Nuclear Technology Development and Economics
2021

Long-Term Operation of Nuclear Power Plants and Decarbonisation Strategies

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NEA No. 7524

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

This edition replaces the previous edition released on 29 July 2021. Corrigenda to OECD publications may be found online at: *www.oecd.org/about/publishing/corrigenda.htm*.

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Foreword

The long-term operation of nuclear power plants is a topic of growing interest as more and more countries using nuclear energy are committing to increasingly ambitious decarbonisation targets. Decisions regarding extending the operating licences for these facilities are complex and require the simultaneous evaluation of multiple factors. In response to this growing interest, the Nuclear Energy Agency (NEA) published in 2019 *Legal Frameworks for Long-Term Operation of Nuclear Power Reactors*, a first-of-a-kind report that provides a comprehensive review of the legal and regulatory implications of LTO of nuclear reactors. During that same year, the International Energy Agency highlighted in *Nuclear Power in a Clean Energy System* the essential role of licence extensions to secure sustainable development targets. Consistent with the holistic approach necessary for long-term operation of nuclear reactors previously described by the NEA, *Long-Term Operation of Nuclear Power Plants and Decarbonisation Strategies* addresses the key policy, regulatory, technical, human and economic aspects necessary to enable licence extensions during the transition towards a low-carbon economy.

This publication is crucial for two reasons. First, with an average age of more than 30 years, the bulk of the existing nuclear fleet worldwide will inevitably be faced with operation decisions in the next decade. It is thus important to have a clear understanding of both the main ageing phenomena related to life-limiting components and of existing technical and operating experience related to the refurbishment of nuclear facilities to support safe nuclear operations beyond the initial licencing period. If most nuclear capacity is shut down after 40 years of operation, it could put electricity systems under considerable stress and place "Net Zero" goals further out of reach. This situation will not only hamper decarbonisation efforts but also undermine the affordability and the security of supply of electricity provision, with countries retiring in parallel significant amounts of dispatchable, fossil fuel generation to meet emission reduction targets.

Second, the timeline is becoming tighter to achieve carbon neutrality because of the increase in government pledges to reach such objectives sooner, and in most cases by 2050. The implementation of mature solutions will be essential to succeed in reaching such objectives. Countries currently operating nuclear reactors will find in long-term operation of their plants a safe, ready-to-deliver and competitive option to support the most ambitious decarbonisation pathways, while reconciling the affordability and security dimensions associated with electricity provision. Although the choice to proceed with long-term operation is a matter of national policy, *Long-Term Operation of Nuclear Power Plants and Decarbonisation Strategies* nevertheless provides timely evidence for policymakers and decision makers on how to decarbonise current electricity systems through the long-term operation of existing nuclear reactors, without making this immense endeavour more challenging than necessary.

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Director-General, Nuclear Energy Agency

Acknowledgements

The present study was written by Antonio Vaya Soler from the Nuclear Energy Agency Division of Nuclear Technology Development and Economics (NTE) under the guidance of the NEA Ad Hoc Expert Group on Maintaining Low-Carbon Generation Capacity through Long-Term Operation (LTO) of Nuclear Power Plants: Economic, Technical and Policy Aspects (EGLTO). The group is chaired by Arnaud Meert (Belgium) and Jan-Erik Lindback (Sweden). Michel Berthélemy (NTE), Marc Deffrennes (formerly at NTE), along with Kimberly Sexton Nick and Pierre Bourdon (NEA Office of Legal Counsel, OLC), participated in the drafting and review of the report. Management oversight and additional input was provided by Sama Bilbao y León and Diane Cameron, the former and current Head of the Division of Nuclear Technology Development and Economics. All are gratefully acknowledged for their contributions.

The NEA would also like to thank the NEA member countries, international organisations and various industry representatives who provided a large number of substantive and insightful comments during the review process of the report. A full list of those who contributed to the study is provided in Appendix 1 of the present report.

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List of abbreviations and acronyms

AMP	Ageing management programme
Aarhus Convention	Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters
BDBEE	Beyond-design-basis external event
BWR	Boiling water reactor
CAISO	California ISO (TSO in California)
CANDU	Canadian deuterium uranium (reactor)
CASS	Cast austenitic stainless steel
CCGT	Combined cycle gas turbine
CCUS	Carbon capture, use and storage
CGD	Commercial grade dedication (process)
COVID-19	Coronavirus-19
CPUC	California Public Utilities Commission
DGR	Deep geological repository
DOE	Department of Energy (United States)
EGLTO	Ad Hoc Expert Group on Maintaining Low-Carbon Generation Capacity through Long-Term Operation of Nuclear Power Plants: Economic, Technical and Policy Aspects (NEA)
EIA	Environmental impact assessment
EPRI	Electric Power Research Institute
Espoo Convention	Convention on Environmental Impact Assessment in a Transboundary Context
GCR	Gas-cooled reactor
gCO_2eq/kWh	Grammes of carbon dioxide equivalent to kilowatt hours
Gen-II, III, III+, IV	Generation II, III, III+, IV (reactors, or reactor concepts)
$GtCO_2$	Gigatonnes of carbon dioxide
GW	Gigawatt
HAZ	Heat affected zones
IAEA	International Atomic Energy Agency
IASCC	Irradiation-assisted corrosion cracking
I&C	Instrumentation and controls
INPO	Institute of Nuclear Power Operators
IPCC	Intergovernmental Panel on Climate Change

JRC	Joint Research Centre (Europe)
kWe	Kilowatt electric
LCOE	Levelised cost of electricity
LTO	Long-term operation
LWGR	Light water graphite reactor
LWR	Light water reactor
MAI	Materials Ageing Institute (France)
MWh	Megawatt hour
NEA	Nuclear Energy Agency
NEI	Nuclear Energy Institute
NRC	Nuclear Regulatory Commission (United States)
NTE	Division of Nuclear Technology Development and Economics (NEA)
OCC	Overnight construction costs
OEM	Original equipment manufacturer
OPEX	Operational expenditures
PHWR	Pressurised heavy water reactor
PSR	Periodic safety review
PTS	Pressurised thermal shock
PV	Photovoltaic (solar)
PWR	Pressurised water reactor
RPV	Reactor pressure vessel
SALTO	Safety Aspect of Long Term Operation (IAEA missions)
SAMGs	Severe accident management guidelines
SBO	Station blackout
SDS	Sustainable Development Scenario (IEA)
SG	Steam generator
SLR	Subsequent licensing renewal (United States)
SSCs	Systems, structures and components
TEPCO	Tokyo Electric Power Company (Japan)
TLAAs	Time limited ageing analyses
TSO	Technical support organisation
TWh	Terawatt hour
UCL	Unplanned capability loss
VRE	Variable renewable energy
WANO	World Association of Nuclear Operators
WENRA	Western European Nuclear Regulators Association
ZECs	Zero-emission credits

Executive summary

Long-term operation: Supporting the sustainability, competitiveness and security of the electricity supply in ambitious decarbonisation strategies

Globally, nuclear power capacity is expected to grow if countries are to meet the carbon emission reduction targets of the 2015 Paris Agreement. The International Energy Agency (IEA) sees nuclear generation doubling to achieve carbon neutrality by 2050. The increasing role of nuclear energy has also been recognised by the Intergovernmental Panel on Climate Change (IPCC). For those countries already operating nuclear reactors, two complementary means can contribute to sustaining nuclear development in the energy transition: i) building new capacity; and ii) pursuing the long-term operation (LTO) of existing nuclear power plants.

Long-term operation can be defined as operation, justified by a comprehensive safety assessment, that goes beyond a previously established time frame corresponding to initial design assumptions (typically referred to as "original design lifetime" and usually 30-40 years depending on the design). These initial assumptions, however, do not represent a technical constraint inhibiting longer operating time frames and should not be confounded with the remaining, useful life of the facility, which is periodically re-evaluated taking into account the actual plant conditions and the latest available knowledge. In almost all cases, the useful life of the facility is greater than the originally assumed design lifetime. Additional support for licence extensions can also be found in most countries' laws and regulations, where original operating licences are not used to establish the ultimate operating lifetime of the plants. In fact, most laws or regulations provide for indefinite terms, or allow for unlimited licence extensions.

As of the end of 2020, over 100 nuclear reactors worldwide were operating beyond their initial 40-year licensed periods, and more than 30% of the nuclear fleet was considered to be operating under LTO conditions, according to existing country regulations. Building on the operational experience of older plants, the role of LTO is expected to expand in the next decade as the average age of the world nuclear fleet is greater than 30 years and more countries are committing to more ambitious carbon emission reduction targets. The value of licence extensions nonetheless goes beyond the decarbonisation dimension. A sustainable energy transition simultaneously tackles: i) environmental protection; ii) economics and affordability; and iii) electricity security and the reliability of electricity supply – or the so-called "energy trilemma". Nuclear power, and in particular licence extensions, perform well in all three of these dimensions.

Carbon management

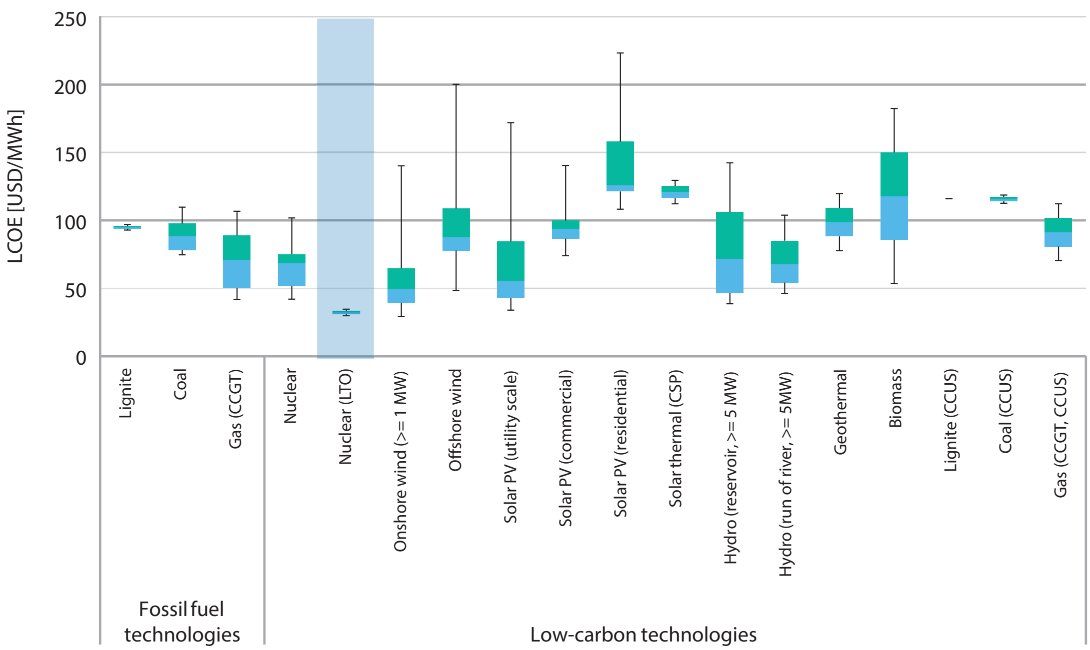
LTO is not a decarbonisation tool per se but are rather an effective way to avoid emissions (i.e. in the case that they are replaced by fossil fuel-burning power plants) and manage decarbonisation pathways in a more predictable manner. Nuclear power could save up to 2.9 gigatonnes of carbon dioxide ($GtCO_2$) annually (almost 10% of today's carbon emission levels) while supporting net-zero emissions by 2050. Around 40% of these savings (i.e. 1.2 $GtCO_2$/year) could vanish without LTO, hampering global efforts to reduce carbon emissions. Recent experience shows that, in the short term, nuclear capacity is likely to be replaced by a combination of variable renewable energy (VRE) backed up by fossil fuel-fired plants, mainly because flexible solutions (e.g. long-term electricity storage, demand response, sector coupling) still do not have the required level of technological and industrial maturity for the large-scale deployment necessary to limit reliance on fossil-fired capacity. In countries with nuclear power, LTO acts as a backbone of low-carbon capacity upon which other low-carbon solutions can be built to enhance overall decarbonisation capabilities while the necessary innovations to meet climate targets progress in parallel towards achieving commercial viability

Affordability and investment efficiency

According to IEA/NEA estimates (IEA/NEA, 2020), in many regions of the world, licence extensions are the most cost-competitive, low-carbon solution at the plant level (see Figure E1). Overnight costs typically range between USD 450-950 per kilowatt electric (kWe) with an associated levelised cost of electricity (LCOE) of USD 25-50 per megawatt hour (MWh). This variability can be explained by the operational and investment history of each plant, as well as by national regulations. Such ranges also capture potential reductions in the load factor over the short term. Refurbishing existing plants is also simpler from a technical and managerial perspective than building a new plant. This, combined with a positive learning curve sustained by a significant number of recent and future projects, contributes to significantly lowering the risks of LTO delays or cost overruns.

At the system level, LTO will extend the dispatchability attributes of nuclear power over time, thus reducing system stress, grid reinforcement needs and other system effects that could increase the overall integration costs of high shares of VRE. Added benefits can be expected from licence extensions, particularly as regards limiting the external costs induced by air pollution and climate change.

Figure E1: **Levelised cost of electricity by technology, 2025**



Note: Values at 7% discount rate. Box plots indicate maximum, median and minimum values. Boxes indicate the central 50% of values (i.e. the second and third quartile). USD/MWh = US dollars/megawatt hour; CCGT = combined cycle gas turbine; CCUS = carbon capture, use and storage.

Source: IEA/NEA, 2020.

Security and reliability of the electricity supply

LTO allows countries to extend the benefits that nuclear power plants provide in terms of fuel availability and diversity, as well as in terms of ancillary services such as inertia, primary and secondary frequency control and load following.

More importantly, one of the major security-of-supply concerns in most countries is system adequacy, or the availability of physical capacity in the mid to long term. This issue is becoming critical in the context of more ambitious emission targets, and will certainly require the closure of dispatchable generators such as coal and gas plants in future. In addition, nuclear phase-out policies will further reduce capacity margins. In Europe, coal and nuclear capacity (40% of dispatchable generation in 2020) is set to drop 66% (160 gigawatts [GW]) by 2040, according to stated policies. The higher VRE additions are expected to have a limited impact given their low capacity factors. Flexibility from interconnectors could also decrease with various countries simultaneously phasing out dispatchable generators. The prospects of a large-scale deployment of other flexibility options (e.g. long-term storage, demand response, sector coupling) remains uncertain. LTO is, on the other hand, part of proven solutions that can enhance electricity security in decarbonisation strategies.

Uncertainty

In general, deciding when to cease operations at an existing facility is subject to significantly less uncertainty than making the decision to initiate new build or determining when innovations have reached full industrial and commercial viability. At the same time, it is extremely difficult to foresee, *ex ante*, the full impact that energy policies will have on societies, particularly when significant political, economic, industrial and social implications are at stake. Multiple factors could impact emission trajectories, raise system costs and undermine the reliability of the system, thus pushing governments to reconsider their initial plans. In addition, in the absence of a fully co-ordinated approach, individual countries do not have control over the decisions of neighbouring countries, adding even more uncertainty to the process.

In this context, technology diversity, time and ease of implementation can be valuable resources for policymakers. They are quickly accessible through timely LTO decisions and provide greater flexibility in energy planning so as to better cope with a wide range of unforeseen risks. Overall, LTO can be considered as a technology option in its own right that policymakers can mobilise to properly manage all of the dimensions of the energy transition and reduce the extent of the challenge.

No major technical showstoppers for longer operations and adaptations

Nuclear facilities are not static assets. During their lifetimes, most of their structures, systems and components (SSCs) are replaced as part of normal maintenance procedures and more extensive refurbishments. These replacements mitigate the impacts of ageing and allow operators to implement the necessary safety upgrades in accordance with the latest available regulations, knowledge and operating experience.

There are, however, SSCs for which replacement is considered unfeasible for technical and/or economic reasons. Consequently, the ageing of these components will ultimately limit the operations of the plant. Critical life-limiting components are the reactor pressure vessel (RPV) and concrete containment structures. Depending on economic considerations, some core internals and cabling systems can also be considered as life-limiting. After several decades of research and operating experience, the main ageing mechanisms, stressors and associated dynamics in life-limiting SSCs are now well understood. In practice, this technical evidence has been combined with ageing management programmes (AMPs) to monitor and ensure that safety margins remain acceptable during operations, regardless of ageing, in particular for life-limiting components. The governing frameworks associated with LTO programmes also allow for internal, periodic re-evaluations and external peer reviews in order to identify potential shortfalls and provide access to the best international practices.

As a result, if utilities implement enhanced ageing management programmes using readily available technical evidence, while performing the necessary repairs and replacements, long-term operation should not face any major, generic, technical barriers. Provisions in safety margins and continuous monitoring through AMPs and research efforts will be needed in order to properly anticipate and manage the potential technical risks that may arise, especially over very long operating periods.

Industrial experience also shows that operators use the long outages of LTO refurbishments to perform additional plant retrofits, such as power uprates, instrumentation and control upgrades, flexible operations and overall plant modernisation activities. The overall objective is to adapt the plant to a changing environment while improving the economic value of the LTO investment.

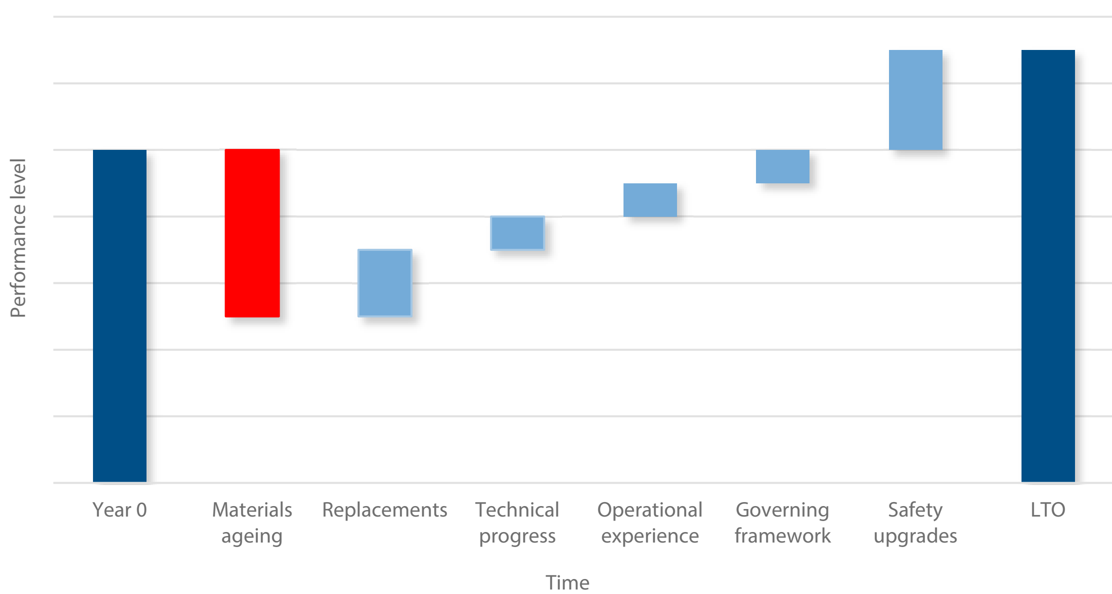
Supply chain capabilities: An emerging source of concern despite continuing improvements in nuclear operations

The evolution of nuclear power plant performance indicators (e.g. unplanned capability loss, unplanned scrams) suggests that, globally, nuclear operations have observed steady improvements despite ageing. To explain these patterns, it is essential to examine all of the technical and organisational factors that will ultimately determine the safety and reliability of a nuclear facility. The combination of replacements, new technical progress (including enhanced ageing management programmes), expanding operational experience and additional safety upgrades enable operators to effectively manage the effects of materials ageing (see Figure E2). The governing framework (e.g. national regulations, international peer reviews) ensures that all these measures are implemented in a timely manner and are reviewed according to international standards so as to continuously improve the operation of the plant from technical and organisational points of view. As a result, performance levels should not abruptly decline (or even improve) as long as the necessary investments and enhancements continue to be carried out as part of the LTO programme.

These performance trends are also supported by industrial capabilities that remain robust thanks to the constant inflow of projects and components being procured. SSC obsolescence and supply chain issues have nevertheless become an emerging source of concern over recent years as a result of policy uncertainties and degraded market perspectives, combined with high qualification needs. These trends vary from country to country depending on the size and standardisation of domestic nuclear programmes. Thus far, the nuclear industry has been able to manage these risks with the introduction of a commercial grade dedication, and higher collaboration and harmonisation levels. Examples exist at the national level of regulators and operators working co-operatively to reinforce the network of qualified suppliers. In parallel, nuclear operators have planned and managed the retirement of an ageing workforce, although attracting and retaining talent has also become a major concern.

With nuclear power plants operating for longer periods, the ability of utilities to sustain operational excellence and economic performance could be undermined by the lack of a qualified SSCs and skilled workforce. Nuclear industrial policies and international collaboration will be key in enabling joint undertakings among governments, industry, regulators, research institutes and academia necessary to sustain supply chain capabilities in the long term.

Figure E2: **Qualitative evolution of the performance level of a nuclear power plant over time**



The role of government in enabling LTO of nuclear power

Most of the factors that could prevent nuclear reactors from operating over longer periods are in fact policy driven. First of all, early closures are principally motivated by policy decisions. In Europe, around 80% of the reactors that will cease operations by 2025 will do so for policy reasons. The absence of stable and long-term policies in relation to the nuclear sector is thus a source of additional risk that can have an impact on nuclear activities and potentially raise LTO costs.

Secondly, in some regions, sustained, low wholesale prices that do not reflect the climate and reliability attributes of existing nuclear reactors are pushing some utilities to close nuclear reactors earlier than initially planned. In the United States, where gas prices are low, eight units have ceased operations since 2013 as a result of negative market prospects, and five more are planned to be retired by 2022 for similar reasons. Market pressures can also reduce the economic attractiveness of plant investments, ultimately inhibiting future LTO decisions. Various regulations and support mechanisms are being used to support the development of low-carbon technologies, and such regulations and mechanisms could be extended to LTO. This has been the case, for instance, for zero-emission credits (ZECs), implemented in some US states to remunerate carbon emission avoidance.

While efforts to keep the highest safety standards and operational performance must continue, policymakers have a key role to play to support LTO in order to facilitate decarbonisation strategies. With suitable and timely policies, nuclear countries hold the keys to enabling LTO programmes, and thus embracing the benefits. Some of these policies can be rapidly implemented as they simply require policy commitment, ad-hoc support mechanisms and/or the review of nuclear taxation regimes. Other policy reforms, such as structural market reforms, may take more time. Overall, policymakers have a solid base to design policy packages that combine various solutions to fit specific national circumstances.

