerland	5 operating	3.3 GWe PWR / BWR	1969	40%	Unlimited operating licences. Planned nuclear phase out by 2034
Turkey	12 planned and proposed		2023		
Ukraine	4 shut down 15 operating 2 under construction 11 planned	13.1 GWe VVER1000	1981	50%	Original shut down dates start at 2017, now likely extended to 2030
UAE	4 under construction		2018		
UK	30 shut down 15 operational 11 planned 2 proposed		1956	21%	Around half the capacity is due to be shut down by 2025

By 2025, it is estimated that over a third of the EU's currently operational reactors will be at the end of their lifecycle and in need of shutdown.[16] The value of the European market could therefore be worth €60bn (£53bn) by 2025, based on 123 reactors being dismantled at a cost of €500m (£442m) each. [17]

European experience of decommissioning so far has been limited to small and prototype plants. Knowledge and expertise, as well as tooling, will have to match the larger and more complex projects of the current and future decommissioning activities.[17]

FRANCE has the largest NPP fleet in Europe, with nuclear power being a significant portion of their electricity supply contributing approximately 75%. The early reactors were gas-cooled UNGG (Uranium Naturel Graphite Gaz), similar to the British Magnox, but developed independently. There were nine of these units, and a further two fast reactors, one of which ran for 30 years. The current fleet are all PWR of one of 3 types. Due to the age of the fleet, the current average age is 30 years (as of 2015), there have already been decommissioning activities in France with 13 experimental and power reactors currently in the decommissioning process. The plans for dismantling are well developed, although are waiting on a repository for the intermediate level waste (ILW) and alpha-contaminated graphite (from the UNGG reactors) repository. Of the current dismantling projects Chooz A is deemed to be the most representative of currently operating NPPs, dismantling is on time and on budget and due to be complete by 2022. A further NPP, Fessenheim, is earmarked to be closed early most likely in time with the opening of Flamanville 3 in 2019. There will be a decommissioning project associated with the closure of the two reactors in this NPP. [18]

- French Atomic Energy Commission (CEA)
- Nuclear Policy Council (CPN)
- France International Nuclear Agency (AFNI)
- Institute for Radiological Protection & Nuclear Safety (IRSN)
- The Nuclear Safety Authority (ASN)
- Ministry of Ecology, Energy, Sustainable Development and the Sea (MEEDDM)[19]

BELGIUM has plans to phase out nuclear power by 2025, with the oldest reactors (two out of seven) having been shut in 2015. There has been some discussion as to the details of the phase out, but the remaining five sites will reach 40-years of operation by 2022 and 2025 (50 years for one plant, Tihange 1). The decision to keep older plants open is based on energy security (nuclear power contributes 50% of electricity supply) and ability to meet carbon reduction targets. The responsible agencies include: the Federal Agency for Nuclear Control (FANC); the AMPERE commission: Commission for the Regulation of Electricity and Gas (CREG); the Association Vincotte Nuclear (AVN), covering nuclear safety; and the Organization for Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS).[19, 20]

[16] European Commission, Decommissioning of nuclear facilities, accessed January 2018.
[17] Thomauske, B., Moloney, B. and Charlier, F., The Strategic Challenge of Capacity for German Decommissioning, International Symposium of Preparation for Decommissioning, 2016
[18] World Nuclear Association, Country Profile: France, Accessed January 2018
[19] Frost and Sullivan, Mega Trends report, European Nuclear Power Sector—Trends and Opportunities, 2012
[20] World nuclear association, country profile Belgium, Accessed January 2018

Decommissioning experience has been gained from the shutdown and dismantling of experimental reactors, a reprocessing plant (the first to be decommissioned, after ceasing operation in 1074) and a fuel fabrication plant. Belgium's NPP fleet is exclusively PWRs.[20]

BULGARIA has two operating VVER1000 model V320 reactors on a site, Kozloduy NPP, that had also had further four VVER440 type reactors. The original reactors, Kozloduy 1-4, were shut down in 2002 (1&2) and 2006 (3&4) ahead of Bulgaria joining the EU. The operating reactors are licensed to 2019 and 2027 with plans for operation until 2047 and 2051, and a further reactor at the site is planned for operation in the mid 2020s. [21]

Licences for the decommissioning of Kozloduy 1&2 were issued by the Bulgarian Nuclear Regulatory Agency (NRA) in 2014, after the operating licences were transferred to State Enterprise 'Radioactive Waste' (SE-RAW) in October 2010. The decommissioning licences permit the carrying out of decommissioning activities such as: decontamination, dismantling, management of materials and waste; management of the site. Funding for the decommissioning of Kozloduy 1-4 is from the national decommissioning fund as well as funding from the European Bank for Reconstruction and Development (EBRD) and the European Commission. Projects as part of the decommissioning include the development of the *Information Centre for Decommissioning* which will include the identification of new media forms, models and equipment required for the purposes of the information campaigns for the decommissioning activities at Kozloduy NPP.[22]

The **CZECH REPUBLIC** has six operational reactors in two plants, all VVER-440 model V-213, four of which have an indefinite licence after uprating and two with licences to 2020 & 2022, but with only 20-year operational lifetime at that point, it is unlikely that decommissioning will commence in the immediate future. The Czech Republic has strong ambitions to increase the number of reactors with proposals for 4 more reactors at the existing sites. The relevant and regulatory bodies are the Czech state power company (CEZ); Czech State office of Nuclear Safety (SUJB); Radioactive Waste Repository Authority Regulatory Authorities (RWRA) and Ministry of Industry and Trade (MIT).[19,23]

FINLAND has four operating nuclear reactors across two plants, there are two BWR type and two VVER-440 model V-213. There is an EPR type reactor currently under construction. The operating reactors have lifetimes extended to 60 years after significant uprating, subject to safety evaluations each decade, resulting in shut downs likely to be in the late 2020s – late 2030s. The relevant and regulatory bodies are the Finnish Ministry of Trade and Industry Regulatory Authorities (KTM) and Finland's Radiation and Nuclear Safety Authority (STUK).[19,24]

GERMANY had 17 operating nuclear reactors until 2011, when in the wake of the Fukushima disaster, it immediately closed eight reactors, and the remaining nine are to be shut down by 2022. The reactors are a mix of six BWR type and eleven PWRs. Germany also has a fleet of previously shut down reactors, dating from the reunification in 1990 when 5 (4 operating, one under construction)

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[21] World Nuclear Association, Country profile, Bulgaria, Accessed January 2018
[22] European Bank for Reconstruction and Development, Procurement Notice, Kozloduy NPP Units 1-4 Decommissioning Programme and the National Disposal Facility, 2017
[23] World nuclear association, Country profile, Czech Republic, Accessed January 2018
[24] World nuclear association, Country profile Finland, Accessed January 2018

VVER440 were shut down. Other reactors, including those that had had faults and were deemed uneconomic to repair and restart, such as Greifswald and Gundremmingen, are also part of the decommissioning process. Of these 19 previously shut down (commercial and experimental) reactors, 11 require full demolition and site clearance. Some are dismantled, others are currently in SAFSTOR. As the decommissioning of the 2011 shut downs, and the ones to come by 2022, are premature from the expected operating lifetime of the sector, the German decommissioning sector is not fully prepared for the level of work required to complete these projects. There are therefore enhanced opportunities for Scottish supply chain companies to work within this sector, providing potentially cost saving innovations and techniques. The decommissioning of the German NPPs is anticipated to cost around €48 billion[25]

ITALY had operated four nuclear reactors, with the first two closed in 1982 and 1987 and the remaining two being permanently shut down in 1990 in the wake of the accident at Chernobyl. Initially put into SAFSTOR, an accelerated dismantling strategy was adopted in 1999, with decommissioning due to be complete and the sites released for new uses in 2024. Licences were transferred to a new company, the Nuclear Plant Management Company (SOGIN), who report to the Ministry of Economy and Finance and the Ministry of Productive Activities. The cost of decommissioning and waste management of Italy's NPPs is anticipated to be €7.2 billion (£6.3bn).[26]

At the invitation of the Italian Government the IAEA conducted an integrated review of radioactive waste and used fuel management, decommissioning and remediation programs in Italy in 2017. The project was referred to as 'Artemis'. Good decommissioning practices were identified, and noted that SOGIN used a mix of proven technologies and novel approaches to solve decommissioning challenges. However, the review highlighted that SOGIN could develop innovative solutions to address technical challenges, which could provide an opportunity for companies to develop technology alongside a team with experience in decommissioning activities.[27]

SLOVAKIA is heavily reliant on nuclear power, with almost 50 percent of its electricity generated from NPPs. As a condition of Slovakia's accession to the EU the two VVER440-V230 reactors were permanently shut down in 2006 (Bohunice 1) and 2008 (Bohunice 2), despite having significant safety upgrades which had addressed vulnerabilities according to the IAEA. A further smaller reactor Bohunice A1, was shut down in 1977 after a series of accidents. A strategic decommissioning plan was developed for the reactors at the Bohunice NPP site and decommissioning activities are underway. Spent fuel has been removed from the site and dismantling operations are due to complete in 2025 with the site being released as a brown field site. JAVYS is the decommissioning licence holder for the sites and is responsible for the decommissioning. The cost of decommissioning of Bohunice 1&2 is anticipated to be €1.239 billion (£1.1bn).[28,29]

SPAIN has seven operational reactors, and 3 shut down reactors, one of which – Santa Maria de Garona- has prospects of being restarted. The two permanently shut down reactors Vandellos 1