Key policy recommendations

1. **Maintain existing low-carbon capacity**: Decarbonising the electricity system will be even more difficult if existing low-carbon nuclear capacity is not included in the equation. LTO is a safe and expeditious solution to avoid carbon emissions for decades to come and to manage emission reduction trajectories in a predictable manner under ambitious decarbonisation pathways.
2. **Enlarge the technical basis of information on ageing mechanisms and their management**: Current LTO trends have been possible thanks to extensive research that has been conducted over the years. Longer operational time frames will increase the demands on materials and life-limiting components and will require continued R&D efforts to provide the necessary technical evidence for safe operation. Initiatives fostering international collaboration on lessons learnt in ageing management should continue to be pursued.
3. **Support new technologies and plant enhancements:** Nuclear operators have at their disposal robust technical options to enhance and adapt their assets to an evolving context. With stable policies and risk-sharing initiatives, governments can facilitate their adoption and encourage additional performance improvements during LTO.
4. **Foster co-operation to capitalise on extensive industrial experience:** An increasing number of utilities around the world are undertaking LTO refurbishments and implementing new technologies. External peer reviews and sharing of international operational experience are effective tools to secure best practices and to enable longer operating periods and plant adaptations. Timely dialogue and co-operation with regulators are in most cases possible to accelerate the adoption of the most innovative solutions.
5. **Sustain supply chain capabilities and nuclear expertise at all levels**: By committing to LTO, countries will directly sustain existing supply chain capabilities and send clear signals to younger generations to renew the nuclear workforce. These actions should be complemented by joint undertakings with regulators, industry and academia to foster nuclear expertise at all levels. Ongoing international collaboration can also play a role in preserving knowledge and developing human capital in the nuclear sector.

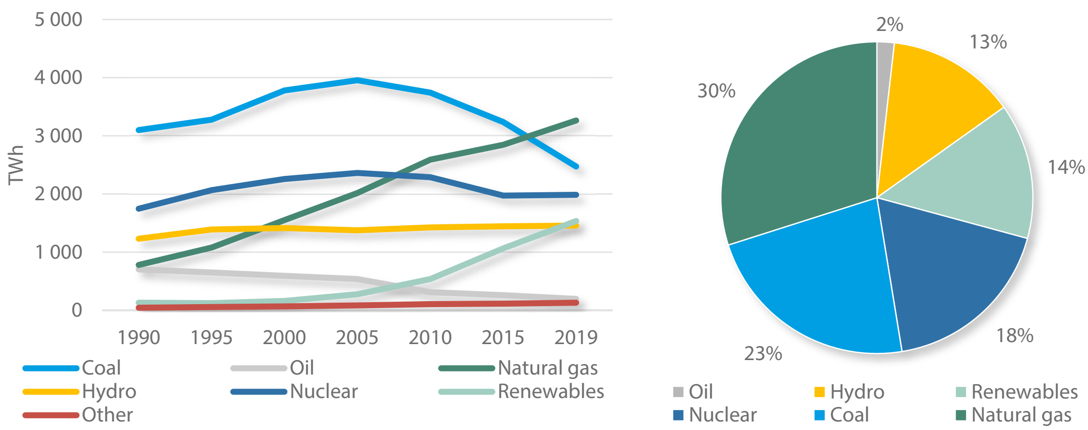
6. **Build long-term and predictable industrial plans**: High fixed cost technologies such as nuclear power require policy certainty. Coping with policy risks is sometimes possible, but with a significant cost penalty. Through nuclear industrial strategies, governments can provide the long-term, stable framework necessary to plan and optimise licence extensions.
7. **Reform market regulations to ensure that the system value of long-term operation is adequately remunerated:** In many regions, different types of regulations and mechanisms are used to overcome market challenges and support low-carbon technologies. These regulations and mechanisms can be extended to LTO in order to adequately remunerate the value that they provide to the system in terms of emission avoidance, but also in terms of system adequacy and grid reliability. Other options such as the review of nuclear taxation regimes can be envisaged as well.

1. Introduction

1.1. The context: The challenge of decarbonisation efforts without the long-term operation of nuclear power plants

Meeting carbon dioxide (CO_2) emission targets at the pace dictated by the Paris Agreement is an enormous and complex endeavour that will require the mobilisation of all mature low-carbon technologies, including nuclear power. Today, with 444 reactors in operation worldwide, accounting for 393 GW of net installed capacity (IAEA, 2021), nuclear power represents around 10.1% of the global electricity consumption, remaining the world's largest source of low-carbon electricity following hydropower (16.2%) (IEA, 2021a). In OECD countries, nuclear energy accounts for 18% of the electricity generation, acting as the top low-carbon source of electricity in these countries (see Figure 1.1). The existing nuclear reactors around the world thus constitute a backbone of low-carbon capacity that saves around 1.6 Gt of CO_2 every year (IEA, 2019a).

Figure 1.1: **Electricity generation by source in OECD countries, 2019**



Note: "Renewables" include contributions from solar photovoltaic (PV), solar thermal, wind power, geothermal energy, biofuels and tidal power. The "other" category regroups waste and other sources. TWh = terawatt hour.

Source: IEA, 2021a.

According to the International Energy Agency (IEA) Sustainable Development Scenario (SDS), the role of nuclear power in low-carbon electricity systems is expected to increase, with global generation growing 55% by 2040 compared to 2019 levels (IEA, 2020c). To reach carbon neutrality globally by 2050, the IEA Net-Zero Emissions by 2050 Scenario (NZE), indicates that nuclear output should at least double from 2020 levels (IEA, 2021d). [1] These figures are consistent with

1. Under the IEA SDS, the temperature rise remains below 1.8°C with a 66% probability, without reliance on global net-negative CO_2 emissions, which is equivalent to limiting the temperature rise to 1.65°C with a 50% probability. Also, global CO_2 emissions will have fallen from 33 Gt in 2018 to less than 10 Gt by 2050 and are on track to net-zero emissions by 2070 (IEA, 2019b). The IEA NZE supplements SDS and provides additional analysis on what would be needed by 2030 to put carbon emissions on a pathway to net-zero emissions globally by 2050 (IEA, 2020d).

the projections of the Intergovernmental Panel on Climate Change (IPCC), which foresees a significant rise of nuclear output by 2030 and 2050 under the large majority of scenarios modelled (IPCC, 2018).[2] There are essentially two nuclear development levers to meet these projections: i) new nuclear build; and ii) long-term operation (LTO) of existing nuclear capacity, the latter being the subject of the present report.

The International Atomic Energy Agency (IAEA) defines LTO of nuclear power plants as "operation beyond an established time frame […] justified by safety assessment [which] may take place within a broader regulatory process […]" (IAEA, 2018). The time frame is typically referred to as "original design lifetime"[3], which is informed by initial design assumptions regarding the minimum expected lifetimes of non-replaceable structures, systems and components. These initial design assumptions, however, do not represent a technical constraint inhibiting longer operating time frames. These initial design assumptions should not be confounded with the actual remaining useful life of the facility, which is periodically re-evaluated by taking into account actual plant conditions and the latest available knowledge. In almost all cases, the remaining useful life is greater than the originally assumed design lifetime.[4]

Supported by an extensive knowledge base on ageing phenomena (NEA, 2006, 2012, 2015) and considerable operating experience beyond 40 years[5], the number of licence extensions of nuclear power plants has been steadily growing in recent years. For example, as of the end of 2020, over 100 operating reactors were older than 40 years (IAEA, 2021), and more than 30% of the nuclear fleet was considered to be operating under LTO conditions, according to existing country regulations (see Chapter 2). At the same time, nuclear reactors nonetheless continue to be shut down prematurely, in some cases even before reaching their initial design lifetime. The cumulative nuclear capacity that has been retired since 2011 will account for 82 GW by 2025 (20% of the today's installed nuclear capacity) according to stated policies in OECD countries.

A closer look at the reasons[6] for these closures (see Figure 1.2) reveals that almost 70% are motivated by external factors, such as policy decisions and negative market prospects. The impact of policies is particularly acute, accounting for 45% of the total closures, and can be largely attributed to the accelerated nuclear phase-out following the Fukushima Daiichi nuclear power plant accident in 2011, especially in Europe. Early closures based on market pressures represent around a quarter of the closures, and they are principally located in several US states and in Sweden. These regions experience low wholesale electricity prices that do not reflect the system value provided by existing nuclear capacity.

Another quarter of closures in OECD countries between 2011 and 2025 results from techno-economic factors. In this case, the refurbishments required for LTO of a plant may constitute a considerable technical challenge and/or be considered too costly to be economically viable under market conditions prevalent at the time (see Box 1.1). This has been the situation in Japan where the investments required to meet new safety standards could not be recovered over the remainder of operating lifetimes, pushing some utilities towards the decision to cease operations (see Figure 1.2).

2. Depending on the decarbonisation pathway, the increase in nuclear supply from 2010 levels varies between 59% to 106% by 2030 and between 150% to 468% by 2050.

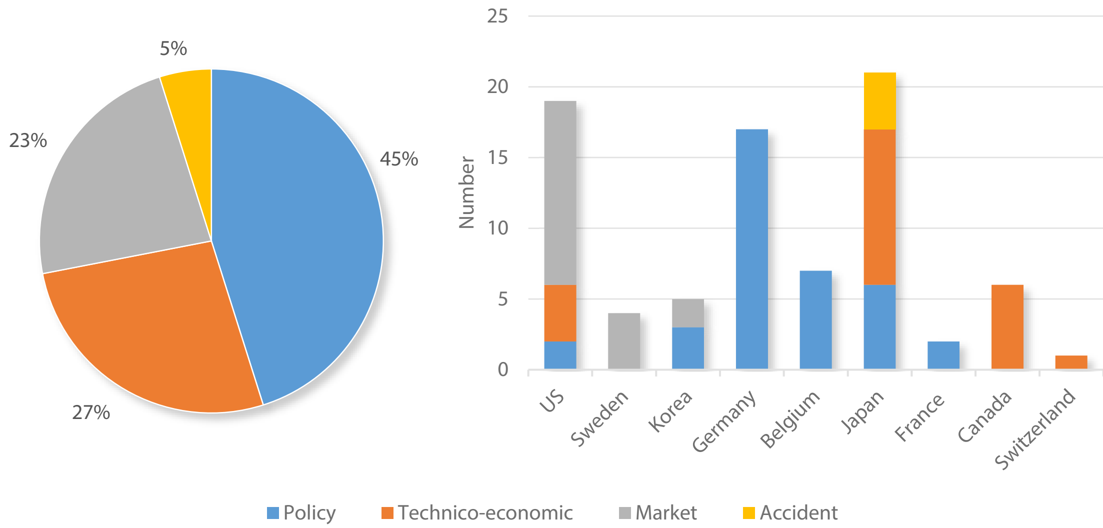
3. The IAEA Safety Glossary (IAEA, 2019) defines design lifetime as "the period of time during which a facility or component is expected to perform according to the technical specifications to which it was produced". Similarly, the Western European Nuclear Regulators Association (WENRA, 2011) defines design lifetime of a nuclear power plant as "the minimal value of lifetimes of all its non-replaceable structures, systems and components", for example the reactor pressure vessel and the containment building (see Chapter 4).

4. This definition also demonstrates that the term "lifetime extension" is not completely accurate since the lifetime of the plant is not extended in practice. What is actually extended is the authorisation term or operating licence based on a technical assessment of the capabilities of the plant to safely operate beyond initial design assumptions. The role of initial design lifetime to inform the initial operating licence and LTO is further explored in Chapter 3.

5. In the present report, it is assumed that a reactor enters LTO after the age of 40 years.

6. It is important to note that the closure of a nuclear power plant is a complex decision involving the evaluation of multiple factors and parameters. The reasons highlighted in Figure 1.2 point to the main drivers that, according to the different experts consulted for the present study, had the most influence on the final decision.

Figure 1.2: **Plant closures by country and reason, according to stated policies in OECD countries, 2011-2025**



Note: The technologies covered are LWRs and PHWRs. Plant closures resulting from policy decisions in Japan were made by the utilities, considering the requests from national and/or local governments.

Box 1.1: **Examples of early closures of nuclear power plants for techno-economic reasons**

Crystal River 3 (United States)

Unit 3 of Crystal River in the United States observed damage in the containment building during the replacement of steam generators in 2009. The operation required a large hole be made in the containment structure. As part of preparations to make the opening in the containment building, tendons in the containment building wall were detensioned. Then, while creating the opening, workers observed concrete delamination[7] affecting the outer building wall. The concrete delamination issue was not expected and had not been seen before during steam generator replacement activities at other nuclear plants. The damage was centred on the steam generator opening and did not affect other bays of containment. Further engineering studies concluded that the main cause of the delamination could be attributed to the scope and sequence of the tendon detensioning. The operator attempted to repair the damage, but later decided to decommission the reactor (NRC, 2010).

Ohi 1 and 2 (Japan)

In Japan, Kansai Electric Power Company decided to decommission units 1 and 2 of the Ohi nuclear power plant in 2017 as a result of the technical difficulties associated with the implementation of new safety standards introduced after the Fukushima accident. These units were in fact the only reactors in Japan using ice condenser emergency cooling systems. In the event of an accident, these systems employ blocks of ice in a basket installed around the containment vessel to rapidly condense the steam that is released and reduce the pressure. In order to comply with the new applicable safety requirements, the walls of the containment building would have had to be thickened, among other significant safety upgrades. Additionally, the new equipment to be installed in the containment building would have narrowed the amount of free space, impeding operating and maintenance work (KEPCO, 2017).

7. Concrete delamination is the detachment of thin layers of concrete from the concrete surface. As a result, the surface becomes more vulnerable, potentially weakening the structure.

Oyster Creek (United States)

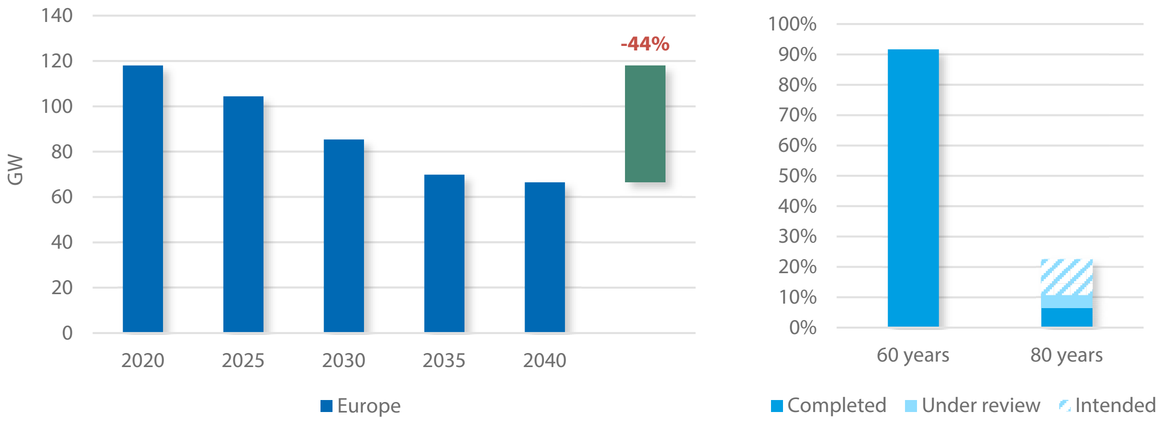
The American utility Exelon decided to decommission the Oyster Creek nuclear power plant ten years earlier than expected in order to avoid the installation of two new cooling towers after revision of the water rule in the state of New Jersey. This plant upgrade was considered too expensive by the owner, given the unfavourable market conditions in the United States (NEI, 2018).

With the average age of the world's nuclear fleet at 31 years (35 years in advanced economies), the next decade will be considered critical for LTO. Without timely licence extensions and slow capacity additions, nuclear capacity could sharply decline by 2040, hindering global decarbonisation strategies. In Europe, a region characterised by higher policy uncertainties, installed nuclear capacity could fall 44%, with a significant number of plants closing before 50 years of operations (see Figure 1.3, left). These closures will have significant implications, not only in terms of emission trajectories but also in relation to the affordability and security of electricity provision by 2040 (IEA, 2019a).

At the same time, carbon emission reductions are far from being on track. In 2019, emissions flattened following two years of increases (IEA, 2020a), but more structural changes will be needed during the recovery phase of the COVID-19 pandemic to prevent emissions from bouncing back (IEA, 2020b). Recent estimates predict that carbon emissions are projected to rebound and grow by 4.8% by 2021, the largest single increase over the last decade (IEA, 2021b). More recently, various countries have pledged to achieve carbon neutrality by 2050-2060, which will require greater decarbonisation efforts and the use of mature and shovel-ready, low-carbon solutions. This task becomes even more challenging when dimensions such as affordability and energy security – at the core of sustainable energy systems and policies – are taken into account.

In the United States, more than 90% of the nuclear fleet has received regulatory approval for 60 years of operation, and the number of reactors approved to operate until 80 years is increasing. (see Figure 1.3, right). Additionally, utilities in France and Canada are also carrying out major refurbishment programmes to enable LTO of most of their nuclear units. These trends confirm that, if utilities continue to implement the necessary repairs, replacements and ageing management programmes using already available technical evidence, no major technical issues should preclude the existing nuclear fleet from operating over longer periods so as to secure more ambitious decarbonisation strategies.

Figure 1.3: **Nuclear capacity projections in Europe absent of further investment in new build (left); and licence renewal regulatory trends in the United States (right)**

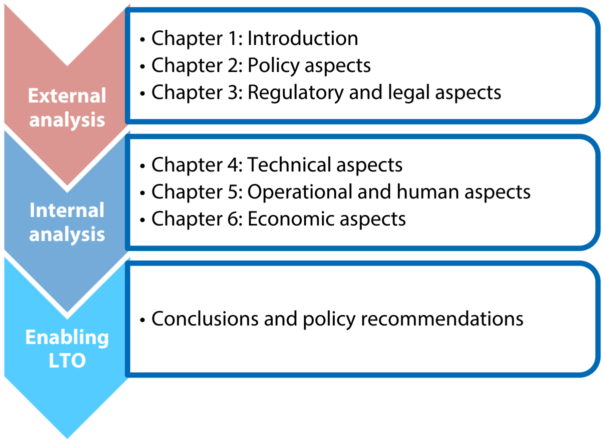


Note: OECD/NEA, based on NRC (2021) and NEI (2020).

1.2. Motivation, methodology and structure of the report

In light of these trends, the NEA Expert Group on Maintaining Low-Carbon Generation Capacity through LTO of Nuclear Power Plants: Economic, Technical and Policy Aspects (EGLTO) was established in 2018 with the purpose of assessing the role of LTO in the energy transition, as well as of identifying a key set of measures that could help maintain low-carbon capacity through LTO.

Figure 1.4: **EGLTO methodological framework and structure of the report**



EGLTO recognised the techno-economic work already performed by the NEA on LTO and proposed a methodological framework for the present study. In line with the conclusions of the NEA study entitled *The Economics of Long-Term Operation of Nuclear Power Plants* (2012), this methodology builds on the holistic nature of LTO decisions requiring the simultaneous evaluation of multiple factors.

To be effective, LTO first needs regulatory approval from national safety authorities. This decision is taken after evaluation of the technical evidence and action plans provided by the utilities, which ensure that the plant will comply with the applicable safety requirements during the extended period. Concurrently, operators will also assess the economic viability of the necessary investment, taking into account expected market conditions and internal capabilities. Finally, even if previous dimensions yield a positive output, there are various external factors influencing the final LTO decision and future economic performance, such as public acceptance, changes in national policies and the introduction of new regulations.

In order to identify the key factors to enable LTO, a three-step strategic assessment is therefore considered in the present report, as follows:

- **Part 1 – Analysis of the external environment for long-term operation**: After recognising the role of LTO in decarbonisation strategies (Chapter 1), a comprehensive analysis of the context in which LTO will take place is undertaken. This analysis includes policy issues (Chapter 2) and regulatory and legal aspects (Chapter 3).
- **Part 2 – Analysis of the internal capabilities of nuclear power facilities for long-term operation**: The external analysis is complemented by an assessment of the internal capabilities of nuclear facilities to withstand the pressures imposed through their ecosystem. In this case, technical issues (Chapter 4), operational and human aspects (Chapter 5) and economics (including market issues) of LTO (Chapter 6) are covered in detail.
- **Conclusions and policy recommendations – Enabling long-term operation**: Based on the outcomes of the two previous steps, it is then possible to identify the key factors that will enable LTO in the years to come under the best possible conditions.

The methodological framework and the structure of the report are summarised in Figure 1.4 above.

While the methodological framework presented above establishes a clear separation between internal and external factors, the interactions and synergies existing between these two dimensions, as well as among the various factors themselves, should not be neglected. As will be illustrated many times in this report, policy action (external) can have a direct impact on the ability of operators (internal) to perform LTO, and ultimately on their overall economic performance. Another example is market issues, which are the result of policy decisions, or regulatory and economic forces. These market issues will be addressed from different perspectives in several chapters.

Lastly, another objective of the present report is to update the LTO cost data presented in NEA (2012) and provide additional insight into the evaluation of such costs. The findings of the present study show a strong rationale for the evaluation of LTO as a technology option in its own right, alongside new nuclear build and other low-carbon technology options. In this respect, the cost and evidence collected within EGLTO for the elaboration of this study were also used for the computation of country-specific LTO cost data presented in the 2020 edition of the *Projected Costs of Generating Electricity* (IEA/NEA, 2020).

Key findings

- Nuclear power is the top low-carbon source of electricity generation in OECD countries, and it is expected to play a growing role in meeting sustainable development goals elaborated via IEA and IPCC projections. Two main nuclear development levers can be mobilised to meet these objectives: new nuclear build; and long-term operation.
- Long-term operation can be defined as operation, justified by a comprehensive safety assessment, that goes beyond a previously established time frame corresponding to initial design assumptions (typically referred to as "original design lifetime" and usually 30-40 years depending on the design). The initial design assumptions, however, should not to be confounded with the actual remaining useful life of the facility, which is periodically re-evaluated taking into account actual plant conditions and the latest available knowledge. In almost all cases, the useful life is greater than the originally assumed design lifetime.
- Long-term operation investment trends are steadily increasing, supported by technical evidence and growing operating experience. Nuclear power plants nevertheless continue to be prematurely shut down in some regions, principally due to phase-out policies and expanding market pressures. Closures for techno-economic reasons have also been observed when the necessary investments to continue operation are not economically viable.
- The next decade will be critical for LTO as the existing world's nuclear fleet will reach an average age of 40 years. Without widespread licence extensions, nuclear capacity could experience a sharp decline, compromising emission targets, as well as the costs and the security of electricity provision.
- Making the decision for long-term nuclear operations is complex and requires the analysis of policy, regulatory, technical, human and economic aspects. The present report therefore proposes a holistic approach that reviews all of these dimensions in order to define potential enabling measures that will help improve LTO prospects so as to support ambitious decarbonisation efforts.

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Part 1:
Analysis of the external environment for long-term operation

2. Energy policy aspects

Policy aspects are key in the decision-making process regarding long-term operation (LTO) of a nuclear power plant. Around 45% of the closures between 2011-2025 in OECD countries are driven by policy decisions (see Figure 1.2). In Europe, the impact of energy policies on decisions concerning LTO is more acute, accounting for about 80% of the total retirements over the same time period; in some cases even before reaching the initial design lifetime.