[25] World nuclear association, Country profile, Germany, Accessed January 2018
[26] NucNet, Italy's €7.2 Billion Decommissioning Cost Estimate is Robust and Thorough, Says IAEA, 2017
[27] World Nuclear News, IAEA praises Italy's decommissioning efforts, 2017
[28] World nuclear association, Country profile Slovakia, Accessed January 2018
[29] IAEA, Country Nuclear Power Profile, Slovakia, Accessed January 2018

(UNGG) and Jose Cabrera (PWR) were shut in 1990 and 2006 respectively. Under Spanish rules, shut down sites are passed from the operators to the state company for decommissioning and waste management, ENRESA once the decommissioning permit is granted. Initial decommissioning work has taken place at Vandellos 1, and in 2003 the site was placed into SAFSTOR for 25-30 years. The cost of the works to the point of SAFSTOR was €93 million (£81m). Jose Cabrera is in DECON, with anticipated completion in 2018 and a cost of €150 million (£131m).[30]

SWEDEN has eight operating nuclear reactors and six reactors currently in decommissioning, one of which has never operated. The permanently shut down plants ceased operation in 1974 and then between 1999 and 2017. The most recent shut downs Oskarshamn 1 & 2, are currently having fuel removed and internal dismantling activities, with full dismantling for Oskarshamn 1 starting in 2019. Regulation is through the state body Swedish Radiation Safety Authority (SSM) and the NPP operator is responsible for decommissioning. There is also a body in Sweden for the management of nuclear waste as well as an R&D remit, Swedish Nuclear Fuel and Waste Management Co (SKB), is jointly owned by the NPP utilities. Funding of decommissioning is through a Nuclear Waste Fund that has been contributed to through the lifetime of the NPP by the operator, with contribution levels set by the government. Current Swedish decommissioning experience is limited to small research reactors and they are looking for international experience to supplement their own activities. Sweden's decommissioning strategy preference is based on the 'immediate dismantling' or DECON strategy.[31,32,33]

Barsebäck NPP and Oskarshamn NPP are estimated to have a decommissioning cost of SEK 6.4 billion (£548m), with the overall estimate for nuclear decommissioning in Sweden being over SEK 12 billion (£1bn). It is also estimated that the dismantling of Barsebäck will take only 5 years, the reduced time is through preparations whilst the plant is still running, e.g. establishing levels of radioactivity across the plant and therefore the level of decontamination required.[34,35]

The UNITED KINGDOM has one of the most advanced nuclear decommissioning sectors in the world based on the age, due to being an early mover in nuclear power, and the complexity of its sites currently engaged in decommissioning, Dounreay and Sellafield, amongst others. The UK has 30 permanently shut down reactors, which started operation in 1956.

In the UK strategic decommissioning policy is the responsibility of the Nuclear Decommissioning Authority (NDA) who own the former nuclear sites within the UK and the decommissioning work is carried out through the Site Licence Companies (SLCs). The NDA's budget for 2018/19 is £3.06 billion. This approach leads to an estate-wide strategy to decommissioning rather than site by site activity.[36] The NDA takes an active role in the development and adoption of new technology, including running competitions to support innovation. E.g. an £8.5 million competition, run in conjunction with Innovate

[30] World Nuclear Association, Country profile, Spain, Accessed January 2018
[31] Vattenfall, Decommissioning of Nuclear Power Plants – what are the challenges?, 2016
[32] Swedish Radiation Safety Authority, Cost Estimating for Decommissioning Nuclear Reactors in Sweden, 2014
[33] World Nuclear Association, Country profile, Sweden, Accessed January 2018
[34] Swedish National Council for Nuclear Waste, Decommissioning of Nuclear Facilities in Sweden, Report 7e, 2007
[35] SKB, Decommissioning of nuclear power plants, 2005
[36] Nuclear Decommissioning Authority, About Us webpage, accessed February 2018

UK, on concepts for the dismantling of 'cells' at Sellafield. Five £1.5 million prizes were awarded to consortia in 2018, including one led by Wood., who are looking at robotic solutions to dismantling these heavily radioactive rooms. The prize money at this stage is for prototype development for testing in a simulated radioactive environment.[37]

Current priorities for the NDA in the next decade include the removal of SNF from all Magnox reactors; four Magnox sites to have entered 'Care and Maintenance'; and progress on operations such as the retrieval of items and waste from legacy ponds and silos at Sellafield, this is an area of particular interest for subsea synergies given the high-hazardous nature of these tasks and the requirement for robotics and automation (see section 3.3).[38]

RUSSIA is the world leader in fast neutron reactor technology, as well as its historic experience in the nuclear power plants from the beginning of this industry, with the first reactor generating electricity at Obninsk in 1954. Nuclear power in Russia is also a big export business with 20 confirmed or planned constructions abroad. Russia itself has 36 operational reactors, which mostly came online in the 1970s and 1980s, although there are more recent sites and an ambition to build more as well. In terms of decommissioning, Rosenergoatom, the operational subsidiary of the state nuclear energy company Rosatom, released a plan in January 2015. The plan states that 9 units will be decommissioned by 2023, including four VVER reactors; three RBMK reactors and four small Bilibino EGPs. Further plans include the retirement of three RBMK reactors and the BN-600 reactor by 2027.[39] Discussions are already taking place between the UK and Russia in relation to decommissioning activities, as exampled by the UK-Russia Nuclear Waste and Decommissioning Roundtable in July 2017.[40] In December 2016 the Novovoronezh 3 reactor was shut down. This is the first VVER440 to enter the decommissioning phase, and with six in Russia and a further 29 in other countries, there will be experience and technology testing and development that will happen here that will be relevant to the future decommissioning of all these plants, worth an estimated $29 billion (£20bn).[41]

In ARMENIA one nuclear reactor provides 31% of electricity for the country. The NPP, Metsamor, had two VVER440 reactors that operated from 1976 and 1980, however, both were shut down in 1989 after safety concerns following a strong earthquake. In 1996 one of the units was restarted and is still operating today. The plant in undergoing an upgrade (2017) which will see a small increase in capacity and a renewed licence until 2026. The operating plant will be retired once the new planned project is operational. The 1976 reactor, which was shutdown in 1989 is now being decommissioned. The reactors are V270 types as they are designed for increased seismic activity, this could mean added complexity for the decommissioning process.[42]

The UKRAINE has three reactors in decommissioning at the Chernobyl NPP site with the activity being undertaken by the State Specialized Enterprise "Chernobyl NPP" (SSE ChNPP), who are the enterprise responsible for the decommissioning of all NPPs. The operating fleet in the Ukraine, which consists of

[37] NDA, News, Robots compete in nuclear decommissioning challenge, 2018
[38] NDA, Nuclear Decommissioning Authority: priorities and progress, accessed February 2018
[39] World Nuclear Association, Country profile, Russia, accessed February 2018
[40] Rosatom, The UK-Russian Nuclear Waste and Decommissioning Roundtable, 2017
[41] World Nuclear News, Russia closes world's first VVER-440 reactor, 2016
[42] World Nuclear Association, Country profile Armenia, Accessed January 2018

15 VVER1000 reactors, had scheduled closed dates starting in 2017 but all are looking at extended lifetimes out to the 2030s.[43,44]

KAZAKHSTAN had one NPP, Aktau, that was operational from 1973 to 1999, after its 20-year operational life it received a life extension for 10 years, subject to annual approval, but in 1999 due to financial and technical issues it was deemed unsafe to continue operations and it was permanently shut. The decommissioning plan had not been completed as it closed ahead of it's planned date in 2003, and an interim 'Plan of priority measures on BN-350 reactor decommissioning' was put forward by the Ministry of Energy and Mineral Resources of the Republic of Kazakhstan.

To date, the following activities have been completed, and there is ongoing decontamination and dismantling happening at the site:

1. "All spent nuclear fuel had been transferred from the interim spent fuel storage facility at the BN-350 site to the long-term spent fuel storage facility at Baikal-1 site.
2. Drainage of primary radioactive sodium has been carried out and is in storage vessels. Secondary nonradioactive sodium is drained and utilized.
3. Technical design of the Liquid Radioactive Waste Processing Facility has been developed.
4. Technical task for the Solid Radioactive Waste Processing Facility design has been developed.
5. The main works on Combined Engineering and Radiation Survey (KIRO) of systems and components of primary and secondary cooling circuits, as well as of other reactor plant engineering systems and external communications have been completed." [IAEA][45]

In Africa, beyond **SOUTH AFRICA**'s two operational plants there are proposals for three more in South Africa and further planned projects in **EGYPT**. Nuclear power has limited traction in much of Africa due to the lack of transmission infrastructure available to export the power from a large single source.[46] South Africa's two PWR reactors at the Koeberg NPP have a design life of 40 year, therefore shutdown could be from 2024 excluding any PLiM. Regulation on nuclear activity is from the South African Nuclear Energy Corporation (NECSA), and decommissioning falls to their Nuclear Liability Management (NLM) division.[47]

4.2. Asia and Pacific

The Asia and Pacific region has a mixture of old and new nuclear players. A number of Asian countries have developed internal nuclear lifecycles, sometimes due to trade restrictions in countries who are not signatories to the NPT, or others through a desire for security of supply and the accompanying resources. There is a significant amount of new build with 31 reactors under construction, and at least 28 planned. Kazakhstan, South Korea and Japan are the only Asian countries with shut down plant,

[43] IAEA, Country Nuclear Power Profile, Ukraine
[44] World Nuclear Association, Country profile, Ukraine
[45] IAEA, Country Nuclear Power Profile, Kazakhstan
[46] Frost and Sullivan, Nuclear Power Market Outlook, 2017
[47] IAEA, Country Nuclear Power Profile, South Africa

with all but Japan having only a single closed plant. Japan, due to a heavy reliance on nuclear power, regulatory changes on decommissioning to promote the shut down of older and smaller plants and the challenges in the wake of the 2011 earthquake and tsunami, have a significant decommissioning portfolio including 17 reactors.