At a time when many governments are undertaking major efforts to decarbonise electricity systems, it is essential for policymakers to understand the opportunities and challenges of the LTO of nuclear power plants in maintaining low-carbon dispatchable generation. Beyond decarbonisation efforts, economic aspects (at the plant, system and social levels) and electricity security concerns also need to be fully acknowledged.

After assessing the status and configuration of the existing nuclear fleet worldwide, this chapter will thus explore the role of LTO under the three pillars of energy policies: i) environmental protection; ii) economics; and iii) affordability and security, and reliability of the electricity supply. While some of the aspects addressed in this chapter are generic to nuclear power, particular attention is given to opportunities associated with LTO, as well as to the potential consequences of a sharp decline in nuclear capacity in the years to come.

2.1. Overview of the existing nuclear fleet

2.1.1. Status and configuration

With 444 reactors in operation (an installed capacity of around 393 GW) in more than 30 countries around the world, nuclear power provides 10% of the global electricity supply, and is thus the second source of low-carbon electricity after hydropower. In OECD countries, this number is even higher, with nuclear power meeting 18% of electricity needs, making it the largest source of low-carbon electricity in OECD countries (IEA, 2021b). Excluding research reactors and other advanced concepts, the world's nuclear fleet is composed of four main technologies: light water reactors (LWRs) [1], pressurised heavy water reactors (PHWRs), gas-cooled reactors (GCRs) and light water graphite reactors (LWGRs). LWR technology dominates, accounting for more than 350 of the reactors (82% of the existing fleet) in operation, principally in Europe, the United States, Japan and Russia (see Figure 2.1). [2] Mainly in operation in Canada and India, PHWRs represent 11% of the reactors in operation globally. GCRs and LWGRs together make up the remaining 7%.

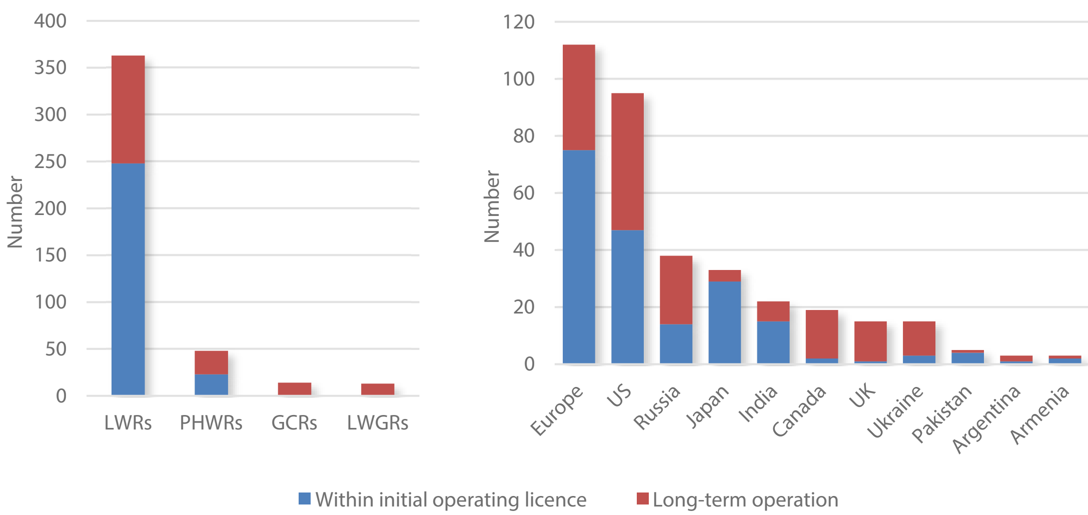
LWRs typically have an initial design lifetime of 30-40 years, depending on the reactor type. Initial design lifetimes for PHWRs, GCRs and LWGRs are typically 30 years. These values are consistent with the initial term length imposed by regulators in some countries (NEA, 2019a). Taking into account these initial design assumptions, it is possible to estimate that about 35%

1. LWRs cover three families of reactors: pressurised water reactors (PWRs), boiling water reactors (BWRs), and Russian-type PWRs or VVERs. Generation-II (Gen-II) LWRs represent more than 80% of global nuclear installed capacity (IAEA, 2021). Throughout this report, the term LWR refers to existing Gen-II designs and not Gen-III/III+ concepts.
2. LWRs, and in particular PWRs and VVERs, also predominate in nuclear development, representing 90% of the reactors under construction around the world.

of global installed capacity (i.e. approximately 150 reactors) is already operating in LTO conditions.[3] In absolute terms, the number of LWRs in LTO is greater than for any other technology. The ongoing expansion of this particular technology around the world offers an explanation as to why most LWR units remain within their initial design lifetimes. PHWRs, GCRs and LWGRs on the other hand were essentially deployed during the first nuclear wave in the 1960 and 1980s, and had more limited global development. These trends, combined with an initial design lifetime of 30 years, result in a relatively high share of reactors in LTO for such technologies. Similarly, LTO patterns by country are also conditioned by reliance in some territories on a particular technology (see Figure 2.1). For instance, Canada, Russia, Ukraine, and the United Kingdom have high shares of reactors in LTO as their fleets have a significant number of Gen-II VVERs, PHWRs and GCRs. Europe and the United States account for approximately 50% of the existing nuclear fleet and licence extensions. Countries such as the People's Republic of China and Korea, where nuclear programmes were initiated in the 1990s, have a relatively young fleet with no reactors in LTO.

Based on this evidence, the NEA Expert Group on Maintaining Low-Carbon Generation Capacity through LTO of Nuclear Power Plants: Economic, Technical and Policy Aspects (EGLTO) considered it appropriate to primarily address LTO issues related to LWRs. Additional insights on PHWRs and VVERs are also provided in some sections of the present report hence covering 95% of the reactors in operation worldwide. While acknowledging the importance of LTO in GCRs and LWGRs, these technologies remain outside of the scope of the present study.

Figure 2.1: **LTO by technology and country, 2020**



Note: European figures include Swiss reactors. The initial operating period by technology has been assumed to be 40 years for western LWRs and 30 years for PHWRs, VVERs, GCRs and LWGRs (see NEA, 2019a).

Source: OECD/NEA, using data from IAEA (2021).

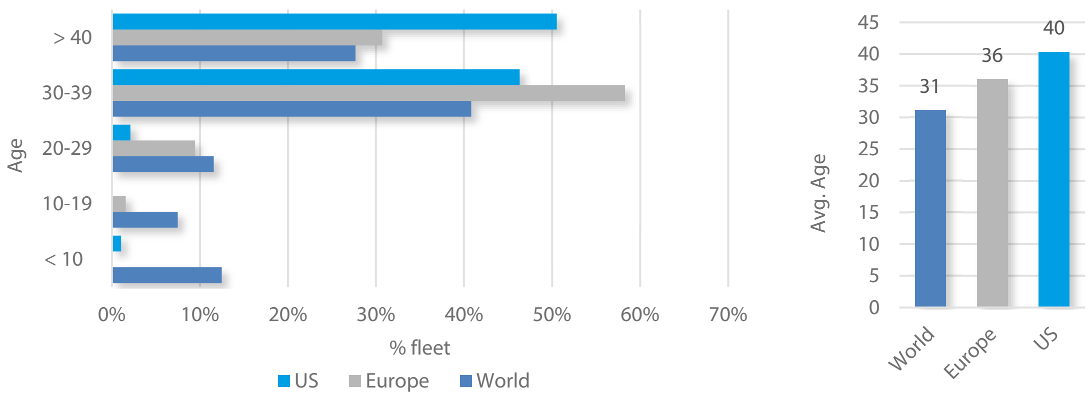
2.1.2. Age distribution and nuclear capacity projections

A closer look into the age distribution of the current nuclear fleet provides some indication of the potential LTO trends in different regions for the coming years. In general, global nuclear capacity is rapidly ageing. During the 1960s, nuclear power experienced a rapid expansion across the United States, and this expansion was then replicated in Europe between the 1970 and 1980s. After the Chernobyl accident in 1986, nuclear development experienced a major

3. A survey performed in NEA (2019b), covering 80% of operating reactors worldwide, reveals that 129 reactors (30% of the global fleet) are already in LTO.

slowdown, and capacity additions have been stagnating ever since in OECD countries. Over the last five years, only 40 GW of new capacity has been added to the grid, mainly in non-OECD countries and predominantly in China (IEA, 2020e). As a result, the age distribution of the global nuclear fleet has "shifted to the top" with an average age worldwide of 31 years (see Figure 2.2). The United States has one of the oldest nuclear fleets, with an average age of 40 years, and 50% of reactors have already entered LTO. While nuclear reactors in Europe are on average five years younger compared to US reactors, almost 60% of the European fleet is within the range of 30-39 years. In other words, in the absence of widespread LTO, a significant share of low-carbon capacity could fade away over the next decade on this continent.

Figure 2.2: **Age distribution of nuclear power by region, 2020**



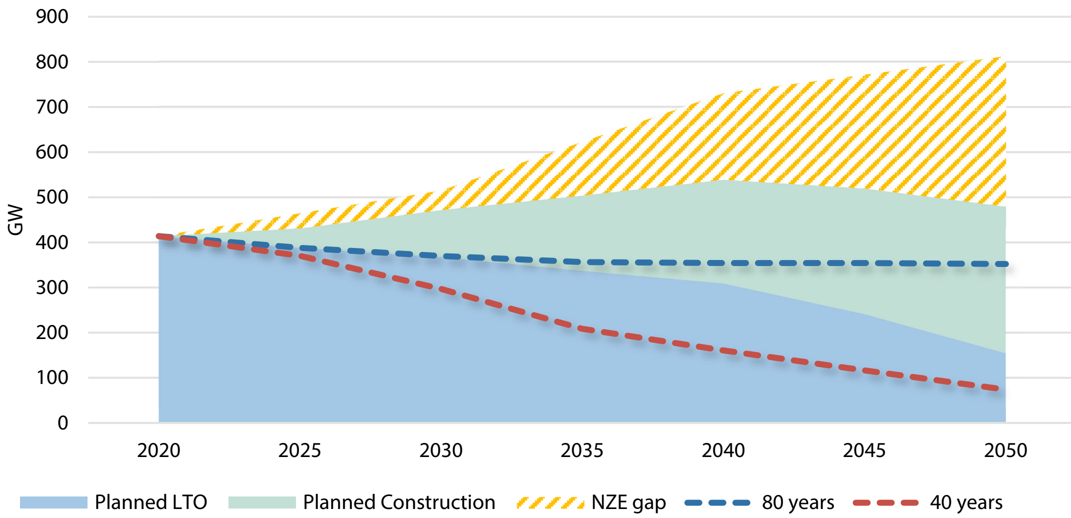
Note: European figures include reactors from Switzerland and United Kingdom.

Source: OECD/NEA, using data from IAEA (2021).

Planned LTO projections illustrated in Figure 2.3, nevertheless, suggest that licence extensions will be a global trend, leading to average operating time frames greater than 40 years. The combination of LTO with planned new build projects will also enable nuclear capacity to develop and keep up with IEA Net-Zero Emissions by 2050 Scenario (NZE)[4] targets by 2030. Beyond this time frame, the NZE nuclear capacity gap steadily grows, adding 330 GW to planned new constructions by 2050. This will require capacity additions to increase up to 25 GW per year starting from 2030: a pace 4 times greater than 2020 levels. Such nuclear deployment rates are consistent with those already observed during the 1980s (IEA/NEA, 2015). Achieving them, however, may require policy actions from today to secure the access to the necessary industrial capabilities. On the other hand, considering 80 years of operations for existing reactors – an increasing trend in the United States – could drastically ease the need for new nuclear projects and help meet carbon neutrality commitments by 2050, in particular after 2040, where planned LTO will experience a sharp decline. Overall, Figure 2.3 confirms the key role of LTO in the near-term to sustain, along with new build, nuclear development prospects as well as its strong potential to secure carbon neutrality by 2050.

4. As indicated previously, NZE complements IEA Sustainable Development Scenario (SDS) and reflects on the higher efforts needed to reach carbon neutrality globally by 2050. Capacity gaps using SDS as the reference scenario are thus of a lower magnitude given the lower ambition of this scenario compared to NZE.

Figure 2.3: **Global nuclear capacity by scenario, 2020-2050**



Note: Planned LTO projections take into account announced closures and licence extensions (i.e. 60 and 80 years), in line with stated policies, market conditions and regulatory approvals principally in Europe and the United States. Planned construction are essentially driven by new build scenarios in India and China. For the remaining projections, plannned LTO trends have been adjusted assuming operating time frames of 40 years (all reactor types) and 80 years (only LWRs and PHWRs).

*2.1.3.**Policy environment***

An overview of the political context surrounding LTO reveals contrasting trends depending on the country. Europe, Japan and North America together possess more than 50% of the existing nuclear fleet. Policy decisions in these regions could hence heavily influence nuclear capacity prospects in the near future.

The United States, the country with the largest and oldest nuclear fleet, is globally very supportive of LTO.[5] The first LTO programme in the United States started in 1983 (NEA, 2019a) and ever since, utilities and regulators have been accumulating extensive experience in LTO with an increasing number of reactors reaching the 40-year threshold. To date, from the 93 operating reactors in this country, 85 (more than 90% of the fleet) have been granted a first licence renewal, allowing operating time frames from 40 to 60 years. More recently, ten reactors have filed for subsequent licence renewals (SLRs) from 60 to 80 years. Two were approved in December 2019, two in March 2020 and another two in May 2021. A total of 4 applications are still under review, three under acceptance review, and the owners of 11 additional reactors have announced their intent to file for SLRs, with 2 units having already submitted official letters of intent to the regulatory body (NRC, 2021b; NEI, 2020). More recently, the NRC has been exploring the possibility of developing a new licensing framework that would allow nuclear reactors to run up to 100 years (NRC, 2021a). In Canada, the Darlington and Bruce PHWR units in Ontario are undergoing a multi-year, multi-billion-dollar refurbishment that will allow the plants to operate well beyond mid-century, reflecting the favourable LTO policies also present in this country. Both projects are progressing well and are expected to be completed by 2026 (Darlington) and 2033 (Bruce).[6]

5. Policies may nevertheless vary from one state to another. For instance, the two units of the Diablo Canyon nuclear power plant in California will be retired for policy reasons by 2025 (NEI, 2018).

6. The Pickering nuclear power plant in Canada is planned to be decommissioned by 2024 for techno-economic reasons. It will continue to secure electricity generation during the refurbishments at the Darlington and Bruce nuclear power plants.

In Europe, however, the political context is more heterogeneous and less favourable towards LTO in some regions (see Table 2.1). Since 2011, a total of 13 reactors have been shut down for policy reasons: 11 in Germany and 2 in France. Considering the strong phase-out policies in Belgium, Germany and Spain, and the uncertain situation in countries such as Sweden and Switzerland, more than 50 reactors could be decommissioned by 2040 in the worst-case scenario:[7] around 44% of the nuclear installed capacity on this continent. Given construction plans announced, this capacity drop could however be limited to 30%.[8] Consequently, Europe could experience the largest decline in nuclear generation in advanced economies, dropping from 25% to 5% by 2040 (IEA, 2020c). These prospects are not on track with the European long-term strategy for a climate neutral economy that sets the share of nuclear generation at 12-15% by 2050 (EC, 2018).

Table 2.1: **Overview of nuclear stated policies in selected European countries**

Country	Nuclear phase-out policy	New build	Policy risks	Comments
Germany	Yes	No		11 units retired following the Fukushima accident; 6 remaining units to be retired by 2022.
Belgium	Yes	No		Complete phase-out by 2025. First units to be retired by 2022.
France	No	Decision to be taken in 2021.		50% nuclear generation by 2035. 2 units shut down in 2020. 12 units to be retired between 2025 and 2035, and 1 unit under construction.
Spain	Yes	No		Complete phase-out between 2027 and 2035.
Slovak Republic	No	Yes		New units under construction.
Slovenia	No	Yes		New unit under consideration.
Switzerland	No	No		No nuclear power plant closure calendar. Energy Strategy 2050 indicates progressive withdrawal from nuclear power.
Sweden	No	No		No nuclear power plant closure calendar. 100% renewables by 2040.
United Kingdom	No	Yes		New units under construction and planned.
Finland	No	Yes		New unit under construction and another being planned.
Czech Republic	No	Yes		New units planned.
Hungary	No	Yes		New units planned.
Bulgaria	No	Yes		New units planned.
Poland	N/A	Yes		New units planned.

Nuclear phase-out policy with a closure calendar.
No phase-out policies, but several units to be retired in the coming years.
Strong support for nuclear power.

7. This scenario considers the retirement of the 7 units in Belgium, 12 in France, the 6 remaining units in Germany, 7 in Spain, 7 in Sweden, 4 in Switzerland and 15 in the United Kingdom, with no additional new projects.
8. New build projects in Europe could add roughly 15 GW of nuclear capacity by 2040, including those in countries such as Bulgaria, the Czech Republic, Finland, Hungary and Poland.

Following the Fukushima Daiichi accident in March 2011, Japan has also experienced the consequences of political turbulence and eroded public acceptance towards nuclear power. In 2019, the Tokyo Electric Power Company (TEPCO) announced the closure of the four units at the Fukushima Daini plant in response to demands from local government (WNN, 2019). As of June 2021, 16 reactors have successfully completed the Nuclear Regulatory Authority (NRA) safety reviews,[9] of which only 9 have already resumed operations. Additionally, four reactors have been granted a licence extension from 40 to 60 years, which, according to current Japanese regulations, can only take place once. At the same time, the 5th Strategic Energy Planning foresees a share of 20-22% for nuclear power in Japan's electricity supply by 2030. Achieving this target will require the restart of at least 30 reactors and a concerted effort among stakeholders to accelerate NRA reviews and local government agreements (IEA, 2021c).

In light of these trends, maintaining low-carbon capacity through the LTO of nuclear power plants will require energy policy frameworks that fully acknowledge the potential societal benefits arising from LTO decisions.

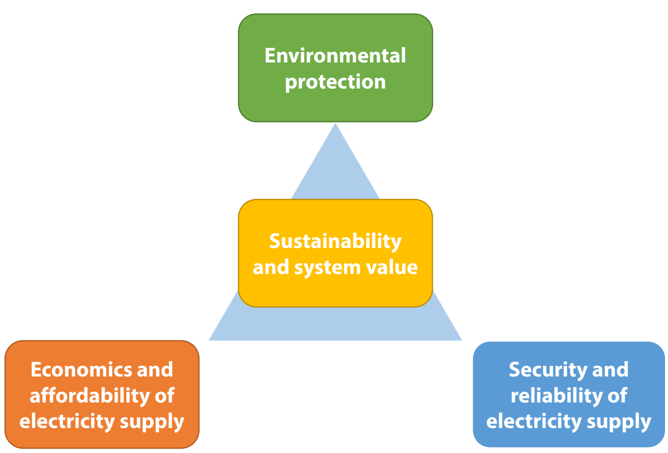
2.2. LTO and energy policy making: Opportunities and challenges

Translating sustainable development goals into energy policy making entails the analysis of several interconnected dimensions. While environmental issues (e.g. carbon emissions) tend to attract most of the attention of policymakers, they are not the sole objective when it comes to improving energy sustainability and the value of electricity systems. A sound energy policy should tackle the three dimensions known as the "energy trilemma" in a simultaneously manner (see Figure 2.4):

- environmental protection;
- economics and affordability of the electricity supply;
- security and reliability of the electricity supply.

In the next sections, the role of LTO is analysed under the prism of the energy trilemma, highlighting the different opportunities at the disposal of policymakers, but also the potential challenges of excluding LTO from the portfolio of the available technical solutions.

Figure 2.4: **The energy policy trilemma for the long-term operation of nuclear power plants**



9. The NRA safety reviews consist of two parts: a safety assessment based on the new regulatory standards in place following the Fukushima accident (in particular on external hazards) and a briefing by operators of concerned local governments.

2.2.1. *Environmental protection*

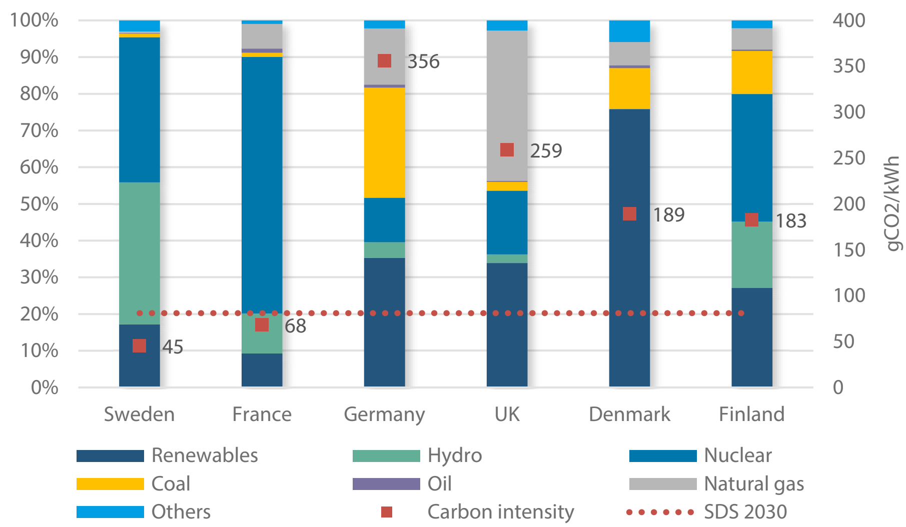
Four aspects deserve particular attention when assessing environmental protection through the lens of the LTO of nuclear power plants: carbon management, safety and performance, decommissioning and waste management, and other environmental impacts.

Carbon management

In terms of the carbon footprint (grammes of CO_2 equivalent emissions per kWh [gCO_2eq/kWh]), nuclear power is one of the cleanest sources of energy with a median value of 12 gCO_2eq/kWh (Bruckner, 2014).[10] Fission is a carbon-free process with no direct emissions. The low-carbon footprint of nuclear power is the result of indirect carbon emissions (construction, infrastructure, etc.) combined with significant amounts of carbon-free electricity, thanks to high-capacity factors (i.e. 85%) and long operating time frames (i.e. 40 years or more).

As an example, European countries that have already achieved IEA SDS 2030 targets in terms of the carbon intensity of the electricity supply (i.e. under 81 gCO_2eq/kWh [IEA, 2020a]) rely on high shares of nuclear generation (greater than 30%) and hydropower.[11] In fact, building a low-carbon mix that takes advantage of the dispatchability of nuclear energy to effectively displace coal and gas plants, enhances overall decarbonisation efforts (see Figure 2.5). This particularly the case in regions with more limited access to hydropower resources and/or interconnections.