Table 4: Countries with previous, current or planned activity in nuclear power in Asia and the Pacific region. Source: World Nuclear Association

Country	Number of nuclear reactors and stage of lifecycle	Type of reactor / nuclear capacity	Year of first commercially operating NPP	Percentage of electricity from NPP	Decommissioning activity / status
Bangladesh	2 planned	2x VVER1200-V523	Expected 2023-5		
China	38 operational 20 under construction More in planning	Largely PWRs 58 GWe by 2020-21, then up to 150 GWe by 2030.	1994 (although mostly since the year 2000)	By 2030 8-10%	Shut down dates not published
India	22 operating 6 under construction 19 planned 57 proposed	5.3 GWe	1969	<3%	No decommissioning at present, focus is on life extension.
Indonesia	1 experimental NPP planned	Target of 5 GWe by 2025	Exp. 2022/23		
Japan	17 Shut down 42 Operable 5 of which restarted 21 in the process of restart approval	44 GWe Mostly PWR / BWR	1966	1.7%	17 in permanent shutdown (research and commercial)
Pakistan	5 operational 2 under construction 1 planned	1.3 GWe 1 PHWR, 4 PWRs	1972	5.5%	1 due to be shut down 2019
South Korea	1 shut down 24 operating 3 under	23 GWe PWR/PHWR	1978	33%	First reactor shut down in 2017. Plans to phase out

	construction 2 planned	/OPR			over 45 years.
Vietnam	10 proposed		2028		

Although CHINA have a significant installation of 34.6 GWe across 38 reactors, their NPP fleet is relatively new with the first NPPs coming online in the mid-1990s, but the most capacity has been installed since the mid 2000s. Decommissioning is therefore not likely to be a significant industry for at least 30 years. China is also working to have a fully internal nuclear fuel cycle and industry, which suggests limited opportunities for the Scottish subsea supply chain in the immediate future.

INDIA has a significant number of nuclear installations with 22 reactors providing 6.2 GWe. The civil nuclear power industry is largely indigenous and, as non-signatories to the NPT, has limited trade in nuclear materials. The Indian industry exploits its locally found thorium deposits. It should also be noted that a 'fundamental incompatibility between India's civil liability law and international conventions limits foreign technology provision'. India's reactors range in age with the first commercially operating in 1969 with new capacity being added every decade after, this rate of building would suggest a gradual build up of decommissioning activity.[48] India has deployed a number of 'Candu derivative' reactors, it is therefore likely that there will be a look to the Canadian decommissioning market, with their similar technology for expertise in decommissioning.

JAPAN was heavily reliant on nuclear power with 54 operational reactors, in 2011 in the time after the earthquake and tsunami, and subsequent incident at Fukushima-Daiichi NPP all operational plants were taken offline. The six reactors at Fukushima-Daiichi have been permanently shut down, the remaining plants are being reviewed and subject to passing a 'Stress-Test' they are gradually being brought back online. In 2018 five reactors were back on line, with a further 21 pending re-start approval, it is anticipated another 12 will be back online by 2025.[49]

A change in 2015 by the Agency for Natural Resources and Energy (ANRE), part of METI, revised the rules on estimating decommissioning costs. The rule change was to promote the decommissioning of smaller and older plants and allowed for the calculation of decommissioning costs in (up to) ten-year instalments instead of a one-time calculation. This propagated the announcements of six NPP retirements, these are all BWR and PWR type reactors.[50]

Fifteen reactors in total are in permanent shut down to be decommissioned. Decommissioning activity is already taking place at three reactors (Tokai NPS and Hamaoka NPS 1&2); a further five decommissioning plans approved by the NRA in April 2017 (Mihama NPS 1&2; Shimane NPS 1; Genkai NPS 1 and Tsuruga NPS 1); and a further DP is awaiting approval for Ikata 1.[51]

There is already a mechanism for the UK and Japanese collaboration, through the UK Department of International Trade, who host annual workshops on collaboration in this space. Examples of themes of decommissioning requirements in Japan include:

[48] World Nuclear Association, Country profile, India, accessed January 2018.
[49] Forbes, Japan Circling Back to Nuclear Power After Fukushima Disaster, 2017
[50] World Nuclear Association, Country profile Japan, accessed January 2018.
[51] IAEA, Country Nuclear Power Profile Japan, accessed January 2018.