Figure 2.5: **Configuration of the electricity mix and associated carbon footprint in selected European countries, 2019**



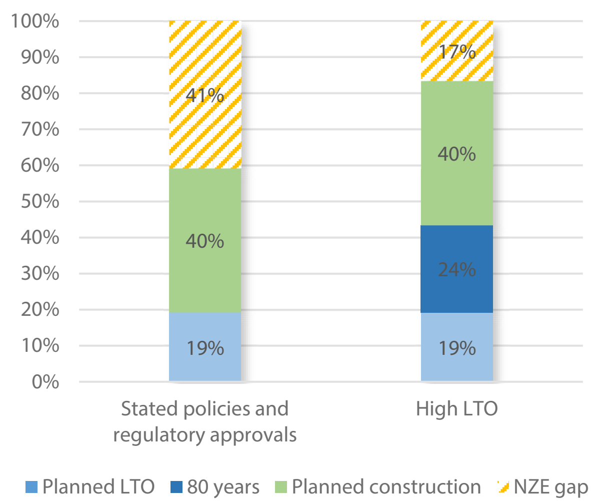
Note: The red dotted line represents a carbon footprint of the electricity system by 2030 – consistent with the Paris Agreement – of 81 gCO_2/kWh in Europe. Carbon intensity has been computed using the mean values for each technology from Bruckner (2014).

Source: OECD/NEA analysis, based on IEA (2020a; 2021b; 2019a).

10. Similar values are reported for wind power. The median carbon footprint for hydropower is 24 gCO_2eq/kWh, followed by solar PV at around 45 gCO_2eq/kWh. The technology with the highest carbon footprint is coal, which has a median value of 820 gCO_2eq/kWh. These numbers can vary depending on the assumptions and methodologies considered for their computation. A methodology that is codified and widely used by the scientific community is the life cycle assessment, based on ISO 14040 and 14044 standards.
11. This is the case, for instance, for France and Sweden.

A contraction of nuclear capacity could therefore have severe implications on the trajectory of carbon emissions (IEA, 2019). Assuming that the nuclear capacity gap to meet NZE targets is essentially filled with gas-fired plants, annual carbon emissions could rise by 2.9 Gt by 2050[12] (approximately 10% of today's carbon emission levels). Around 40% of these emissions (1.2 $GtCO_2$) are avoided by planned licence extensions, but their share sharply declines after 2040. A high LTO scenario relying more extensively on 80 years of operations keeps carbon avoidance capabilities of the current nuclear fleet beyond 2040 while supporting new build to achieve carbon neutrality targets (see Figure 2.6). Moreover, reactors with 80 years of operation could account for 25% of the emissions avoided by 2050, offering an effective way to cope with potential delays in the deployment of new nuclear builds and/or to absorb shortfalls in emission reductions, if they do not materialise at the expected rate.

Figure 2.6: **Breakdown of annual CO_2 emissions avoided with nuclear power in the IEA NZE by LTO scenario, 2050**



Note: It is assumed that nuclear power is displaced by gas with a carbon footprint of 490 gCO_2eq/kWh (Bruckner, 2014).

Because LTO only concerns reactors already in service, it cannot be considered as an overall decarbonisation option per se but rather can be seen as an effective means to manage carbon emissions in a predictable manner. The predictability of LTO results from two main reasons: i) the maturity of this option built upon significant industrial experience[13] and ii) the low uncertainty around closure decisions compared to licensing, building and commissioning new capacity. Furthermore, recent experience shows that the closure of existing nuclear power plants without the construction of new low-carbon dispatchable capacity (e.g. nuclear and hydropower) could result in an increase in the carbon footprint of the electricity sector in the short-term, as nuclear capacity is likely to be replaced by a combination of VRE backed up by fossil-fired plants, especially gas plants. For the time being, stability and flexibility solutions (e.g. long-term electricity storage, demand response, sector coupling) do not have the required level of technological and industrial maturity for the large-scale deployment required to limit reliance on fossil-fired capacity, in particular at high shares of VRE (see Box 2.1). In those countries with nuclear power, LTO secures a backbone of low-carbon capacity upon which new

12. These numbers could double if nuclear capacity is replaced by coal plants.

13. As indicated previously, more than 30% have already entered LTO.

low-carbon solutions can be built so as to enhance overall decarbonisation capabilities while innovative solutions gain in maturity. The necessity for mature and shovel-ready solutions such as LTO also becomes more apparent since emissions reductions target by 2030 are becoming increasingly ambitious and more countries are pledging to reach carbon neutrality by 2050.[14]

Box 2.1: **Replacing nuclear power in the short term**

A nuclear power plant produces large amounts of low-carbon electricity upon demand. Load factors for nuclear reactors are typically of 85% and these facilities possess certain manoeuvrability allowing to control their power output. Furthermore, they are synchronous generators with a rotating mass coupled to grid that stabilises the system by providing inertia and short-circuit power (i.e. system strength). When the system faces a disturbance, these machines automatically help to stabilise the grid frequency by releasing some of the kinetic energy stored in their rotating rotor before other reserves take over. These aspects are essential for the smooth operation of any electricity system, and conventional generators with a rotating mass such as nuclear station are the cornerstone network stability. Consequently, when replacing a nuclear power plant, an equivalent amount of low-carbon electricity will be required but also solutions that provide the same level of service to the grid in order to avoid potential system disruptions.

A low-carbon technology option with similar attributes to nuclear power stations is hydropower. Most of the best locations, however, are already equipped reducing overall hydropower potential. In addition, its dependence on orographic conditions makes of hydropower a low-carbon resource not available in all countries, which stunts its scalability. Wind and solar power are also part of the low-carbon solutions available to fill the gap left by a nuclear facility. These technologies are cheap, scalable and can be deployed in short lead-times, however, they are intrinsically variable and dependent on weather conditions. Their output can be predicted and curtailed but never dispatched on demand, requiring the rest of the residual (and dispatchable) system to adapt once they are generating. Additionally, in contrast to conventional power plants, VRE are non-synchronous generators and their capability to provide power strength to stabilise the network is very limited. In practice, VRE should be complemented with other technologies and measures to equate the level of service provided by a nuclear power plant.

While the variability of solar and wind is manageable at low shares, higher penetration rates will increase the stress on the system, especially at shares greater than 30-40% (NEA, 2019). According to the IEA (2021a), an electricity system solely built upon high shares of VRE resources must meet four strict conditions to be technically feasible: i) ability to provide system strength under significant inertia reduction ii) adequate system adequacy and flexibility levels at all times iii) availability of sufficient operational reserves and iv) substantial grid development. The report finds that, while solution exist to provide system strength and flexibility in networks with high shares of VRE, they are still at the research and development stage and therefore not ready to be deployed at scale. Greater technical difficulties are likely to be encountered in highly distributed systems. This is consistent with the findings of IEA (2020b) which indicates that more than 50% of the technologies needed to meet carbon neutrality by 2050 have not still reached industrial maturity. At the same time, given the absence of proof of concept and operating experience of large-scale electricity systems with high shares of VRE, technical challenges may arise. Moreover, costs and social implications associated which such systems may be significant, which could hinder their adoption.

As a result, and without the possibility to install new hydropower and nuclear units, existing nuclear reactors are likely to be replaced by a combination of VRE backed by fossil-fired plants (principally gas plants and to a lesser extent coal) in order to provide the necessary stability and flexibility to the system. Gas plants have also the benefit to be relatively affordable for mid-merit and peak generation and have short construction lead-times, if properly anticipated. This situation, however, will directly lead to an increase of CO_2 emissions in the short-term in the absence of further mitigation measures, as illustrated by the examples below. Energy efficiency and system flexibility measures can be envisioned in parallel to reduce the reliance to fossil fuel in the mid and longer run. The latter include interconnections, storage, demand-side response and sector

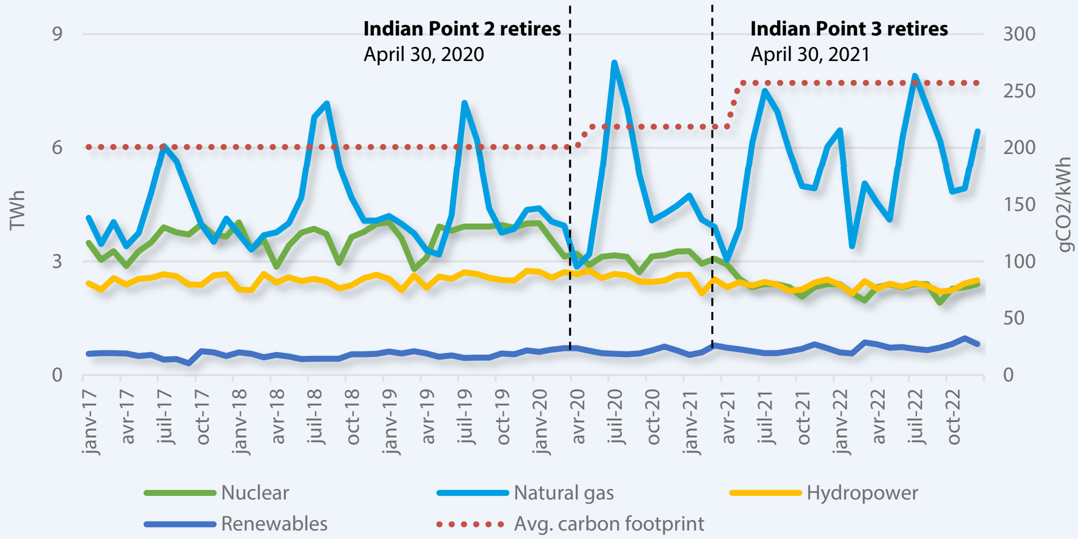
14. The European Green Deal, for example, sets out a clear vision for the European Union (EU) to achieve climate neutrality by 2050, with emission reductions of up to 50-55% by 2030 compared to 1990 levels (EC, 2019), an increase from the former goal of 40% More recently, countries such as China, Japan, Korea and the United States have also pledged their intentions to reach carbon neutrality by 2050-2060.

coupling approaches. Prospects of large-scale deployment of flexibility options, nevertheless, remain uncertain with significant efforts still to be made in coming years to take some technologies to industrial-scale deployment, for example large-scale flexibility from electric vehicles or synthetic fuels production (power-to-hydrogen or power-to-gas) and storage (IEA, 2021a).

United States

In the state of New York, in the United States, nuclear units of Indian Point 2 and 3 where retired earlier than planned after a settlement agreement between Entergy Corp, operator of the reactors, the state of New York (Larson, 2017) amid negative market prospects. The capacity gap was compensated with electricity generation coming from the gas plants of Bayonne Energy Center II (120 MW), CPV Valley Energy Center (678 MW), and Cricket Valley Energy Center (1 020 MW), built three years before in anticipation of the closure of Indian Point units (EIA, 2021b). Figure 2.7 illustrates how gas plants take over nuclear generation soon after the reactors ceased operations, as well as the subsequent increased in the carbon footprint of the New York State's electricity system.

Figure 2.7: **Electric power generation by fuel, New York ISO, Jan 2017-Dec 2022**



Note: Carbon intensity has been computed using the mean values for each technology from Bruckner (2014).

Source: OECD/NEA using data from EIA (2021b).

In the state of California, in preparation for closure of the Diablo Canyon nuclear power plant units and ageing gas-fired plants, the California Public Utilities Commission (CPUC) is working on a procurement order of 11.5 GW to be rolled out between 2023 and 2026. While significant efforts are being made to include only clean energy sources in the proposal, the fossil fuel option is still open (Balamaran, 2021a; S&P Global, 2021). Depending on the outcomes of further system adequacy analyses, new gas plants could be procured to replace Diablo Canyon units hampering climate action.

Japan

Before the Fukushima accident, nuclear power accounted for 25% of the electricity generation in Japan. After the accident, all reactors were shut down for safety inspections and upgrades to comply with new regulatory requirements, leading to a surge of gas and coal consumption. As a result, annual carbon emissions in the electricity sector immediately rose of around 25%. Since 2014, the carbon footprint of the Japanese electricity sector is steadily declining thanks to the development of VRE and more reactors resuming operations. As of 2019, nevertheless, emissions were still higher than pre-Fukushima levels (IEA, 2021b).

Belgium

Nuclear power is an important part of the electricity mix in Belgium. In 2019, nuclear generation represented nearly 50% of the total electricity of the country, and 70% of the total low-carbon electricity generation.

The federal government reconfirmed the nuclear phase-out in October 2020. Under current legal requirements nuclear reactors in Belgium will cease operations between April 2022 and December 2025. However, the government indicated that 2 GW of nuclear capacity may be needed beyond 2025 to ensure generation adequacy.

The nuclear phase-out will have a large impact in the Belgian electricity system. In the short term, in order to mitigate electricity security risks, gas generation is expected to increase along with VRE. Consequently, carbon emissions are estimated to grow 30% with gas representing a sizeable share of the electricity generation by 2030 and beyond, in particular if no additional policy efforts are undertaken (BFP, 2017; EEA, 2018).

Safety and performance

Nuclear power plants are assets in constant evolution. Most of the structures, systems and components (SSCs) of a nuclear power plant are replaced as part of normal maintenance procedures and more extensive LTO refurbishment. In fact, regulatory frameworks in most countries impose periodic and LTO-specific safety reviews to assess if the plant complies with its licensing basis during the initial design lifetime, as well as during the LTO period (see Chapter 5).

On the other hand, there are SSCs for which replacement can be considered unfeasible for technical and/or economic reasons.[15] Consequently, the ageing of these components will ultimately limit the operation of the plant. Critical life-limiting components are typically the reactor pressure vessel (RPV) and concrete containment structure (NEA, 2012b), and these are subject to specific ageing management programmes (see Chapter 3). Extensive research and operating experience nonetheless support safe operation beyond 40 years (NEA, 2006, 2012b, 2015). In addition, global performance indicators suggest that older plants do not necessarily face more operational issues as they can benefit from experienced teams and refined organisational procedures resulting from 40 years of operation (see Chapter 4).

Decommissioning, waste management and other environmental aspects

According to the European Joint Research Centre (JRC) (2021), there is an international scientific consensus that nuclear energy does not do more harm to human health and environment than other low-carbon technologies. This conclusion includes both radiological and non-radiological impacts over the entire life cycle of a nuclear power plant, and thus the LTO period.

The decommissioning process is independent from the lifetime of the plant, meaning that LTO will have a very limited impact on the technical aspects of decommissioning (NEA, 2016). In addition, from an economic perspective, some financial benefits may arise from delaying the decommissioning decision (see Box 6.1).[16]

In terms of high-level waste (i.e. spent nuclear fuel, reprocessing), however, LTO will automatically lead to additional quantities of nuclear waste, proportional to the duration of LTO.[17] Such a situation would therefore require the availability of physical infrastructures to safely store waste. Available solutions include interim or centralised wet storage in pools or

15. That is, it would either present too great a technical challenge, and/or it would simply be too costly to be justified.
16. Assuming that the benefits outweigh potential cost escalations and inflation.
17. After 40 years of operation, for example, adding 20 years of operations would increase the amount of nuclear waste by roughly 50%.

dry storage in casks, and these solutions can be implemented as part of the LTO programme.[18] In parallel, long-term disposal solutions such as deep geological repositories (DGRs) have made significant progress in various countries. There is a strong, international and scientific consensus that DGRs are a safe, appropriate and effective approach to the permanent disposal of high-level waste and spent nuclear fuel (NEA, 2020a; JRC, 2021). The first DGR to be commissioned will likely be in Finland, with operations beginning around 2023, but similar projects in France and Sweden are well advanced.

Other environmental impacts of power generation activities include aspects such as air pollution, land use, resource depletion and water use. As a carbon-free, energy-dense resource, nuclear power performs well in terms of air pollution and land use, including via mining activities (IAEA, 2018; NEA, 2018b; JRC, 2021). Similarly to carbon emissions, LTO offers the opportunity to efficiently manage these issues and extend the environmental benefits over time.

In terms of resource depletion, uranium reserve-to-production ratios remain high with values typically around 100 years or more (NEA, 2018b, 2020b).[19] LTO of the existing global fleet will therefore not represent a threat in terms of resource depletion. In parallel, progress continues to be made in minimising the environmental impacts of mining activities (NEA, 2020b). Beyond uranium resources, the demand for critical minerals (e.g. copper, lithium, silicon, rare earths) is set to rise during the energy transition given the higher material intensity of a low-carbon mix that relies on high shares of VRE.[20] (IEA, 2021c) As for carbon emissions, LTO can be regarded as a lever to manage critical resource supply issues, as well as to limit the potential environmental impacts associated with increased mining activities (Beylot et al., 2020). Moreover, the life cycle impacts per GWh of generated electricity originating from concrete, steel and other building materials used in the construction of a plant, from construction and decommissioning activities and from the decommissioning of waste will decrease substantially over time through LTO (JRC, 2021).

The water footprint is also a growing concern, especially in light of heatwaves and draught episodes that are expected to be more frequent and intense in the years to come. In general, reactors in operation have been designed to adequately meet site-specific environmental and water-cooling constraints. Technically, it is possible to increase the efficiency of the cooling systems and adapt nuclear facilities to meet more stringent regulations and water footprint limits, even during the LTO period (NEA, forthcoming).

Finally, in most legal and regulatory frameworks, environmental impact assessments are part of the LTO-review process. These assessments are designed to ensure that nuclear power plants continue to operate in a safe and environmentally friendly manner (NEA, 2019a).

2.2.2. ***Economics and affordability of the electricity supply***

Having access to cheap and stable sources of electricity is key to the development and competitiveness of each country. At the same time, national realities differ, leading to a myriad of possible ways to combine technologies so as to build a low-cost electricity system. Carbon constraints are nevertheless reducing the choice of technologies available to provide an affordable, low-carbon system. Meeting ambitious emission reduction targets require the deployment of mature and proven low-carbon solutions, including nuclear power. For those countries choosing LTO of existing nuclear assets, it is essential for policymakers to have a clear understanding of the implications of this decision from a full cost perspective. This full cost perspective entails looking beyond individual plants and technologies and considering system and socio-economic considerations. To do so, the different regulations and policy measures in place should properly recognise the value that LTO can provide to the electricity system while sustaining affordability over time. Residual risk, however, will always remain, and governments are best placed to absorb them and create the appropriate context for optimal industrial performance, and therefore lower costs.

18. Storage pools have been characterised as a mature technology based on over 50 years of operating experience and dry cask storage systems as passive systems with over 30 years of operating experience (NEA, 2020c).

19. Taking into account conventional resources that are not exploitable under current uranium prices, proven reserves could satisfy more than two centuries at current consumption levels.

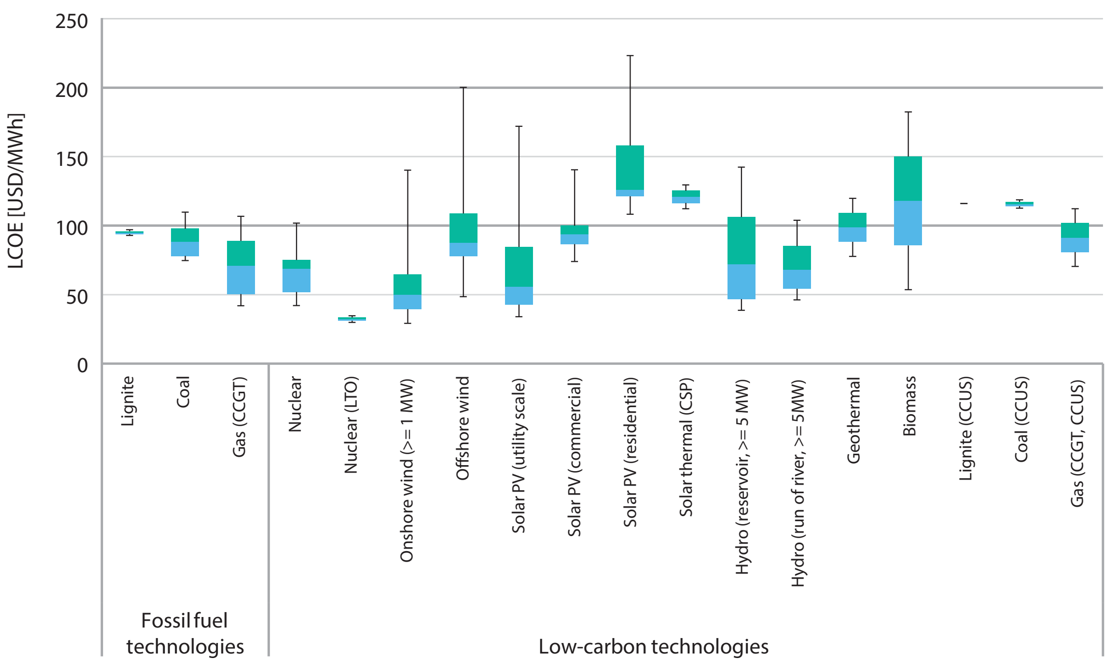
20. Four-fold under SDS and six-fold under NZE, compared to 2020 levels.

Technology costs and market issues

The full costs of electricity provision typically fall into three categories: plant-level costs, system costs and social costs (NEA, 2018a). LTO, similar to other power generation technologies, contribute to each category.

From a plant-level cost perspective, the results of the present study confirm that LTO of the existing nuclear fleet is one of the most cost-competitive options on the basis of the levelised cost of electricity (LCOE) in many regions, with overnight construction costs (OCC) ranging from USD 450-950/kWe and a LCOE between of USD 25-50/MWh (see Chapter 6). Similar results are reported in IEA (2019) and IEA/NEA (2020) (see Figure 2.8).

Figure 2.8: **LCOE by technology, 2025**



Note: Values at 7% discount rate. Box plots indicate maximum, median and minimum values. Boxes indicate the central 50% of values (i.e. the second and third quartile).
USD/MWh = US dollars/megawatt hour; CCGT = combined cycle gas turbine; CCUS = carbon capture, use and storage.

Source: IEA/NEA, 2020

Despite these favourable cost trends, nuclear power plants are being retired earlier than expected as a result of negative market prospects, especially in the United States. Fixed costs remain high for licence extensions, which makes these assets particularly sensitive to availability downturns and/or sustained, low electricity prices. In parallel, market conditions have dramatically changed over the last decade with the irruption of higher shares of VRE, underscoring the limits of current market designs to secure low-carbon capacity in the long term. As a result, various regulations and support mechanisms cohabit within competitive markets to support the development of low-carbon technologies, and these could, theoretically, be extended to LTO (see Chapter 6). This is the case, for instance, for zero emission credits in the United States (see Box 6.5).

Beyond plant-level costs, system costs arise from the interaction of individual technologies with the overall electricity infrastructure in order to meet demand at all times. With nuclear capacity fading away without timely LTO decisions, and assuming that wind and solar power are the main technologies being considered as a replacement for nuclear power, low-carbon energy systems could be more expensive. Without the dispatchability attributes of nuclear power, electricity systems could also be subject to higher strains (e.g. steeper and more frequent ramps) and require grid reinforcement in order to accommodate higher peak loads from the higher shares of nuclear power and VRE. As a result, electricity supply costs could be close to USD 80 billion higher per year on average for advanced economies as a whole (IEA, 2019). Additional quantitative evidence on the systems costs of electricity systems with shares of nuclear power and VRE is provided in NEA (2019b). The extent of these effects may vary depending on the structure of the generating portfolio and the availability of flexibility resources, for instance in the case of hydropower, interconnections and storage.

Finally, social costs quantify the impact of a generation technology on individual and community well-being. This category covers a multitude of social and environmental costs, involving local and regional air, water and soil pollution, climate change, the consequences of major accidents, land use and resource depletion. While acknowledging the uncertainties behind these full cost estimates, a comparison with the external costs of fossil fuel reveals that the benefits in terms of climate change and air pollution offered by nuclear power largely outweigh the social costs (Burtraw et al., 2012; NEA, 2018b). LTO, alongside with other low-carbon sources, is therefore an effective and predictable lever to manage and attenuate the negative externalities of air pollution and climate change.