- contaminated water treatment (containment, removal, storage and clean-up)
- remote technologies to enable working in high-level radiation zones
- bespoke technology development
- collaboration with the existing large Japanese corporations in the provision of components and technologies
- emerging decommissioning opportunities[52]

Due to PAKISTAN's weapons program it is outside the Nuclear Non-Proliferation Treaty (NPT) which has meant it is largely excluded from trade in nuclear plant or materials, hindering its development of civil nuclear energy. Pakistan however does have five operational reactors, four reactors at the Chashma NPP have only begun commercial operation since 2000 and therefore are not anticipated to close until the 2040s and 2050s. The oldest NPP, Karachi, is due to be closed in 2019, after operating since 1972, excluding shut downs for improvements and life extension works. The unit is a Canadian PHWR type reactor. When decommissioning does commence involvement of Pakistan Atomic Energy Commission (PAEC) and Pakistan Nuclear Regulatory Authority (PNRA), the licence issuers, will be required.[53,54]

SOUTH KOREA has 24 operating nuclear reactors, mostly PWR and PHWR type. In July 2017 the oldest reactor in Korea, Kori 1, was permanently shut down, after being in service beyond its 30-year planned lifetime and having suffered a blackout and a number of faults. The spent fuel will be removed from the reactor in a project lasting until 2022, when dismantling will begin and is expected to last 10-15 years. Responsibility for decommissioning lies with Korea Hydro & Nuclear Power (KHNP) who are also the sole NPP operators in Korea.[55,56]

4.3. The Americas

The USA has the most installed NPPs globally, and generates more than 30% of its electricity generated from nuclear power. It has already decommissioned ten commercial and research reactors. Within the rest of the Americas region, there is limited nuclear activity with only a further four countries operating reactors, their first reactors however were all commissioned in the 1970s and 1980s meaning that there will be a decommissioning market on the near horizon. Technology and experience from earlier shut downs in Europe may be beneficial in this case.

Table 5: Countries with previous, current or planned activity in nuclear power in the Americas. Source: World Nuclear Association

Country	Number of nuclear reactors and stage of lifecycle	Type of reactor / nuclear capacity	Year of first commercially operating NPP	Percentage of electricity from NPP	Decommissioning activity / status
Argentina	3 operational	1.6	1974	>10%	No shut down

[52] DIT, Next steps in British-Japanese nuclear cooperation, 2015
[53] World Nuclear Association, Country profile, Pakistan, accessed January 2018
[54] IAEA, Country Nuclear Power Profile, Pakistan, accessed January 2018
[55] World Nuclear Association, Country profile, South Korea, accessed January 2018
[56] IAEA, Country Nuclear Power Profile, Republic of Korea, accessed January 2018

	1 under construction 2 planned 2 proposed	GWe PHWR			dates published.
Brazil	2 operating 1 under construction 8 proposed	1.9 GWe PWR	1982	3%	No shut down dates published.
Canada	19 operating 2 more in planning (although deferred)	13.5 GWe	1971	~15%	Earliest shut downs are due in 2022, with timelines out to 2037 for the most recently refurbished sites.
Mexico	2 operating	1.6 GWe BWR	1989	>4%	Operating to 2029 and 2034 (operating life extended to 40 years)
USA	24 shutdown 99 operating 2 under construction 2 large 12 small planned 21 large 7 small proposed	98.7 GWe Largely PWR and BWR	1960	19%	24 reactors have been shut down, 11 in SAFSTOR and 4 in DECON.

ARGENTINA has three operating PHWR reactors, although one is currently offline undergoing life extension upgrades aiming to add 25-30 years to operation. The Atucha 1 reactor has a unique PHWR design from Siemens, no date is currently given for shut down of any of the Argentinian NPPs. The Argentinian National Atomic Energy Commission (CNEA) is responsible for documentation of decommissioning of NPPs, the Argentine Atomic Energy Commission Nuclear Regulatory Authority (ARN) is responsible for the dismantling and closure of operations licences. Each operating plant is responsible for accumulating a decommissioning fund.[57,58]

CANADA has a strong nuclear power industry including the development of its own nuclear power reactors. The first Candu (Canadian deuterium uranium) reactor was developed in the 1950s by the Atomic Energy of Canada Ltd (AECL) crown corporation. The Candu reactor has a heavy water moderator and uses natural (i.e. non-enriched) uranium as a fuel. Canada has used this technology internally but also exported it with 31 reactors in seven overseas, as well as 13 'Candu derivative'

[57] World Nuclear Association, Country profile Argentina, accessed February 2018
[58] IAEA, Country Nuclear Power Profiles, Argentina, accessed February 2018

reactors in India.[59] Decommissioning of NPPs has yet to begin in Canada[60], although some experience is being gained from the decommissioning of research reactors.[61] A number of the Ontario Power Generation plants have preliminary decommissioning plans associated with them, as part of this there are cost estimations for decommissioning of the reactors. The cost estimates range from $2.81 billion (£1.54 bn) to $5.19 billion (£2.85 bn) in 2015 Canadian Dollars.[62]

Canada has 19 operational reactors, plans for new reactors have been put on hold. The first plants to shut down will begin in 2022.[59]

The **USA** has a long history with nuclear power and PWR and BWR reactors were both developed in the country. The USA has 99 operational reactors, two under construction and 34 commercial and research reactors in permanent shut down. Of the commercial reactors eleven are currently in SAFSTOR, seven are declared as Independent Spent Fuel Storage Installations (ISFSI) where the plants are decommissioned to a point where they are then used as a used fuel and contaminated waste repository; four are in DECON; and one has had its licence terminated (i.e. decommissioning is complete). [63,64,65] Descriptions of these phases can be found in section 2.1.

Decommissioning regulations in the US state that NPPs must be decommissioned within 60 years of permanent shut down. Regulation and oversight of decommissioning in the US is provided by the Nuclear Regulatory Authority (NRC). Other federal agencies involved in nuclear decommissioning include the Environmental Protection Agency (EPA); the Occupational Safety and Health Administration (OSHA) and the Department of Transportation (DOT). The NRC estimates that $53 billion (£37.5 bn) has been set aside for decommissioning in the US (end 2015) and that estimated costs for NPPs range from $280 million (£198m) to $612 million (£434m). Operators must regularly report on the state of their fund to the NRC.[63]

[59] World Nuclear Association, Country profile, Canada, accessed February 2018
[60] Aikens, A. E., Decommissioning in Canada, IAEA Work Shop INT9175 9001, 2012
[61] World Nuclear News, Decommissioning progress for unique Canadian reactor, 2018
[62] Ontario Power Generation, Preliminary Decommissioning Plan – Darlington Nuclear Generating Station, 2016
[63] IAEA, Country Nuclear Power Profiles, USA, accessed February 2018
[64] World Nuclear Association, Country profile USA, accessed February 2018
[65] Nuclear Energy Institute, Decommissioning Nuclear Power Plants, Fact Sheet, 2016

Appendix 1: List of Acronyms

AGR	Advanced Gas Cooled Reactor
AUV	Autonomous Underwater Vehicle
BWR	Boiling Water Reactor
DECON	Immediate dismantling
EGP	Light Water Graphite Reactor
FBR	Fast Nuclear Reactor
FED	Fuel Element Debris
GWe	Gigawatts of electricity
IRM	Inspection Repair and Maintenance
Magnox	Type of gas cooled reactor previously used in the UK
MWe	Megawatts of electricity
NDA	Nuclear Decommissioning Authority (NDA)
NPP	Nuclear Power Plant
NPT	Non-Proliferation Treaty
NRC	Nuclear Regulatory Authority (USA)
O&G	Oil and Gas
PLiM	Plant Life Management
PWR	Pressurised Water Reactor
PHWR	Pressurised Heavy Water Reactor
RBMK	High Power Channel-type Reactor (Light water graphite reactor)
ROV	Remotely Operated Vehicle
SAFSTOR	Delayed dismantling
SNF	Spent nuclear fuel
SSM	Swedish Nuclear Regulatory Authority
VVER	Water-Water Energy Reactor (a type of PWR)

Appendix 2: Nuclear energy and reactor types

Nuclear power is the means of using fission, the splitting of nuclei to form neutrons and fission products (lighter elements) in a controlled reaction, often as a controlled chain reaction. This is used in a number of ways, including from research reactors; the generation of isotopes for use in medical and scientific research purposes; breeder reactors to generate specific nuclear fuels (such as ^{239}Pu from ^{238}U); and using the heat generated from the reaction to generate steam, which is then used to directly or indirectly drive a turbine, generating electricity.

Focusing on nuclear power plants (NPP) where nuclear fission is used for the generation of electricity, although other biproducts such as heat and desalinated water are also made use of in some cases, there are a number of reactor types that are commonly deployed. These are detailed in Table 6 below. The type of reactor used will have a bearing on the decommissioning plan largely based on the complexity of the plant. There are a number of ways of classifying reactors including by the moderator and by the cooling agent.

Table 6: Description of different nuclear reactor types. Source: World Nuclear Association[66]

Type of Reactor	Description	Number in Operation/ Operable worldwide (total capacity)	Countries they are used in (not exhaustive)
Boiling water reactor (BWR)	A fission chain reaction is used to generate heat which is used to boil water, generating steam which drives a turbine generating electricity	292 (275 GWe)	US, Japan, France Russia and China
Pressurised water reactor (PWR, VVER)	Similar to a BWR, but the water heated from the fission reaction is pressurised to keep it from boiling it is then piped to a secondary supply of water that forms the steam to power the turbines. The VVER type are water cooled, water modified energy reactor. They are Soviet designed and have horizontal steam generators.	75 (73 GWe)	Russia, US, Japan, Sweden
Pressurised heavy water reactor (PHWR)	As with the PWR, but the moderator is D_2O, known as heavy water	49 (25 GWe)	Canada and India
Gas cooled reactor (AGR & Magnox)	Carbon dioxide gas (CO_2) is used as the coolant in the reactor, with light water as a moderator. All Magnox reactors in the UK have now been shut down.	14 (8 GWe)	UK