Insights on policy making and economic performance

Policy aspects and the economic performance of projects or industrial sectors are intimately related, in particular if the socio-economic impacts at stake are high. The context under which critical activities are executed thus takes on great importance and becomes a potential source of policy risk – typically out of the reach of industrials – that can severely undermine the final economic outcomes if not properly managed. This is the case for any major energy infrastructure upgrade, including LTO programmes.

In order to address potential policy risks associated with licence extensions, long-term industrial policies can be developed for a better risk allocation between the industry and the government, while providing high levels of policy commitment and adequate regulations:

- **Policy commitment**: governments are best placed to ensure the long-term stability, visibility and planning that LTO activities require. These conditions are of utmost importance for various reasons. First, most costs are fixed, meaning that any sudden deviation from the initial strategy will come at a higher economic penalty. In addition, longer amortisation periods and stable prices usually improve the profitability of LTO investments. Second, meeting high safety standards requires continuous technical assessments in co-ordination with regulators and across the entire value chain. These activities are better performed under more predictable policies since any unexpected change could trigger significant amounts of rework and undermine the overall economics (see Box 2.2 below).

- **Regulations:** policymakers have various options to improve the economic performance of a technology (or of the electricity system as whole) either affecting the costs, revenues or both. The speed of deployment and potential impacts can also vary. For instance, reviewing taxation regimes (lowering costs) and support mechanisms (guaranteeing revenues) for a given technology are easy to do and can lead to rapid and effective results. More structural market reforms, however, may require careful planning to avoid undesirable distributional effects or public opposition, but the reward can be higher and more noticeable in the long term (see Chapter 6). The resulting policies will certainly be a combination of various measures tailored according to the specificities of the context and various policy motivations in order to maximise the social benefits.

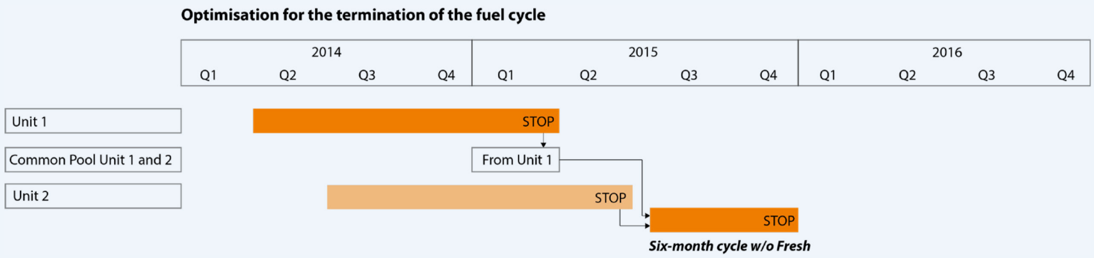
Box 2.2: Policy uncertainty and nuclear power industry performance – The case of Belgium

In 2003, the "Progressive phase-out of nuclear power for electricity for industrial purposes" law was enacted in Belgium, according to which construction of new reactors for the generation of electricity was banned. At the same time, the remaining reactors would cease operations once the 40-year limit was reached. The first units impacted by this law were Doel 1 and 2, and Tihange 1, all of which were to be shut down by 2015.

Despite this phase-out policy decision, the main Belgian utility, Electrabel, anticipated between 2009 and 2012 the safety LTO-review necessary to operate these plants beyond the 40-year threshold. Following regulatory approval, received in 2012, the operator started to implement the necessary safety upgrades and plant enhancements at Tihange 1 and decided to start decommissioning work on Doel units 1 and 2.

The decommissioning plans for Doel units 1 and 2 were optimised in order to make the best use of the energy in the fuel assemblies, whether in the core or in the storage pool, and to minimise the size of the fresh reloads in the terminating fuel cycles. This required the implementation of a new fuel management strategy consisting of the design of a specific core loading for unit 2 that combined 2/3 of the irradiated assemblies of unit 1 with 1/3 of the counterparts of unit 2. This approach provided enough reactivity margins to run unit 2 at hot full power until the end of 2015, minimising overall fuel costs (see Figure 2.9). The approach of course required specific safety studies to demonstrate that such unusual core loading met all the safety criteria.

Figure 2.9: **Foreseen fuel management strategy for Doel units 1 and 2 in 2015 to meet 2003 Belgian phase-out law**



Source: Courtesy of Electrabel.

When approaching 2015, it appeared that new VRE installed capacity was not enough to compensate for the closure of the three nuclear units, giving rise to security and energy independence concerns. Consequently, in 2014 the government reconsidered its initial phase-out decision and allowed Doel units 1 and 2 to operate beyond 40 years until 2025. The law was finally amended in mid-2015.

However, from an industrial perspective, this political reversal implied a major redesign of the previous decommissioning plans and fuel management strategy under a very challenging schedule. Unit 2 was immediately stopped in order to perform all of the necessary inspection and maintenance activities to safely operate the plant beyond its initial term of termination. Further, with the fuel assemblies of unit 1 already loaded in unit 2, a full new core had to be procured. Going back to the usual conditions also required fuel assemblies with very special characteristics and complex negotiations with suppliers, resulting in higher overall fuel costs.

This case provides valuable insights into the actual technical and economic implications of performing nuclear activities under uncertain conditions. While adjustments are possible, experience has shown that these are often carried out in far from optimal conditions, potentially leading to additional costs that would have been avoided with more anticipation and a long-term vision. The Belgium examples also indirectly illustrate how LTO can absorb shortfalls in electricity supply if low-carbon capacity additions do not progress as initially planned.

2.2.3. *Security and reliability of the electricity supply*

Security of electricity is at the heart of economic progress in modern societies. The COVID-19 pandemic has more recently illustrated the critical importance of having a reliable and robust electricity system in order to ensure the smooth operation of economy-wide essential activities and business continuity to limit economic losses.

The characteristics of a secure electricity supply may vary according to different stakeholders. While the final consumers are essentially concerned about uninterrupted supply, transmission system operators rely on robust methodologies and technical criteria.[21] The NEA report *The Security of Energy Supply and the Contribution of Nuclear Energy* (2010) identifies three dimensions relevant for policymakers when assessing the contribution of different technology options for the security of supply:

- the physical availability of fuel and generating capacity (i.e. system adequacy) at all times;
- the ability of generating capacity to the smooth operation of the electricity system in the presence of sudden shifts in demand, particularly during periods of peak demand;
- the contribution of generation capacity to the stable economic behaviour of the electricity system when supply is scarce.

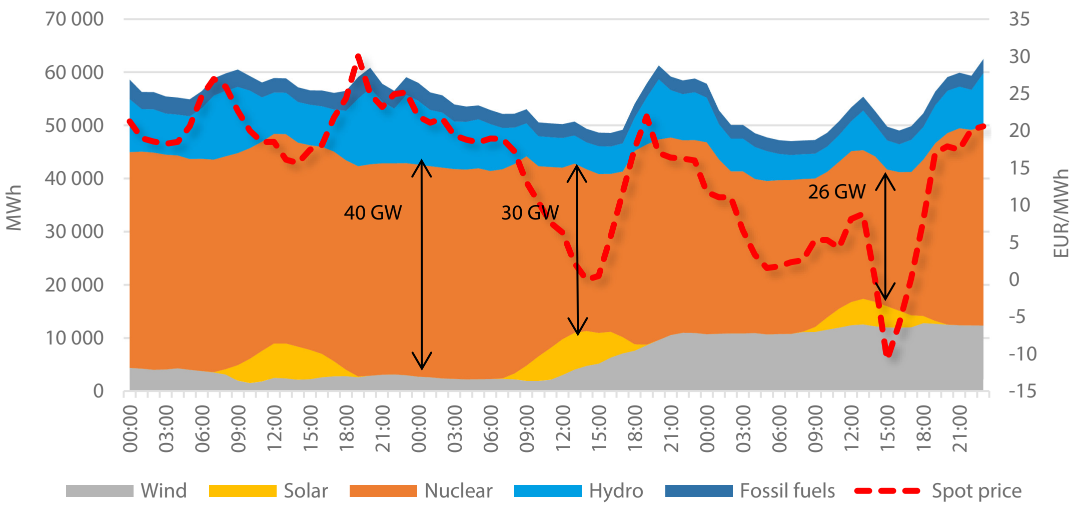
These dimensions also cover different physical and temporal scales. For instance, in highly interconnected networks, security of supply concerns may be more adequately addressed in close co-ordination with neighbouring countries, or even at the continental level. Accommodating demand and price shifts are routine activities in modern electricity systems, but ensuring system adequacy requires long-term planning and specific regulations. Nuclear power, and more specifically LTO, performs well in all three of these dimensions.

Nuclear fuel and dispatchability attributes

In terms of fuel availability, nuclear fuel is an energy-dense resource,[22] which can be easily and safely stored. In this sense, countries with nuclear power plants can secure strategic fuel stockpiles for several years of operation[23] improving overall fuel security and diversity. As baseload generators, nuclear reactors usually run without interruptions during cycles of 18-24 months between fuel loading outages. This results in average load factors of 85%.[24] The dispatchability of nuclear power also contributes to the reliability and quality of the electricity supply. As a manoeuvrable asset with a rotating mass, nuclear power plants can, for example, provide ancillary services such as inertia, primary and secondary frequency control (low rapid power variations ranging from 5 to 2% of the nominal power) and load following (slower power variations of more than 50%), all while respecting technical and safety constraints (IEA, 2019; NEA, 2012a). The body of knowledge surrounding flexible operations in considerable and future innovations could also enhance flexibility attributes including non-electric applications (NREL, 2020) (see Chapter 6) These dispatchability attributes also have implications in terms of the economic behaviour of the system. The possibility to accommodate load fluctuations through load following stabilises electricity prices, thus limiting the impact and occurrence of negative prices (see Figure 2.10). These conditions also facilitate the integration of higher shares of VRE at lower system costs while reducing the reliance on fossil-fired backup. With electricity systems becoming more and more interconnected, these effects are becoming noticeable across a number of countries.

21. According to the electricity security standards of the French transmission system operator, ensuring the perfect balance of supply and demand may require exceptional load shedding measures (e.g. interrupting the production of electro-intensive industries, reducing the voltage in the distribution network, implementing rolling blackouts) on average for three hours per year (France Stratégie, 2021).
22. As an order magnitude, 1 tonne of natural uranium extracted for a PWR provides 10 000 times more energy than 1 tonne of oil or coal, and 1 000 cubic metres of natural gas (CEA, 2018).
23. For instance, it is estimated that France has enough nuclear fuel on its territory to secure three to five years of full operation for the entire nuclear fleet (SFEN).
24. This value is also dependent on system constraints. In France, where the existing nuclear capacity covers more than the baseload region in the load duration curve, capacity factors are at around 75%, with reactors performing load following.

Figure 2.10: **Electricity generation mix in France between 27-29 March 2020**



Source: OECD/NEA, using data from RTE (2021) and Nord Pool (2021).

Thanks to LTO, nuclear power can continue to offer its support to the security and reliability of the electricity supply at reasonable costs, all the while avoiding carbon emissions. Industrial experience has furthermore shown that existing reactors can be retrofitted to improve their manoeuvrability capabilities. Operators undertaking major refurbishments for LTO may see value in implementing additional plant enhancements to adapt the plants to a changing context, while mutualising costs and licensing efforts. The associated technical requirements, as well as the potential economic advantages of flexible operations during LTO, are further explored in Chapters 3 and 6, respectively.

System adequacy considerations

Ensuring system adequacy (or the availability of physical generating capacity) is becoming a critical issue in light of more ambitious emission targets, which will most likely require the closure of dispatchable generators such as coal and gas plants. Nuclear phase-out policies may also further reduce capacity margins. In some regions, the capability of the electricity system to respond to peak demand surges under extreme events (e.g. heat and cold waves) is already being undermined and could worsen beyond the 2025 time frame in the absence of remediation action (see Box 2.3).

The installation of additional VRE capacity will certainly have a positive impact in terms of the security of supply – especially if wind and solar power additions are combined– but their contributions will be very limited given their low capacity credit.[25] The flexibility provided through interconnectors could also be reduced, with various countries simultaneously phasing-out dispatchable generators. Storage (e.g. batteries and long-term storage solutions), sector coupling and other innovations are part of the solutions required to accommodate high shares of VRE, but their large-scale deployment prospects remain uncertain.

25. Capacity credits give an appreciation of how much a system operator can rely on a technology to meet peak demand. On-shore and off-shore wind have capacity credits of around 10-20%, respectively, and solar PV at 2%. The higher penetration level of VRE in the electricity system, the lower their capacity credit is. This can be explained by the intrinsic variability of renewables and their high autocorrelation. Conventional, dispatchable generators, on the other hand, have capacity credits of around 85%, similar to their load factor (NEA, 2019; France Stratégie, 2021).

As long as uncertainty exists in relation to the transformation of the power system, realistic and proven solutions need to be pursued as a technological hedge against such uncertainty. Countries with nuclear reactors in operation can enhance electricity security by fostering a diversified low-carbon mix that benefits from the dispatchability of nuclear power through LTO (IEA, 2020f). Higher levels of cross-country co-ordination would also be beneficial. While some initiatives exist, in the majority of cases capacity closures are largely decided in a unilateral manner (see Box 2.3 below). These measures could be complemented with market regulations that send the right price signals to support the construction of new capacity in the long term (see Chapter 6).

Box 2.3: **Assessing reliability concerns in low-carbon electricity systems**

The energy transition is profoundly transforming the electricity system. Significant amounts of fossil-fired, dispatchable generators (i.e. mainly coal plants) are being replaced by VRE additions. While necessary to reduce emissions, these replacements could lead to capacity shortfalls in meeting peak demand, especially if nuclear power is also removed from the grid. Achieving carbon emission reductions at the expense of electricity security is not a sustainable approach. Recent episodes of grid stress and capacity projections underscore the impacts of deploying VRE without adequate planning and new measures, which are needed to avoid rising reliability concerns.

California

The state of California in the United States is committed to achieving carbon neutrality by 2045. As a result, electricity generation from coal has already been completely abandoned and additions of solar PV have more than doubled over the last five years. In 2019, solar and wind power represented around 21% of electricity generation in California, with the remainder procured essentially from gas (43%), hydropower (19%), nuclear (8%) and geothermal power (5%) (EIA, 2021a). The rapid deployment of solar PV has strongly impacted the residual load profile of dispatchable generators and increased flexibility needs.[26] When the sun sets, ramps of around 13 GW are required to rapidly compensate for the reduced generation of solar power (CAISO, 2016).

In August 2020, in the midst of a heat wave, the Californian grid operator, California ISO (CAISO), issued a "Stage 3 Electrical Emergency" and implemented load-shedding measures for several days to maintain grid reliability, including through rolling blackouts that impacted around 200 000-250 000 consumers per hour. An ex-post root cause analysis of the main reasons behind this event demonstrated that a lack of resource planning to keep up with a changing electricity mix, exacerbated by excessive demand induced by the extreme heat wave and some market practices, was the primary cause (Morehouse, 2021). In 2019, CAISO had already warned the California Public Utilities Commission (CPUC) of a capacity shortfall of 4.7 GW by 2022 (GTM, 2020). The CPUC and CAISO are working in close co-ordination to install new capacity in 2021 and to increase resource adequacy targets for specific hours of peak demand. CAISO is also expediting a stakeholder process that will allow it to more accurately determine real time supply and demand during constrained conditions. In the short term, some of these measures may include further contracts for additional electricity generation with gas plants, threatening the state's clean energy goals (Balamaran, 2021b)

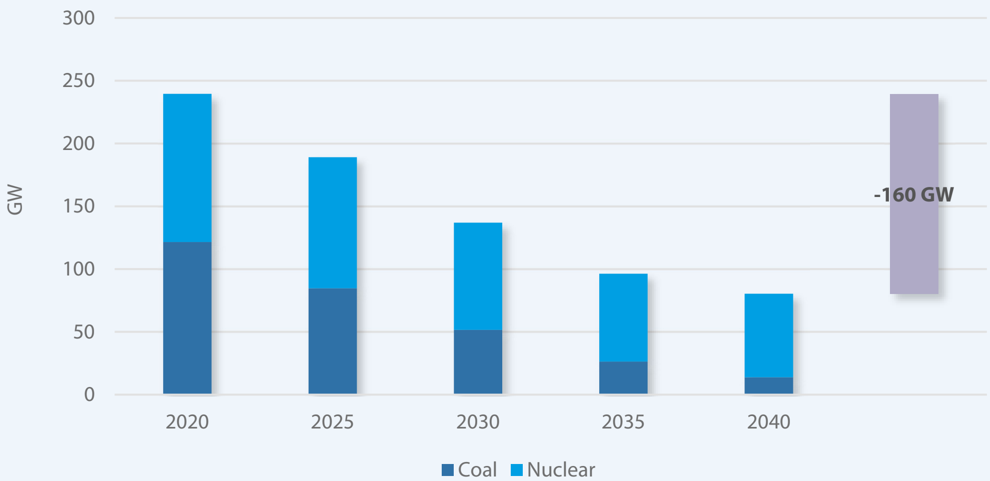
Europe

In 2019, some European grid operators underscored increasing grid reliability risks in the years to come as more countries were phasing-out dispatchable capacity, without consulting neighbouring countries, and relying on more imports to compensate for the capacity loss (Reuters, 2019). As of 2020, there was around 240 GW of combined coal and nuclear capacity, representing 40% of dispatchable generation in Europe. Projections based on stated policies show a 66% reduction in this capacity (160 GW) by 2040, which should be compensated by other resources. Assuming that nuclear energy remains at 2020 levels, the fall in capacity could be limited to 45% (see Figure 2.11 below).

26. Because of the particular form of residual demand (i.e. very low when solar panels are generating and rapidly increasing as the sun goes down), this phenomenon is typically known as the duck curve.

A recent study from France Stratégie finds similar grid reliability concerns (France Stratégie, 2021) with Belgium, France and Germany the countries impacted the most. All three countries foresee the phase-out of nuclear capacity in the short term. According to France Stratégie (2021) estimates, Germany in particular would not be able to meet peak demand by solely relying on dispatchable generation beyond 2025. France could experience a similar situation by 2035 when around 12 nuclear reactors will be retired from the grid. The European electricity network is more and more interconnected, and therefore interdependent. Structural decisions on the energy mix (e.g. capacity retirements), however, rely exclusively on national authorities and are still taken with limited co-ordination among EU member states. Initiatives such as the European Resource Adequacy Assessment should help to collectively identify and address potential resource adequacy issues while new co-ordination mechanisms at the European level are explored.

Figure 2.11: **Evolution of nuclear and coal capacity in Europe according to stated policies, 2040**



Note: It is assumed that no additional investments in new nuclear build would take place by 2040.

2.2.4. *The full value of the LTO option*

While the consequences of current energy policies by 2030 may be known, it is more difficult to elucidate what the optimal low-carbon energy system might look like in 2050, and the full economic and social implications of such a system. Sizeable risks and unexpected costs exist in any major energy transformation endeavour and should be acknowledged in existing energy policy frameworks. Beyond the energy trilemma objectives (decarbonisation, affordability and security of supply), issues such as time and technology maturity or choice are valuable resources that will help to cope with unforeseen situations while increasing the chances of success for the different decarbonisation pathways. At the same time, it is important for policymakers to keep in mind that the technical and economic spillover of nuclear energy could be useful in recovery times. Including the LTO option in policy frameworks can offer the following additional benefits:

- **Ensuring the availability of funding and infrastructure for decommissioning and waste management activities**: LTO can provide additional time to secure the necessary funding for back-end activities, if necessary, while limiting the financial burden on operators in the short term (see Box 2.4). The LTO period can be used to upgrade the waste management infrastructure in order to perform back-end activities under optimal safety, industrial and economic conditions.

- **Investment efficiency**: The transition towards a low-carbon system will require the mobilisation of massive amounts of capital in a relatively short period. Policymakers should seize any opportunity to smooth these investments, while securing emission targets and system affordability. The relatively low generation costs of LTO compared to other low-carbon options can limit the overall, upfront financial burden of building low-carbon systems and bring additional value by delaying and/or staggering decommissioning expenses over time. At the system level, additional savings in VRE integration can be realised by prolonging the dispatchability of nuclear power through LTO. These considerations are even more important in the post-COVID-19 era, wherein LTO could be an effective measure to guarantee investment efficiency under severe budgetary constraints.
- **Risk management**: When policies are designed, it is difficult to identify and properly address all of the risks associated with a particular decarbonisation pathway. This is even more the case with strengthened emission reduction targets since these targets require that extensive economic, industrial and social transformations take place across shorter timelines. As illustrated in the different sections of this chapter, multiple factors could impact emission trajectories, raise system costs and undermine the reliability of the system, pushing governments to reconsider their initial plans (see Box 2.2). Technical challenges remain in relation to the large-scale deployment of flexible solutions, such as long-term electricity storage, demand response and sector coupling. In addition, in the absence of a co-ordinated approach, individual countries do not have control over the decisions of neighbouring countries, adding more uncertainty to the process. In this context, an enlarged technology portfolio combining innovative and ready-to-deliver solutions that include LTO allows for greater flexibility in energy planning so as to properly manage unexpected risks. In general, LTO emerges as a well-suited solution to simultaneously tackle carbon emission reduction shortfalls, affordability and reliability concerns.
- **Industrial development and innovation:** The additional time provided by LTO can be used to optimise industrial plans, build supply chain capabilities in different sectors and develop new technologies. As indicated by (IEA, 2020b), more than 50% of the technologies necessary to reach carbon neutrality are still at the research and development stage or lack of the industrial maturity to be rolled out at scale. LTO could in this way be considered as a bridging technology towards more disruptive innovations, or until some technologies become commercially viable.
- **Shovel-ready projects and jobs for recovery times:** LTO projects face low construction and financing risks, representing a credible, shovel-ready option to support decarbonisation strategies and boost economic recovery in the short term (IEA, 2020d). Its economic potential, however, may be constrained by the limited number of ongoing projects, as well as the dependence on regulatory approval. In terms of employment, nuclear sector salaries are typically higher than for any other technologies (Oxford Economics, 2019), and an important proportion of the jobs are local and long term.[27] Around 700-1 700 workers are needed to run a nuclear site, depending on the number of units (NEA, 2018a).

27. Considering the entire life cycle of a nuclear power plant, these activities could last for over a century in a given community.

Box 2.4: **Ensuring the adequacy of funding for decommissioning and waste management activities through LTO – The case of Spain**

According to the "polluter pays" principle, decommissioning and waste management costs (i.e. those related to the back-end of the fuel cycle) are fully internalised, and operators must make annual contributions to dedicated funds through an allocation of provisions or through specific fees levied from the operators' revenues during operations of the plant. The amount of these annual contributions is calculated based on estimates of back-end costs, which are periodically re-evaluated.

The aggregated value of these annual contributions combined with the accumulated return of the fund during operations should, in theory, ensure the full coverage of initial decommissioning and waste management cost estimations. In practice, these costs may be subjected to inflation, escalation, new regulations and other uncertainties that can jeopardise their availability as the plant approaches the end of its operations.

In 2018, the Spanish Court of Auditors estimated that the gap in the funding of nuclear back-end activities was around EUR 3 billion. This amount represented several years of economic contributions from nuclear operators under the 40-year nuclear power plant operation scenario contemplated in the 6th edition of the General Radioactive Waste Plan approved in 2006.

The Spanish government, nuclear operators and Enresa initiated a series of discussions to determine a realistic scenario to cover this funding gap. Based on the reference of 40-years of operations, a 60% increase of the fee levied from nuclear operators would be necessary. In contrast, operations of 50 years (i.e. 10 years of LTO) would lead to a 19% reduction of the fee and still meet funding needs (El Economista, 2019). Finally, in January 2020, a compromise was agreed among the involved parties on a scenario that set a 19% increase of this fee (from EUR 6.69/MWh to EUR 7.98/MWh) and a new average operating time for the Spanish nuclear fleet of 46 years (i.e. 6 years of LTO) instead of the initial 40-year reference. Enresa now expects to collect the necessary funds by 2035, the same year during which the last Spanish reactor will be shut down.

The financial benefits associated with licence extensions in terms of decommissioning and waste management trust funds are assessed in more detail in Box 6.2.

Key findings

- More than 30% of the existing nuclear fleet is already in LTO according to the regulations of different countries. Most of these reactors are LWRs operating in Europe, Russia and the United States. With an average of 31 years, most of the world's nuclear fleet will be confronted with LTO decisions in the next decade. Assuming that most nuclear power plants are shut down after 40 years of operation, global nuclear capacity could be halved by 2040.
- The policy environment for LTO varies geographically. While most US states are supportive of licence extensions, the context in Europe and Japan is more uncertain. Policy uncertainty can be an impediment for the performance of nuclear activities, including LTO, in the best optimal conditions.
- LTO performs well in every dimension of the energy trilemma: i) environmental protection, ii) affordability and iii) security and reliability of the electricity supply). By avoiding around 1.6 Gt of CO_2 emissions annually, current nuclear capacity could help, along with new build, keep decarbonisation trajectories on track by 2030. The role of 80-year licence extensions becomes particularly relevant beyond 2040 bridging the gap to meet net-zero targets by 2050. At the same time, LTO remains one of the most competitive, low-carbon options in many regions and can bring sizeable benefits in terms of VRE integration and social costs. Potential security and reliability concerns resulting from the closure of significant amounts of dispatchable fossil-fired generation could be mitigated with LTO of existing nuclear reactors.
- The LTO option holds additional value for policymakers beyond the energy trilemma. The time, technical maturity and enlarged portfolio of technology options provided through LTO can make positive contributions in terms of the adequacy of funding for back-end activities, investment efficiency, new technology development and overall risk management of ambitious decarbonisation pathways.

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3. Regulatory and legal aspects

A necessary condition of any long-term operation (LTO) programme is to have authorisation or approval [1] from a governmental body (i.e. the government/ministry or regulatory body) to continue operations. How the LTO of nuclear power reactors is integrated into nuclear regulations and the associated review process varies from one country to another. An LTO-review process, although not necessarily an LTO-specific review process, is always required, and in most cases its scope is not limited to safety aspects. At the same time, this process can result in new safety requirements that need to be fulfilled by nuclear operators and can, ultimately, affect the economics of LTO. The objective of the present chapter is to provide additional information about the intersection of nuclear regulations with the technical and economic aspects of LTO.

This chapter builds on the outcomes of three previous NEA publications:

- "*The Economics of Long-Term Operation of Nuclear Power Plants*" (NEA, 2012): This study provides technical information on the safety requirements and approaches for LTO, in particular the necessary post-Fukushima upgrades, which are still relevant today.
- *"Legal Frameworks for Long-Term Operation of Nuclear Power Reactors"* (NEA, 2019): This study is based on a survey covering 80% of reactors in operation worldwide, with the report providing unique insights into laws, regulations and policies for LTO, including country-specific reports.
- *"Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders"* (NEA, 2020): Some of the conclusions drawn in this report on the economics of nuclear regulation are also applicable to the case of LTO.

3.1. LTO in nuclear regulations

According to the IAEA (2018), LTO is "operation beyond an established time frame […] justified by safety assessment … [which] may take place within a broader regulatory process […]" (IAEA, 2018). This definition contains two terms that are key to understanding how regulators interpret LTO and when potential technical and economic implications of the regulatory process for LTO may arise:

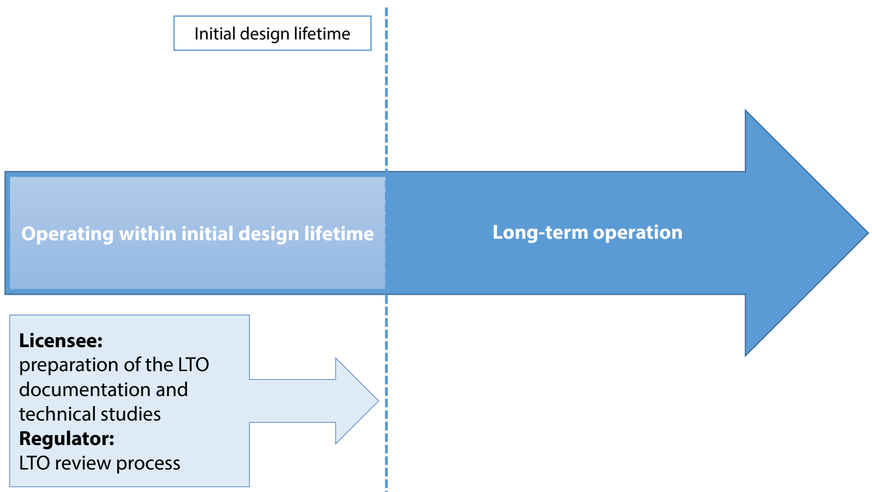
- **Established time frame**: First, it is necessary to define an initial period during which a nuclear power plant is allowed and expected to operate in safe conditions. This time frame corresponds to the **authorisation term** for nuclear operations [2] (i.e. operating licence), which in turn is typically defined using initial design assumptions.
- **Safety assessment**: second, in order to continue operations after a certain time frame, the licensee must undergo a comprehensive safety assessment to verify that the plant will continue to meet regulatory requirements. New safety requirements – specific to LTO or not – can often be imposed as a result of the safety assessment. While the safety assessment is a critical regulatory step in LTO, the broader term **"LTO-review process"**

1. The survey carried out in NEA (2019) revealed that, depending on the country, regulators employ different words to refer to the same or very similar concept to LTO. The present report will use as much as possible the generic legal terms defined in the Chapter 1 of NEA (2019).
2. For the sake of simplicity, referred to as the "authorisation term" in the remainder of this report.

will be used in the present chapter because it encompasses safety considerations and other aspects that are an integral part of the LTO evaluation, such as: environmental impact assessments, transboundary notifications, the provision of information, and public consultation and participation.

After the LTO-review process, regulators may authorise a given nuclear power plant to operate over a new time frame known as the LTO period (see Figure 3.1). The next sections in this chapter provide a more detailed picture of the regulatory frameworks that have been adopted in different countries based on the concepts of "authorisation term" and "LTO-review process". This approach is consistent with that used in previous NEA reports (2012; 2019) and covers most of the key regulatory aspects for LTO.

Figure 3.1: **Generic definition of LTO**



3.1.1. *Insights on the initial authorisation term*

The development of a nuclear programme in a given country is accompanied by several strategic decisions that will have important implications in the long-term governance of this technology. From a regulatory point of view, the choice of the length of the authorisation term of a nuclear power plant is one of these decisions. An overview of the different authorisation terms in various selected countries is provided in Table 3.1.

Typically, there are two types of authorisation terms: a specific, time-limited term, or an indefinite duration. Most countries use a specific, time-limited authorisation term[3] of 30 or 40 years. This duration is usually aligned with the initial design life of the reactor design.

The initial design life (or initial design lifetime) corresponds to "the period of time during which a facility or component is expected to perform according to the technical specifications to which it was produced" (IAEA, 2019). At the plant level, the Western European Nuclear Regulators Association (WENRA) defines the initial design lifetime of a nuclear power plant as the "the minimal value of lifetimes of all its non-replaceable structures, systems and components" (WENRA 2011). As described in Chapter 3, there are few, non-replaceable components in a nuclear power plant (e.g. the reactor pressure vessel and containment building). Moreover, the original design lifetime does not represent a technical limit inhibiting

3. Of the countries responding to the NEA (2019) survey, 60% provided specific, time-limited authorisation terms, while 40% provided an indefinite duration authorisation.

operations since, from a safety perspective, there may be no real cliff edge effect[4] resulting from ageing when a nuclear power plant operates longer than the initial design lifetime (WENRA, 2011).

For this reason, the regulatory provisions of countries with specific, time-limited authorisation terms foresee longer operating time frames via a specific authorisation for LTO. The decision is granted after assessing the capability of a given plant to comply with the applicable safety requirements over the LTO period (i.e. safety aspects of the LTO-review process). The length usually considered for the LTO authorisation term is 10-20 years. In most cases, there is no limit in the number of renewals of the LTO authorisation.[5]

On the other hand, there are some countries that have adopted an indefinite or open-ended authorisation for nuclear operations. In these countries, the definition of LTO, built on the notion of the initial design lifetime, is not so relevant.[6] A nuclear power plant subjected to this type of licence term can operate as long as it complies with the applicable regulatory requirements, without any time limitation. The initial design lifetime of the plant thus becomes a sort of technical input to anticipate and inform the regulatory process. According to the countries surveyed in NEA (2019), no specific authorisation for LTO is required with an indefinite licence term.

Overall, the overview of the authorisation term adopted in different countries confirms that: i) the original design lifetime is not used to set the ultimate operating lifetime of nuclear power plants; and ii) laws or regulations stating that nuclear reactors are not allowed to operate beyond an ultimate operating lifetime are also rare. In fact, most laws or regulations provide for indefinite terms or allow for unlimited licence extensions.

Table 3.1: **Overview of the authorisation term for nuclear operations in selected countries**

Country	Term type	Initial term length (generally)	Type of reactor	Notes on the initial term length	Term length for LTO (generally)	Notes on the term length for LTO
Argentina	Specific	10 years	PHWRs	Initial design life of reactors is approximately 30 years.	10 years	LTO programme is designed to allow another 25-30 years.
Belgium	Indefinite	Indefinite	PWRs	Initial design life of reactors is 40 years.	10 years	Three nuclear power reactors were allowed to generate electricity for ten additional years.
Canada	Specific	10 years	PHWRs	Determined on a case-by-case basis; the initial design life of reactors is approximately 30 years.	10 years	Refurbishment process can enable LTO of a reactor for several decades (e.g. another 30 years).
Czech Republic	Indefinite	Indefinite	PWRs	Initial design life of reactors is approximately 30 years.	Indefinite	No limit on operation as long as the reactor continues to meet its safety obligations subject to continuous safety assessment, a special safety assessment and PSRs, among other requirements.

4. An instance of severely abnormal plant behaviour caused by an abrupt transition from one plant status to another following a small deviation in a plant parameter, thus giving rise to a sudden large variation in plant conditions in response to a small variation in input.
5. The exceptions include countries such as Hungary, Japan and Slovenia where the nuclear power plant operation lifetime (initial authorisation term plus LTO period) is limited to 60 years.
6. WENRA (2011) indicates that, in general, the initial design lifetime of some non-replaceable components (e.g. pressure vessel) may no longer be relevant as actual plant operations and conditions, as well as current knowledge about ageing phenomena, provide a more accurate prediction of the ultimate useful life of these types of components.

Table 3.2: **Overview of the authorisation term for nuclear operations in selected countries** *(cont'd)*

Country	Term type	Initial term length (generally)	Type of reactor	Notes on the initial term length	Term length for LTO (generally)	Notes on the term length for LTO
Finland	Specific	30 or 40 years	PWRs and BWRs	Determined on a case-by-case basis, usually based on the initial design life of reactors.	Case-by-case basis (in practice, 20 years).	No limit on the number of renewals.
France	Indefinite	Indefinite	PWRs	Initial design hypothesis for certain equipment is 40 years.	Indefinite	No limit on operation as long as it fulfils its safety obligation, as reviewed during decennial, periodic reviews.
Hungary	Specific	30 years	PWRs	Based on initial design life of reactors.	20 years	Only one licence extension allowed.
Japan	Specific	40 years	PWRs and BWRs	--	20 years	Only one renewal allowed.
Korea	Specific	30, 40 or 60 years	PWRs and PHWRs	Based on initial design life of reactors.	10 years	No limit on the number of renewals.
Netherlands	Indefinite	Indefinite	PWR	Initial design life of the reactor is 40 years.	Determined on a case-by-case basis.	Operation beyond the 40-year technical design life specified in the safety report required an update of this safety report, which also required an amendment of the operating licence. The licence remained indefinite although the reactor's technical design life was extended for an additional 20 years.
Romania	Specific	30 years	PHWRs	Based on the initial design life of reactors and other factors.	Determined on a case-by-case basis.	No limit on the number of renewals.
Russia	Specific	30 years	PWRs, LWGRs and FBRs	Determined on a case-by-case basis according to the initial design life of the reactors and other factors.	Determined on a case-by-case basis.	No limit on the number of renewals.
Slovak Republic	Indefinite	Indefinite	PWRs	--	Indefinite	No limit on operation as long as the reactor fulfils its safety obligations, as reviewed during decennial PSRs.
Slovenia	Specific	40 years	PWR	Based on the design life of reactors.	10 years	Only 2 licence extensions allowed (for a total of 20 years).
Spain	Specific	10 years	PWRs and BWR	Determined on a case-by-case basis; the initial design life of reactors is approximately 40 years.	10 years	Determined on a case-by-case basis.
Sweden	Indefinite	Indefinite	PWRs and BWRs	The initial design life of reactors is 40 years.	Indefinite	No limit on operation as long as the reactor fulfils its safety requirements, as reviewed during decennial PSRs.

Table 3.3: **Overview of the authorisation term for nuclear operations in selected countries** *(cont'd)*

Country	Term type	Initial term length (generally)	Type of reactor	Notes on the initial term length	Term length for LTO (generally)	Notes on the term length for LTO
Switzerland	Indefinite	Indefinite	PWRs and BWRs	--	Indefinite	No limit on operation as long as the reactor fulfils its safety obligations; operation past 40 years requires proof of safety for LTO and a decennial PSR.
Ukraine	Specific	30 years	PWRs	Based on the initial design life of reactors.	10-20 years	No limit on the number of licence extensions.
United Kingdom	Indefinite	Indefinite	AGRs and PWR	--	Indefinite	No limit on operation as long as the reactor fulfils its safety obligations, including a decennial PSR.
United States	Specific	40 years	PWRs and BWRs	--	20 years	No limit on the number of renewals.

Notes: Pressurised water reactors (PWRs), boiling water reactors (BWRs), pressurised heavy water reactors (PHWRs), advanced gas reactors (AGRs), light water graphite reactors (LWGRs) and fast breeder reactors (FBRs). PSR = periodic safety review.

Source: NEA (2019).

3.1.2. *The LTO-review process*

Approach

Two main regulatory approaches have traditionally been identified for the LTO-review process: i) licence renewal (LR); and ii) periodic safety review (PSR) (NEA, 2012). The primary difference between the two processes lies in how often the authorisation or approval to continue nuclear operations is renewed. LR is directly linked to the use of a specific, time-limited authorisation. At the end of the term, (i.e. typically corresponding to the end of the initial design lifetime) operators must apply to the competent authority for a licence renewal and provide all the necessary technical evidence that the plant will continue to comply with the licensing basis during LTO. Under a PSR approach, the authorisation or approval to operate is granted based on the outcome of safety evaluations carried out periodically, typically every ten years. Both approaches are part of the broader regulatory process that generally allow safety improvements on a continuous basis, based on set criteria, and regardless of the LTO dimension.

Actual regulatory practice shows that most countries rely on the principles of the PSR, with some countries adopting features from both approaches (NEA, 2012; 2019). In fact, NEA (2019) emphasises that the LR and/or PSR dichotomy is perhaps not the most appropriate distinction to use. A new distinction could necessary since LR is a specific approach used by only three responding countries. Approaches for the LTO-review process instead fall into three distinct categories (see Figure 3.2):

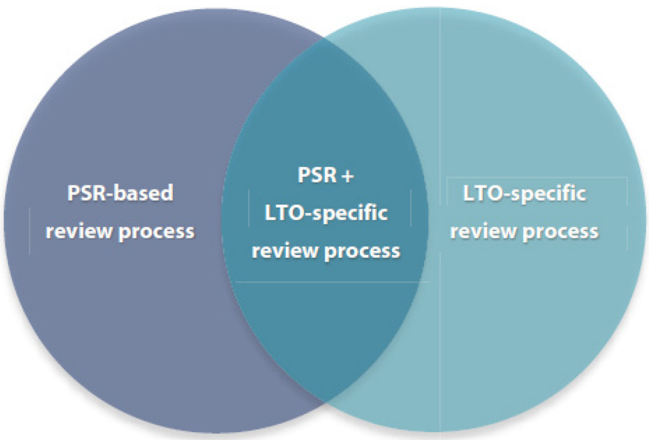
- PSR-based review process;
- PSR with an LTO-specific review process;[7]
- LTO-specific process.

7. "Because not all LTO-specific review processes (whether linked or not to a PSR) result in a licensing action, it is more precise to speak generically of an LTO-specific review process, which may or may not be linked to the decennial PSR, within which an LTO-specific licensing process is a subcategory." (NEA, 2019)

According to this new categorisation, around 45% of the responding countries in NEA (2019) undertake a PSR process combined with LTO-specific considerations. This hybrid approach takes advantage of the efficiency associated with traditional PSR processes while allowing some adjustments to assess specific LTO-related issues (e.g. ageing).

The authority responsible for performing the LTO-review process (either PSR-based, LTO-specific process or both) is, in most countries, the regulatory body. In some cases, this process is carried out in co-ordination with technical support organisations (TSOs).[8] Regulatory bodies are also responsible in most cases for approving or authorising LTO. In some countries, the final LTO approval or authorisation is granted either by a ministry or the government on either the binding opinion of the regulatory body or based on the regulatory body's LTO review (NEA, 2019).

Figure 3.2: **LTO approval approaches**



Source: NEA (2019).

Safety assessment and its technical implications

During any LTO-review process, and independent of the approach undertaken, regulators will evaluate – using the inputs provided by the licensees and their own verifications – if a given plant will comply with applicable safety requirement during the LTO period.[9] The scope of the regulatory safety review for LTO focuses on the following topics (NEA, 2012):

- ageing issues;
- safety and security improvements based on operating experience, the latest knowledge of the technology, new safety standards and other emerging issues.

Ageing issues require a comprehensive evaluation of the actual conditions of the plant in order to identify the most critical ageing-related phenomena during the foreseen LTO period. While the main ageing mechanisms are generally common across all nuclear power plants, there can be specific concerns depending on the type of design, and the operational history and experience of the plant. By means of time limited ageing analyses (TLAAs), operators are able extrapolate the impact of ageing mechanisms to assess operational margins. Some issues will require specific ageing management programmes (AMPs) to ensure that the concerned structures, systems and components (SSCs) perform as expected during LTO (Chapter 3).

8. Depending on the country, the TSO is either an external body or is integrated within the regulatory body.
9. This is the most fundamental principle for all regulators (NEA, 2012) and operators.

At the same time, original plant design deficiencies may be revealed through operating experience (both in a given plant and internationally[10]) or when compared with recent knowledge and technology developments, and new emerging issues. All of these aspects are considered by regulators during the LTO-review process and can lead to the introduction of new safety and security requirements with their associated design modifications and investments. It is important to underline, however, that these new requirements are not necessarily related to LTO and can be simply the result of a continuous safety improvement logic. In fact, most of the regulatory frameworks have additional processes to introduce new safety requirements outside of the LTO-review process (NEA, 2019).

One clear example of safety improvements is the introduction of post-Fukushima measures to enhance the protection of existing nuclear power plants against external hazards. Some of the plant modifications and upgrades for severe accident management following the Fukushima accident are illustrated in Box 3.1. Other emerging issues involve the revision of cybersecurity guidelines for the utilisation of digital instrumentation and controls (I&C) (NRC, 2020a), as well as the surveillance of climate-related events, such as heatwaves.[11] All operating nuclear power plants are potentially concerned by these regulations either as part of, or outside of, the LTO-review process depending on the regulatory framework. This is particularly the case for post-Fukushima measures (see Box 3.1). Additionally, operators can opt for the implementation of additional plant enhancements on a voluntary basis as part of LTO (e.g. power uprates). In general, these types of plant retrofits require an update to the licensing basis and thus a specific review to obtain regulatory approval.

Lastly, the scope of the regulatory safety review for LTO is not the same across plants and countries, for various reasons. First, LTO ageing issues may vary depending on the condition of the plant, operational history and past investments. Second, LTO-specific provisions can change depending on regulatory frameworks. Third, additional reviews may be required to evaluate the safety impacts of specific plant enhancements. All these aspects explain, to some extent, the differences in the LTO costs observed across plants and countries (see Chapter 6).

Box 3.1: **Examples of post-Fukushima safety measures**

After the Fukushima accident in 2011, many countries with operating nuclear power plants initiated comprehensive risk and safety assessments to evaluate the ability of plants to withstand site-specific, extreme natural hazards that could potentially lead to severe accidents across several units. This work was performed under regulatory oversight and in parallel to other international initiatives led by the NEA and IAEA. The studies concluded that, in general, existing nuclear power plants have satisfactory safety levels against external hazards and did not require immediate shutdown (NEA, 2012). The lessons from these evaluations revealed, however, areas in need of safety improvements, and new regulatory guidelines were introduced in existing frameworks in order to increase the robustness of nuclear power plants under extreme scenarios.

Post-Fukushima measures involve safety upgrades against extreme events and their combined effects to enhance mitigation capabilities for station blackout and the loss of ultimate heat sink, affecting the reactor and the spent fuel storage pools. Such measures would need to be evaluated on a case-by-case basis, as not all plants are equally exposed to the risks associated with external hazards. As a result, some plants could require extensive plant modifications, involving the installation of new fixed equipment on-site, as well as organisational improvements in terms of severe accident management and emergency preparedness. The implementation of such measures could take a considerable amount of time, which may necessitate specific planning and prioritisation of measures in co-ordination with regulators (see the French case below). Post-Fukushima safety requirements are already an integral part of existing regulations, meaning that any plant, independently of its age or its intention to seek LTO authorisation or approval, should perform the necessary safety upgrades. At the same time, the evaluation and implementation of post-Fukushima measures could be part of an LTO-review process (particularly in the case of major safety upgrades) in order to take advantage of economies of scale and potential efficiency gains on both the regulator and licensee side.