[66] World Nuclear Association, Nuclear Power Reactors, 2018

Light water graphite reactor (RBMK & EGP)	In this set-up, the coolant is (light) water and the moderator is graphite. It is a similar design to the BWR. They have only been deployed in the Soviet Union. (This is the type of reactor used in Chernobyl.)	11 RBMK / 4 EGP (10 GWe)	Russia
Fast nuclear reactor (FBR)	As this type of reactor does not use a moderator (or very little) the neutrons are therefore faster moving. The fuel rods are made of enriched Uranium which has approximately 20% more ^{233}U than standard. This is to improve the rate of fission, thereby maintaining the chain reaction as ^{238}U is more likely to absorb the neutron (halting the reaction) than with ^{233}U. There is only one in commercial operation, but there is significant research into this technology ongoing as 60x more energy can be extracted from the fuel than in other technologies.	3 (1.4 GWe)	Russia
Small modular reactors or Small and medium reactors (SMR)	The IAEA defines small as up to 300 MWe and medium as up to 700 MWe (very small is up to 15 MWe) these can be used in remote communities, or as modular installations for a larger project. They can be any of the reactor types listed above.	3 (531 MWe)	There is a resurgence in these in the US and UK as well as China, India, Russia

In addition to the types of reactors described in Table 6, Rosatom, the Russian state atomic energy company, has developed a floating NPP. The floating NPP will be available capacities from 70 – 600 MWe, and will be mounted in pairs on a barge, permanently moored. It is primarily for the generation of electricity, but could also be used as a desalination plant. The first of these has been deployed in Siberia, hosting two 40 MWe reactors.[66] Such technology is similar to those found on nuclear power submarines and ships, such as ice breakers. Figure 3 below shows a breakdown of nuclear submarines per country that operates them. Although small reactors, they will still require decommissioning when the reach the end of their serviceable life.

Differences in reactors relate to cost, complexity and different nations research programme (e.g. RBMK and FBRs are Russian technology, AGR and Magnox in the UK, PHWRs (CANDU) are Canadian). The type of reactor, coolant and moderator (if used) has an impact on fuel requirements, such as natural Uranium (often as Uranium dioxide, UO_2) used in PHWRs and Uranium metal in AGRs or whether the fuel must be enriched e.g. BWR, PWR. Decisions about type of reactor can also be political where countries who have not signed the non-proliferation treaty (NPT) are not permitted to trade in nuclear components and therefore depending on their indigenous resources and supply chain may not have access to enriched uranium.

In addition to NPP, research reactors and breeding reactors, there are a host of other facilities that use, process or handle radioactive waste, such as uranium mines, uranium milling facilities, enriching facilities, reprocessing facilities, and other industrial facilities etc. although these will not be covered in this report, it is possible that there will be some synergistic opportunities in the decommissioning of these facilities as well and should not be discounted.

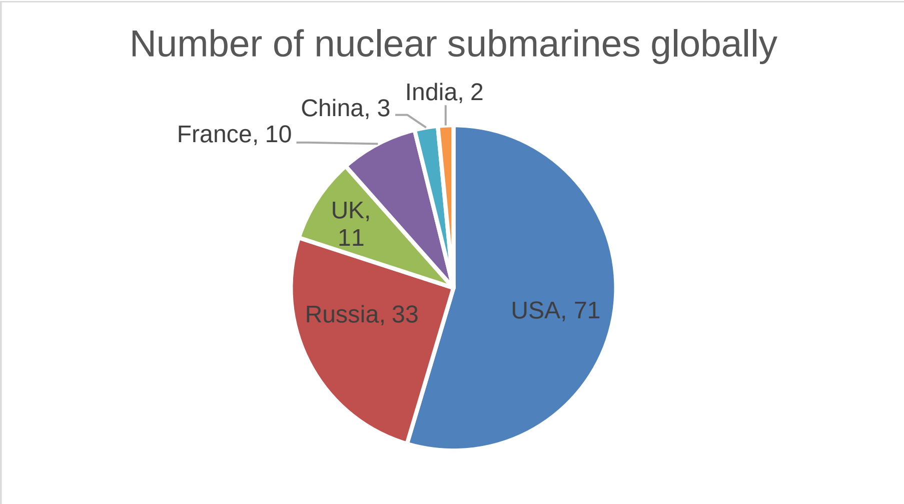

Figure 3: Pie chart showing the number of nuclear submarines per country that operate them. Source Nation Master