10. As described in Chapter 4, nuclear power plants are part of a governance model that enables operating experience to be shared among operators around the world (e.g. WANO).
11. In France, since the heat wave episode of 2003, the capability of nuclear power plants to withstand extreme heat conditions has been continuously monitored by the regulator (IRSN, 2020) and evaluated as part of decennial PSRs (Vicaud, 2019).

United States

As part of safety enhancements envisaged after the Fukushima accident, the US Nuclear Regulatory Commission (NRC) adopted the industry's proposed safety strategy called "Diverse and Flexible Mitigation Capability" or FLEX (NRC, 2020b).

Before the Fukushima accident, defence-in-depth levels [12] required protective measures for plant equipment based on design-basis external events, as well as certain coping capabilities to prevent fuel damage in the case of station blackout (SBO). In order to mitigate the potential consequences of nuclear accidents, nuclear power plants also had severe accident management guidelines (SAMGs) and emergency response plans. The introduction of the FLEX strategy would increase the level of defence in depth in a nuclear power plant in case of beyond-design-basis external events (BDBEEs) that could simultaneously lead to the loss of external power and ultimate heat sink. These higher defence-in-depth levels are achieved via:

- **The use of portable equipment** that provides a means to obtain power and water so as to maintain and restore safety functions for all of the reactors at the site. This equipment includes portable pumps, generators, batteries and battery chargers, compressors, hoses, couplings, tools, debris clearing equipment, temporary flood protection equipment, and other supporting equipment or tools.
- **Reasonable staging and protection of portable equipment** from BDBEEs applicable to a given site in order to provide assurance that the equipment would be deployable after such an event.
- **Development of procedures and guidance to implement FLEX strategies** and to improve existing procedures to cope with BDBEEs.
- **Programmatic controls that ensure the continued viability and reliability of FLEX strategies**. To do so, standards are established for quality, maintenance, testing of FLEX equipment, configuration and management, and periodic training of personnel (NEI, 2016).

The implementation of FLEX follows a systematic approach that assesses the vulnerability of plants against BDBEEs. The initial coping capabilities of a plant relying on already installed equipment are first determined before transitioning to on-site FLEX equipment and additional off-site support at the regional level. This approach is consistent with the NRC's guidance on mitigation strategies for BDBEEs (NRC, 2017).

France

Between 2012 and 2014, the French Nuclear Safety Authority, ASN, issued new safety requirements and plant modifications to be implemented at each of the 19 French nuclear power plants, based on lessons learnt from the Fukushima accident (ASN, 2014). These measures were the result of complementary safety assessments carried out by the ASN with a strong focus on BDBEEs not properly covered by the safety standards available before the accident. The main, post-Fukushima safety provisions included:

- **Definition of new "hard core" safety measures for severe accidents**: These measures would rely on existing SSCs in nuclear power plants, and new SSCs built redundantly, whenever possible, as independent systems to ensure ultimate power generation, cooling capabilities and accident management. Specific "hard core" plant modifications involved the installation of ultimate diesel generators, ultimate heat sink, additional water inventories and cooling circuits for both the primary circuit and spent fuel storage pools, a complementary control room for "hard core" systems and regional response centres.
- **Establishment of a specialised force of fast response (FARN)**: Since 2016, four FARN units are operational at the Civaux, Dampierre, Paluel and Bugey nuclear power plants. This special force can be mobilised at any French nuclear power plant in less than 24 hours, and the force is specifically trained to restore power water supplies using portable equipment in the case of a major accident. Regular training and emergency simulations are performed at particular sites in order to sustain and improve FARN capabilities (EDF, 2020).

Different phases have been considered for the implementation of post-Fukushima measures in France. The deployment of FLEX strategies (i.e. availability of portable equipment) and the establishment of FARN took place between 2012 and 2016. The plant modifications associated with "hard core" safety measures will be performed progressively by 2030, as part of the ongoing French LTO programme called "Grand Carénage" (i.e. the "Major Refit").

12. Prevention, control and mitigation measures for nuclear accidents.

Environmental impact assessment and transboundary notifications

While denominations may vary in different countries, an environmental impact assessment (EIA) is broadly defined as a tool to assess the impacts of a specific project or activity on the environment, which typically includes the preparation of specific documentation, consultations with members of the public and evaluations by decision-making authorities, which are expected to integrate the results of assessments in the decisions.[13] In most countries, applicable national, regional or international legal frameworks clearly require that an EIA is carried out prior to the initial licensing of nuclear facilities, including nuclear power plants.

There is, however, significant legal uncertainty in many countries regarding whether an EIA is required before a nuclear power reactor enters the stage of LTO, as part of an LTO-related review (NEA, 2012; 2019). From the 20 countries surveyed in NEA (2019), 65% reported requiring an environmental review as part of the LTO-related review, and 35% indicated no such requirement. However, the survey noted that the extent of such environmental reviews differs and may not always amount to a full-fledged EIA or the equivalent.[14]

In addition, many national legal frameworks provide for an obligation to notify and consult the authorities of other countries whose environment may be affected by a project or activities as part of their EIA requirements – a process commonly referred to as “transboundary EIA”. The primary source of this obligation is found in the Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention),[15] which counts 45 parties within the United Nations Economic Commission for Europe (UNECE) region, including the EU and its member states. The issue concerning the applicability of the Espoo Convention to the LTO of nuclear power plants has been the subject of significant review at national and international levels for over a decade.[16] With a view to clarify this situation, and notably to assist the Convention’s Implementation Committee in its review of several LTO cases,[17] the Meeting of the Parties to the Espoo Convention endorsed in 2020 the “Guidance on the applicability of the [Espoo] Convention to the lifetime extension of nuclear power plants”.[18] This guidance provides and elaborates on the criteria according to which the Espoo Convention may or may not apply to LTO of nuclear power plants,

13. See, for example, Article 1(2)(g) of Directive 2011/92/EU of the European Parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment, as amended by the Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014, OJ L 124 (25 April 2014) (EIA Directive). In the field of nuclear energy, an EIA may include all or some of the following issues: uranium fuel cycle impacts, waste management, surface water quality, aquatic ecology, groundwater use and quality, terrestrial resources, threatened or endangered species, air quality, land use, human health, socio-economics, postulated accidents, decommissioning and environmental justice (NEA, 2012).
14. Country specificities include, but are not limited to, the body responsible for performing the EIA, the scope of the EIA, the need to systematically perform a full EIA, or perform one just in the case of major plant modifications, and whether the EIA is formally linked to LTO or not (NEA, 2019).
15. Convention on Environmental Impact Assessment in a Transboundary Context (1991), 1989 UNTS 310, entered into force 10 September 1997 (Espoo Convention).
16. In 2011, an NGO introduced a communication before the Espoo Convention Implementation Committee alleging that Ukraine had breached its obligations under the Espoo Convention regarding the LTO of the Rivne nuclear power plant. This case was reviewed by the Implementation Committee and, in 2014, the Meeting of the Parties to the Espoo Convention endorsed its findings and recommendations that a transboundary EIA should have been carried out prior to this specific licence extension. See UNECE (2014), “Decisions adopted by the Meeting of the Parties to the Convention”, “Decision VI/2, Review of compliance with the Convention”, ECE/MP.EIA/20.Add.1 – ECE/MP.EIA/SEA/4.Add.1, Meeting of the Parties to the Convention on its sixth session and of the Meeting of the Parties to the Convention serving as the Meeting of the Parties to the Protocol on its second session, Geneva, 2-5 June 2014, p. 14.
17. At the time of the drafting of the present report, there were five LTO-related cases pending before the Espoo Convention Implementation Committee, under references EIA/IC/INFO/15, EIA/IC/INFO/18, EIA/IC/INFO/19, EIA/IC/INFO/20 and EIA/IC/INFO/28.
18. UNECE (2020), “Guidance on the applicability of the Convention to the lifetime extension of nuclear power plants”, ECE/MP.EIA/2020/9, Meeting of the Parties to the Convention on Environmental Impact Assessment in a Transboundary Context, Vilnius, 8-11 December 2020.

acknowledging variations in the legal frameworks of parties to the convention. In this regard, the guidance recognises that “as there is no one-size-fits-all approach, when assessing possible cases of lifetime extension, a case-by-case determination through the consideration of the principles and factors laid down in the guidance is recommended” (UNECE, 2020). It should also be noted that the obligation to carry out an EIA, including transboundary consultations, was also subject to legal review under EU law. In particular, the Court of Justice of the European Union rendered a preliminary ruling in July 2019 concluding that a specific national law enabling LTO of a specific nuclear power plant had been adopted in breach of EU law as a result of the absence of a preliminary EIA.[19] In that instance, the court considered that the LTO project, which included major works intended to modernise the concerned nuclear power plant, “must be found to be of a scale that is comparable, in terms of the risk of environmental effects, to that when those power stations were first put into service”.[20]

These cases illustrate some of the legal uncertainties surrounding LTO-related processes and decisions, but also the trend of increasing requirements applicable to such decisions in terms of environmental reviews. Operators should take in account these uncertainties early in the LTO programme in order to minimise the exposure to legal risks that could impact LTO.

Provision of information and public consultation and participation

Public interest in LTO projects is high, and it is generally considered desirable for the regulatory frameworks to consider legal provisions that would make the information of the LTO reviews available whenever possible (NEA, 2012). Among the various legal instruments dealing with public access to environmental information (including nuclear safety-related information), the Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters (Aarhus Convention)[21] establishes requirements[22] regarding:

- access to environmental information held by public authorities upon request from a member of the public;
- collection and dissemination of environmental information by public authorities in the absence of a request.

Similar provisions are found in the EU secondary legislation, mainly in the Directive on Public Access to Environmental Information.[23] While these legal instruments are not specific to nuclear energy nor to LTO, most of the responding countries that took part in the NEA (2019) study indicated that they include in their regulatory frameworks specific provisions on the dissemination of information to the public as part of the LTO-review process, or they make information available to the public on request. Some specific exemptions limit public accessibility to confidential information that would *inter alia* adversely affect public security or commercial interests.

In addition to legal requirements related to public access to environmental information, most countries’ legal frameworks include requirements that public authorities provide members of the public with an opportunity to participate in decision-making processes for a wide range of nuclear, energy-related activities. In this regard, Article 6 of the Aarhus Convention sets out the legal requirement that public authorities provide for a public participation procedure in decision making for activities that may significantly affect the environment, including those related to

19. Court of Justice of the European Union, Judgment of 29 July 2019, Inter-Environnement Wallonie ASBL and Bond Beter Leemilieu Vlaanderen ASBL v. Conseil des ministres, C-411/17, EU:C:2019:622.

20. Ibid. paragraph 79.

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

22. See UNECE (2014), The Aarhus Convention: An Implementation Guide, 2nd edition, United Nations, Geneva, pp. 75-117.

23. Directive 2003/4/EC of the European Parliament and of the Council of 28 January 2003 on public access to environmental information and repealing Council Directive 90/313/EEC, OJ L 041 (14 February 2003) (Directive on Public Access to Environmental Information).

nuclear power plants. In the context of LTO, Article 6(10) of the Aarhus Convention provides that the requirements for public participation in the initial decision-making procedure must be applied *mutatis mutandis* whenever a public authority "reconsiders or updates the operating conditions" of a concerned activity. In line with the findings of NEA (2012), NEA (2019) revealed contrasted requirements regarding public participation as part of the LTO-review process among the different countries consulted. Most of the countries reported having legal requirements to engage with the public in various forms (e.g. hearings, comments) as part of their LTO-review process and indicated that due account was taken of comments received in the final decision. On the other hand, eight countries reported no specific legal requirements for public consultation in the LTO-review process, primarily because of the absence of a formal and dedicated decision-making procedure for LTO in their respective domestic laws.

The aforementioned report also concluded that in the majority of instances, the body in charge of ensuring public access to environmental information (either upon request or through dissemination) and responsible for public participation is the decision-making public authority (e.g. the nuclear regulatory authority, another environmental public authority or the government). However, some countries reported that under their national legal frameworks the licensee is responsible for these activities either alone or in collaboration with the decision-making authorities.

3.2. Regulation and LTO economics

Interaction between nuclear regulations and economics usually receives limited coverage, but its analysis is necessary to have a complete picture of the economic performance of nuclear power, including during LTO. In general, regulations, as is the case for any other economic activity, tend to increase costs. These additional costs, however, should be regarded as the price to pay to reduce the externalities associated with nuclear power, and thus maximise social benefits. Theoretically, the regulatory optimum in economic terms is achieved when the marginal cost of protection equates to the marginal social benefits of the harm avoided. In practice, this is more difficult to achieve given the high uncertainties associated with both the marginal costs of regulatory practices and the benefits of the risks avoided (Lévêque, 2014).

Nuclear regulations can impact the economics of LTO in two principal ways. First, the introduction of new regulations once the LTO project has already been launched can provoke delays and productivity downturns. This is particularly detrimental for the on-site works because of the presence of significant fixed-cost equipment and manpower. Second, regulatory changes can lead to plant retrofits and the installation of new SSCs. This is the case, for instance, for post-Fukushima safety improvements, which can represent up to 20-25% of the overnight costs for the refurbishment needed for LTO of a plant[24] (see Box 3.1).

NEA (2020) proposes some principles to enhance regulatory interactions without compromising safety and environmental standards. They are supported by actual past and recent experience in nuclear constructions. Two of these principles are particularly important for LTO:

- **Ensure regulatory stability and predictability:** The adoption of new rules has to be anticipated and planned well in advance in order to avoid costly retroactive project changes and rework, particularly with ongoing on-site work. The new safety standards pursued by regulators should be clear and adequately translated into technical specifications so as to facilitate subsequent engineering studies and design modifications.
- **Avoid misinterpretation of safety requirements:** Linked with the principle of predictability, poorly interpreted requirements resulting from a lack of communication among regulators and licensees can lead to unnecessary and dispersed engineering efforts with limited added safety benefits.

24 These are generic orders of magnitude that could vary considerably depending on plant conditions at the moment of initiating the LTO programme.

For the implementation of these principles, it is important that licensees adopt a proactive role and work closely with regulators in developing clear and robust safety cases, and resolving potential shortfalls when they arise. Governments can also foster enhanced regulatory interactions by aligning stakeholders' interests and objectives while providing the necessary means to guarantee the independence and transparency of regulatory decisions.

Key findings

- The authorisation term and the LTO-review process are the main dimensions to be addressed when assessing the regulatory aspects of LTO and their technical and economic implications.
- An overview of the authorisation terms adopted in different country regulations confirms that: i) the original design lifetime is not used to set the ultimate operating time frame of nuclear power plants; and ii) laws or regulations stating that nuclear reactors are not allowed to operate beyond an ultimate operating time frame are also rare. In fact, most laws or regulations provide for indefinite terms or allow for unlimited licence extensions.
- In terms of safety, ageing issues and new safety and security requirements are the main areas of concern for the LTO-review process. Safety improvements, however, may not necessarily be related to LTO but may respond to a continuous safety improvement logic instead. In some cases, extensive plant modifications may be required to comply with these new regulations (e.g. post-Fukushima measures).
- Environmental impact assessments (EIA), including in a transboundary context, access to information and public participation are the main environmental, procedural aspects likely to be part of the LTO-review process. Recent legal issues suggest that operators should consider associated legal provisions well in advance of their LTO programmes in order to avoid potential concerns.
- Regulations, as is the case for any other industrial activity, tend to increase the cost of nuclear power. Post-Fukushima measures, for instance, can represent around 20-25% of the overnight costs of LTO in some cases. Regulatory stability, predictability and a clear interpretation of safety requirements are also important aspects that could impact the economic performance of LTO.

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Part 2:

Analysis of the internal capabilities of nuclear power facilities for long-term operation

4. Technical aspects

Most nuclear reactors currently in operation are Generation II (Gen-II) reactors built in the 1970s and 1980s, using the technical basis of the first prototypes and the materials performance in energy systems available at that time. Commercial operating experience for Gen-II reactors was thus limited and initial conservative assumptions were introduced in the design of critical structures, systems and components (SSCs), including significant safety margins to cope with potential technical uncertainties. These criteria also served to develop regulatory requirements so as to evaluate whether reactors were operating according to safety standards (i.e. licensing basis) and be able to issue licences for new reactors.

As with any energy assets, materials ageing is a major concern for nuclear reactors, potentially reducing their operating time frame. Since the start-up of the first Gen-II reactors, extensive research has been carried out in order to identify and understand the main ageing mechanisms and their associated kinetics under nominal and transient operating conditions. Today, this research, combined with more than 13 500[1] years of nuclear operating experience worldwide, constitutes solid technical evidence supporting the long-term operation (LTO) of nuclear power plants. Technical uncertainties have been significantly reduced, and in most cases original safety margins remain adequate for critical SSCs to be operated beyond their initial design lifetime. This knowledge base continues to be enriched with new national and international research activities, alongside growing operating experience.

LTO is therefore based on the technical evaluation that a nuclear power plant will comply with a given "licensing basis" during LTO. How this is demonstrated, and the technical basis needed, will depend on regulatory strategies in individual countries. In general, LTO programmes are the result of a systematic process mobilising the available technical evidence and best international practices to assess current and projected plant conditions, and to identify the necessary actions that will ensure that "important-to-safety" SSCs remain capable of performing their intended functions during LTO. Periodic re-evaluations are also part of the process. Lastly, the role of LTO refurbishments is not limited to ageing issues since nuclear operators often take the opportunity to introduce additional plant enhancements to improve the overall safety, availability and economics of the plant.

Most of the technical evidence presented in this chapter is based on the operating experience of light water reactors (LWRs). This technology is of the greater interest because it represents more than 80% of the existing fleet. Specific aspects associated with pressurised heavy water reactors (PHWRs) and other reactor designs are also addressed in different sections of this chapter.

4.1. Materials challenges for LTO

The operating time frame for a nuclear power plant is ultimately governed by the ageing of critical SSCs. Having an extensive understanding of the main ageing phenomena in different conditions and nuclear systems is hence key to enabling LTO. In general, assessing material degradation in nuclear systems is a complex endeavour, owing to the variety of materials[2]

1. An average of 31 years of operation for 444 operating reactors worldwide.
2. There are around 25 different metal alloys within the primary and secondary systems of LWRs (Allen et al., 2010). Additional types of materials can be found in the containment building, instrumentation, and control equipment and cabling.

and the unique combination of environmentally-induced stressors (high pressure and temperature, intense neutron irradiation and chemical compatibility with the coolant), which vary depending on their position in the system. After several decades of research and operating experience, the main ageing mechanisms, stressors and related impacts in nuclear systems are nevertheless well-known and understood today (NRC, 2006).

Of particular importance are non-replaceable components in nuclear systems. If these components fail, the nuclear power plant may be forced to cease operations, thus limiting the lifetime of the plant. Such components are hence considered as "life-limiting". While ageing phenomena are observed in most nuclear systems regardless of the reactor type, some designs have specific features and configurations that may slightly redefine the boundaries between SSCs that are life-limiting and those that are replaceable, as well as alter the dynamics of ageing. Moreover, the duration of particular plant conditions (e.g. full power versus cold shutdown) will also influence final degradation levels. As knowledge on materials ageing in nuclear systems progresses, some operators are envisaging longer operational time frames that could lead to new materials challenges, which will need to be properly assessed.

4.1.1. *Potential life-limiting components and associated ageing phenomena*

In the past, life-limiting components of LWRs included the reactor pressure vessel (RPV), vessel internals, steam generators, main pumps, cables and the concrete structures (NEA, 2000). Technical advances and new engineering techniques have resulted in the re-classification of components that were initially considered non-replaceable, with significant industrial experience demonstrating that steam generators and vessel internals can be replaced (IAEA, 2008a).

Currently, all of the components of LWRs can be replaced, except perhaps[3] the RPV and some containment structures (NEA, 2006, 2012b). Nevertheless, economics plays an important role in the decision-making process to replace some of these components. The economic attractiveness of a major refurbishment increases with the size of the reactor and the remaining operating time. As a plant ages, the remainder of the operating time frame may be too short to ensure recovery of the investment in heavy equipment and components. Market conditions and future electricity price projections can also condition the final outcome. Some RPV internals and cabling are typically some of the components that could be considered life-limiting, or not, depending on economic considerations[4].

Based on this evidence, the following SSCs may become life-limiting:

- RPV (LWRs);
- reactor coolant system piping, welds and core internals (LWRs, PHWRs);
- large, civil and concrete structures, such as the containment building (LWRs, PHWRs);
- large sections of the plant's electrical cable system (LWRs, PHWR).

Reactor pressure vessel (LWRs)

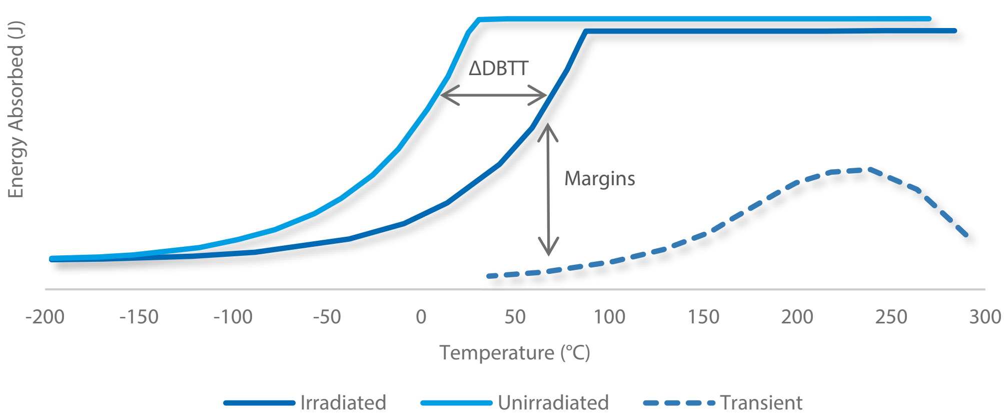
RPVs are fabricated by welding together 20 cm-thick ring forgings of bainitic, low alloy and plain-carbon steels.[5] RPV ageing occurs as a result of microstructural changes in materials due to both thermal and irradiation exposure; the latter being the most marked and a major life-limiting factor. Low-alloy steels show reduced toughness at low temperatures. While the onset of reduced ductility is initially below temperatures of operational concern, irradiation induces a high density of nanoscale defects and the formation of precipitates, which impede dislocation motion, leading

3. Studies have demonstrated the technical feasibility of replacing the RPV in BWRs (Mizutani, et al., 2001).
4. The type of technico-economic analysis, for example, behind some of the early plant closures, as reported in Box 1.1.
5. The typical composition is 1-2% manganese (Mn), 0.5-1% nickel (Ni), ~0.5% molybdenum (Mo) and 0.15-0.4% silicon (Si) (Zinkle, Was, 2013).

to a hardening and embrittlement of these types of materials. Consequently, the yield and ultimate strengths of the RPV walls increases, with a corresponding decrease in materials ductility and resistance to flaw propagation (fracture toughness). The toughness at all temperatures is therefore reduced with the shift from ductile to brittle transition temperature (DBTT)[6] to higher temperatures (see Figure 4.1). The shift of the DBTT (or ΔDBTT) is thus important because it limits the pressure and temperature conditions to which the reactor pressure boundary systems can be exposed, which consequently reduces the margins, particularly during heat up and cool down cycles[7] and those related to pressurised thermal shock (PTS) conditions.[8] Under PTS conditions, the resulting loss of fracture resistance can accelerate the propagation of a critical-size flaw through the embrittled wall, jeopardising the integrity of the RPV (NEA, 2012).

It appears that the impact of irradiation is strongly dependent on the chemical composition of the vessel materials (e.g. copper [Cu], sulphur [S], phosphorus [P] and nickel [Ni]) and is particularly sensitive to Cu content. Welds and heat affected zones (HAZ) are also relatively more sensitive to radiation exposure than the base metal resulting from potential variations in composition and microstructures during their execution. Embrittlement is significantly acute in the "beltline" region (and associated welds and HAZs) corresponding to the region surrounding the active height of the core.

Figure 4.1: **Illustration of the impact of irradiation on fracture toughness margins in the inner wall of an RPV**



Approaches to RPV ageing management use surveillance capsules containing samples of the vessel materials and associated welds that are strategically placed inside the vessel in order to accumulate an accelerated dose similar to the vessel itself, or even greater.[9] These capsules are periodically removed and the contents tested to monitor changes in materials toughness within temperature ranges that are relevant to reactor service (i.e. heat up and cool down transients) and potential emergency conditions. The results from these tests also serve to develop and calibrate embrittlement trend models that predict vessel material properties, including the crucial changes in toughness expected with longer lifetime service. These activities are complemented with in-service inspection of most irradiated zones in the vessel

6. This phenomenon is also referred to in the literature as reference temperature for nil ductility transition.
7. During the start-up or shutdown of the reactor.
8. PTS conditions arise from certain low-probability accidental scenarios (e.g. loss of coolant), potentially involving the injection of cold water or overpressure at low temperature.
9. Depending on their position in the vessel, these specimens can be exposed to a neutron fluence four times higher than the inner wall, which enables the prediction of mechanical properties beyond 40 years.

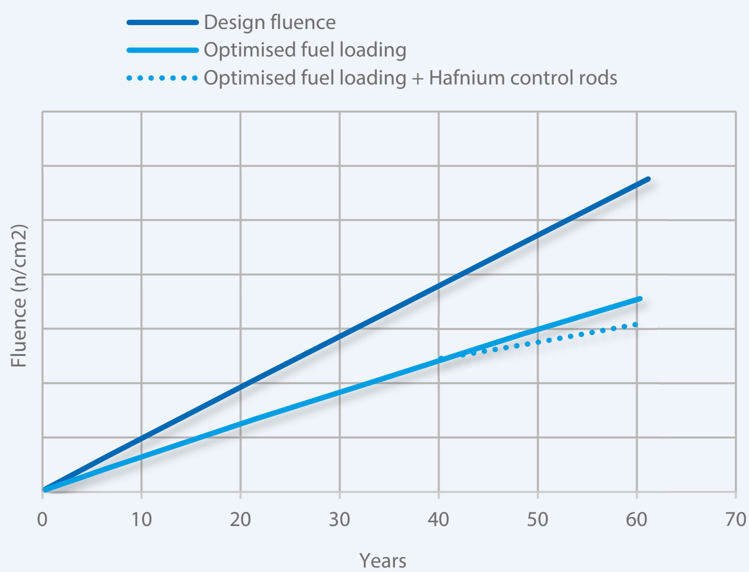
(i.e. beltline region) using non-destructive evaluation (NDE) techniques to detect flaws and/or follow their evolution in size through the wall.[10] The process is fully automated with robotic ultrasonic and gamma radiography testing machines that are capable of scanning the RPV inner wall and of identifying flaws with high accuracy within regions of 125 mm^2 or less (Benhamou, Vidard, 2019). Several strategies can also be envisaged to mitigate embrittlement on RPV walls and remediate ageing effects (see Box 4.1 below).

Additional degradation phenomena that have been observed in RPV structures involved corrosion phenomena, in particular stress corrosion cracking of Ni-based alloys present in the vessel penetrations (i.e. upper and lower head), combined with boric acid corrosion of low-carbon steels. The most notable example of such a degradation mode was observed in the pressure vessel head of the Davis Besse reactor in 2002 (Zinkle, Was, 2013). This type of degradation mechanism is not usually life-limiting as pressure vessel heads can be easily replaced during normal outages.

Box 4.1: **Overview on RPV embrittlement mitigation strategies in LWRs**

In order to mitigate RPV embrittlement, it is necessary to limit the exposure of the inner wall to irradiation. This is possible with the adoption of core designs that minimise neutron leakage. For example, with in-out fuel loading patterns, depleted (and thus more absorbent) fuel assemblies are placed in the periphery, acting as a shield against excessive neutron irradiation while improving overall fuel economics. Shielding effects can be further enhanced by inserting highly absorbent Hafnium control rods in some peripheral fuel assemblies. Other mitigation approaches foresee higher temperatures of the water in the emergency safety injection to limit PTS risks in accidental conditions. The effect of all these measures on the evolution of the fluence observed by the RPV wall is illustrated in Figure 4.2.

Figure 4.2: **Qualitative impact of different RPV embrittlement mitigation measures**



10. Most of the cracks found in the beltline region are shallow cracks ranging from 10 to 15 mm (Chen et al., 2014).

Reactor coolant system piping welds and core internals (LWRs, PHWRs)

The reactor vessel internals and most of the piping in LWR systems are usually fabricated from high-alloy[11] austenitic stainless steel of grades 304, 316 and 347. These materials are selected because of their desirable combinations of moderate strength, good corrosion resistance, and excellent ductility and toughness. They are also easily formable into the plate, forgings, bolts and tubular structures needed to fabricate some of the components. The "austenitic" structure of these materials means that they are more highly resistant to embrittlement than the bainitic steels used for the higher stress-bearing and larger pressure-retaining components, such as the reactor pressure vessel, vessel heads, steam generators and pressurisers.

Different ageing mechanisms can be identified depending on the type of stainless steel and its position in the primary circuit. Pressure vessel internals perform in an environment characterised by elevated temperatures[12] and very intense neutron fields. Austenitic stainless steels are susceptible to irradiation-induced – but not thermally-induced – hardening and loss of toughness. However, this occurs at much higher irradiation fluences (around 1 000 times) compared to low-alloy steels. The higher irradiation regimes also induce void swelling and irradiation creep that can cause undesirable stress relaxation. Combined with corrosion, it can lead to irradiation-assisted corrosion cracking (IASCC). This phenomenon is a generic challenge across all LWRs, observed in at least four reactor designs, eleven different alloys and dozens of components (Zinkle, Was, 2013), but it does not represent a safety-related pressure boundary issue.[13] Potential mitigation measures include chemistry control, upflow conversion to reduce mechanical solicitations in the core baffle and better cooling of the bolts via holes in the former (Pokor et al., 2018). Vessel internals (including bolts and springs) can also be replaced (IAEA, 2008a).

IASCC is not an issue for primary circuit piping, since the dose is much lower than on reactor vessel internals. Piping and some internals structures are often fabricated by welding and a cast form of the austenitic stainless steels (CASS). These materials can be susceptible to loss of toughness on extended thermal exposure (i.e. thermal ageing), even in low-irradiation environments. This greater susceptibility is derived from the structure of welds and castings, which contain some volume fraction of ferrite phase that is responsible for the severe irradiation and thermal embrittlement found in low-alloy and plain-carbon steels. This phase is intentionally induced to assist in the production of crack free welds and castings. In general, added susceptibility is managed and controlled by limiting the amount of the deleterious "ferrite" phase in the weld and casting structures. Welds are also periodically inspected using several NDE techniques and can also be repaired, depending on their level of degradation.

Large, civil and concrete structures (LWRs, PHWRs)

Large, civil and concrete structures are of high priority when assessing nuclear power plant ageing. In fact, most of the concrete systems are not replaceable, and in some cases, they cannot be directly accessed for inspection (US DOE, 2012). Among all large, civil and concrete structures present in nuclear power plants, those that are critical for LTO include the containment building, biological shielding and spent fuel pools.

The containment building of a nuclear power plant represents the third barrier (after the nuclear steam supply system and the fuel) against radioactive releases. It consists of thick, reinforced concrete structures using low-carbon rebar, which are post-tensioned with tendons to provide additional tensile strength in case of overpressure during severe accidents.[14] Additional

11. High-alloy steels have a higher content of chromium and nickel compared to low-alloy steels.
12. Temperatures typically range from 288°C in a boiling water reactor (BWR) and up to 360°C in a PWR (in some locations with high gamma heating).
13. For instance, in case of baffle bolt degradation, only peripheral fuel assemblies could be impacted.
14. The differences in containments across reactor designs are essentially driven by the internal pressure of the primary circuit, which will determine the ultimate internal energy that the containments must withstand in case of an accident.

leak tightness can be obtained with a steel liner. The containment building structures are exposed to three main ageing phenomena:

- **Concrete drying**: As concrete ages, it loses its water content. This induces macrostructural changes such as shrinkage, creep (especially in post-stressed concrete structures) and increased permeability, leading to a reduction of the leak tightness of the containment over time. Given the low tensile strength and lack of ductility of concrete, these changes will also lead to the formation of cracks. Cracking occurs virtually in all concrete structures and can never be completely eliminated.
- **Rebar corrosion**: In general, the high alkaline conditions provided by concrete inhibits corrosion of the reinforcing steel in the concrete systems. However, the increased permeability and microcracking over time may favour carbonation [15] processes, the presence of chloride ions and moisture that ultimately can result in corrosion. Corrosion is also the main ageing issue of the steel liner (low carbon steel) and follows similar patterns as those for conventional reinforcing steels. Typically, liner steels are coated (i.e. zinc-rich primer with polyamide epoxy or modified phenolic coatings) to provide higher resistance against corrosion.
- **Alkali-silica reaction (ASR)** [16]: ASR occurs when reactive silica in the aggregate reacts with hydroxyl ions (-OH) and alkali ions (Na+, K+) in the concrete pore solution. When this concrete is in contact with water, a gel can form around the aggregate that induces tensile stresses on the surrounding concrete, which then results in microcracking. With a sufficient amount of internal expansion and tensile stresses, the result is pattern cracking (see Figure 4.3) that could lead to complete destruction of the concrete (NRC, 1996). Pop-outs and glassy appearing seepage of varying compositions can also appear (see Figure 4.3). Since no means of preventing chemical attack existed before the 1990s, the past few years have been characterised by intense research efforts to provide the technical basis, the necessary early detection tools and the ageing management measures for ASR-affected concrete structures (EPRI, 2015, 2017).

Figure 4.3: **Example of pattern cracking and pop-outs of ASR-affected concrete**

Source: Baills-Barraco, Courtois, 2018, courtesy of EDF.

15. Calcium hydroxide is converted to calcium carbonate (calcite).
16. Other, less frequent forms of chemical attack in nuclear power plant containment buildings involve internal sulphate (-SO2) reactions with similar consequences as those of ASR.

Overall, the above ageing patterns are slow and are not necessarily detrimental to the point that reinforced concrete would not be able to meet its functional and performance requirements. Experience also shows that severe degradation mechanisms in concrete systems are very dependent on material selection, construction methods, procedures and curing approaches.[17] Thus far, quality control/quality assurance programmes at nuclear power plants generally have been very effective in ensuring that these factors are adequately addressed (NRC, 1996).

Concrete biological shielding (BS) is the reinforced concrete structure surrounding the RPV, which protects the environment from the radiation emanating from the core while providing structural support to heavy components. It is the only concrete system that is expected to experience severe degradation due to neutron fluence and gamma heating. When neutrons from the reactor core exit the RPV and encounter the concrete BS, they cause heating and point defects in the concrete aggregates. Gamma rays produce radiolysis of water exacerbating concrete drying effects to a limited extent. Similar to the low-carbon steel in the RPV, rebar can also experience embrittlement and hardening. Consequently, prolonged exposure to radiation can result in a loss of tensile and compressive strength, decreases in the modulus of elasticity and radiation-induced volumetric expansion (RIVE) (NRC, 1996; Bruck et al., 2019). Irradiation effects have a primary impact on the structural capability of the BS but not on the shielding properties, which remain practically the same.[18] Work performed by Hilsdorf (1978), Field (2015) and Maruyama (2017) have shown that degradation of mechanical properties in concrete is possible beyond neutron fluence levels of 1×10^{19} n/cm^2 (E > 0.1 MeV) and gamma irradiation levels of around 2.3×10^{10} Rad. These fluence and gamma thresholds are likely to be achieved for operating lifetimes above 60 years (Bruck et al., 2019) but individual plant evaluations would be necessary to provide precise values for a specific plant application. Recent studies performed by Oak Ridge National Laboratory and the Electric Power Research Institute (EPRI) provide guidance on evaluating in detail the RIVE of concrete and the potential effects that expansion may have on structural capacity (EPRI, 2018a). The mitigation measures used to limit RPV embrittlement can also attenuate degradation of the BS.

Lastly, spent fuel pools are concrete structures containing water at high concentrations of boric acid for criticality control. Most of them have a stainless-steel liner that is seam welded together from stainless steel plates, acting as the primary moisture barrier. The ageing of spent fuel pools causes cracks in the seam and weld plugs with borated water potentially leaking into a drainage collection system. As a result, the boric acid can interact with the concrete substructure and the constituents of the concrete, leading to boric acid attack and delamination/cracking of concrete. Recent research performed by EPRI provides a good technical basis for the characterisation of degradation of concrete due to aqueous boric acid, and presents a basis for the development of plant-specific ageing management programmes (EPRI, 2016).

When accessible, concrete structures are subjected to periodic visual inspection and monitoring. In containment buildings, displacements are measured by means of pendulums, extensometers and vibrating wire strain gauges embedded in the concrete structure. Periodic overpressure tests are performed to check if leak tightness levels conform to the licensing basis. The data collected through in-situ inspections are then analysed to evaluate the kinetics of the defects and ultimately adopt reinforced corrective methods, if necessary. Repairs and other remediation strategies can be foreseen for most concrete structures, particularly when they are easily accessible. Extensive industrial experience exists regarding the evaluation of defects on concrete structures and the identification of repair criteria and methodologies (NEA, 2002).

17. During the construction of concrete civil structures most of the components are sourced locally, which can lead to slightly different ageing patterns depending on the plant. Additionally, the Crystal River 3 case described in Box 1.1 illustrates the accelerated degradation mechanisms that can be triggered in concrete structures in the case of non-respect of procedures.
18. Little variations can be observed as a result of the accelerated reduction in water content due to gamma heating.

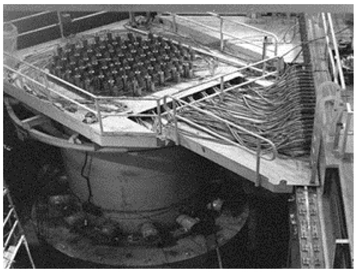
Plant electrical cabling system (LWRs, PHWRs)

Cables are made of conductor materials (i.e. copper or aluminium) insulated and arranged in different configurations (coaxial, triaxial, etc.) within a cable jacket. Both the wire insulation and the cable jacket are made of different types of polymers,[19] depending on the design and requirements. Most of the cabling in a nuclear power plant is used for I&C signals (i.e. to activate relays, pumps, valves and motors), and it is typically designed for low voltage (< 1 kV) and ampacity. On the other hand, power cables withstand higher voltage and the currents necessary for medium- and high-voltage equipment such as pumps.

Cable ageing induces embrittlement and cracking of the polymers (i.e. the insulation and jacket) surrounding the conductor. This physical ageing combined with environmental stressors, such as high temperatures, humidity or wet environments, cycling mechanical stress, and radiation exposure, can accelerate insulation degradation (see Figure 4.4). Electrical cable systems were initially categorised as long-lived, passive components that did not require any specific periodic maintenance, except the cables that were required for safe shutdown of the plant under accident conditions.[20] As long as the cables were installed properly and were not exposed to environmental conditions beyond their design basis, they could be assumed to be reliable without requiring condition monitoring for the original design life of the plant (typically 30-40 years). Operating experience has nevertheless shown that cables could fail earlier than expected[21] in cabling that operated energised in wet conditions, near design limits and for which initial design and installation had not been carried out properly. The most common failure mode has been insulation degradation from water treeing. When moisture reaches the polymers in continually energised power cables (> 2 kV), tree-shaped cracks propagate as a result of electrochemical reactions, leading to a loss of dielectric properties and potentially jeopardising the integrity of the insulation.

Figure 4.4: **Cable exposed to high ambient, mechanical stress (sharp metal edge), and radiation effected cables on reactor head**





Source: Courtesy of EPRI.

This situation, combined with the need to ensure reliable operation of the cabling during the LTO period, has led both licensees and regulators to re-evaluate how cable insulations will perform throughout plant life. Most of these issues can be managed with condition monitoring approaches, mainly involving plant visual inspections and electric measurements.[22] Periodic walkdowns with trained personnel are very effective to visually identify cases where a harsh

19. The most common are polyethylene, cross-linked polyethylene, polyvinyl chloride and ethylene propylene rubber.
20. Nuclear power plant cables have different qualification levels depending on their expected function in different scenarios. For instance, the cabling in the nuclear island is expected to perform at high temperature and irradiation levels (even under loss-of-coolant accident conditions), whereas cables in the conventional island have lower requirements.
21. Around 90% of the failures occurred in normally energised power cables that had been in service between 11 and 30 years. The failures took place either in service or during inspection tests (NRC, 2010).
22. Chemical and mechanical tests also exist.

environment, as well as possible installation-related stressors, may require reinforced condition monitoring. At the same time, various non-destructive electrical measurements can also be performed in-situ [23] to check the quality of the insulation and identify other anomalies. They usually involve impedance measurements, partial discharge and Tan Delta [24] testing, among many other techniques. Nevertheless, these methods provide very little information about cabling degradation levels and kinetics, nor about the remaining useful life. How to monitor cable degradation and determine the remaining useful life of cables remain two of the main challenges for plant operators during LTO. There are several approaches [25] that can be employed to re-evaluate the qualified life of cables. Their cost varies significantly depending on the type of technique. The most economic strategies simply recalculate the qualified life reducing conservatisms and harnessing actual environmental plant conditions. Another possibility consists of leveraging on condition monitoring measurements and elongation at break curves to reassess the residual life. Ongoing research is making significant progress in establishing relationships between the condition measurements and the kinetics of ageing stressors, but this approach has yet to be implemented at an industrial scale. The remaining methods use harvested cables that are artificially aged to the desired ageing period (i.e. 60-80 years) and then subject them to requalification testing to establish the new lifetime. These methods are very expensive and have typically been driven by specific regulatory-driven demands.

Large-scale cable replacements, while being technically possible, [26] may be prohibitively expensive. Operators will therefore favour the implementation of cable qualified life re-evaluations and ageing management programmes for cables during LTO. If performed in the most severe localised environment, cable ageing can be managed economically and efficiently since cabling in more benign conditions is covered by analyses performed in more severe conditions. Alternatively, replacing small sections of cabling may be envisaged as a more attractive option from an economic point of view. Obsolescence issues can also motivate the replacement of some cables (see Chapter 5).

4.1.2. ***Ageing considerations during long-term shutdowns***

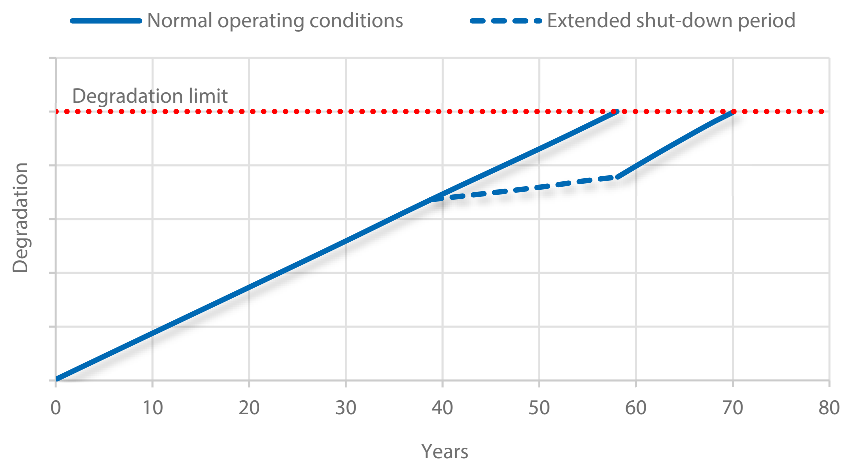
The ageing phenomena affecting critical components described in the previous section, as well as their associated kinetics, have been observed in reactors operating at nominal conditions [27] for long periods. However, nuclear reactors accumulate a significant amount of time during which they are not operating at full power. This is typically the case for normal outages or long-term shut-down periods necessary to undertake major refurbishments and/or safety upgrades. If long-term shut-down periods are considered as fully operational years from an ageing degradation point of view, the economic attractiveness of performing LTO could be significantly reduced, especially is those countries where the LTO period is fixed and limited by the law (e.g. in Japan).

In order to assess the impact of long-term outages on SSC ageing, it is necessary to understand the physical state of the plant under these conditions. When reactors are shut down, the fission reaction is stopped (i.e. zero nuclear power) and the primary circuit is progressively cooled down until it reaches "cold" conditions corresponding to temperatures lower than 100°C and atmospheric pressure. The decay heat removal system is also connected to evacuate decay heat from fission products. As a result, most major environmental stressors (e.g. intense neutron fluxes, high temperatures, pressure and fatigue) are removed, and maintenance and inspection work are also facilitated.

23. Tests that can be performed without disconnecting the cable from its in-service connections or removing the end device.
24. Also known as dissipation factor, this technique can be used to effectively manage water treeing and thermal insulation degradation in medium-voltage cables. Standards such as IEEE 400.2 provide the necessary guidance.
25. Standards such as IEEE/IEC 323/60780, for instance.
26. This was the case, for instance, for the Beznau nuclear power plant in Switzerland (Murty, 2013).
27. Full core power with the primary circuit at 285-320°C and 155 bars for PWRs, for instance.

Recent research confirms that the main ageing degradation mechanisms are significantly slowed down in life-limiting components during long-term shut-down conditions (JNO, 2018; EPRI, 2018b). If complemented with the adequate maintenance approaches and punctual replacements, when necessary, long-term outages should not reduce the typical duration of LTO periods (see Figure 4.5).

Figure 4.5: **Qualitative representation of the impact of long-term shut-down periods on SSC ageing**



4.1.3. *Recent progress on operation beyond 60 years in LWRs*

LTO of nuclear reactors beyond 60 years will increase demands on materials and components, potentially increasing their susceptibility to ageing phenomena or even triggering new degradation modes.

The United States is one of the countries with the oldest LWR fleet. In 2012, the United States initiated a systematic review to identify the main technical issues and to prioritise the necessary research activities that would support LTO beyond 60 years through subsequent licence renewal (SLR). The main research areas for SLR involve:

- **RPV neutron embrittlement:** Data on embrittlement and hardening phenomena at high fluences is sparse, or non-existent in some cases. Specimens can be irradiated in core and in test reactors to accelerate ageing and generate the necessary experimental data. Available research data for fast reactors could also be used. However, technical limits may arise from the use of surrogate materials and the validity of accelerated testing that may lead to non-conservative extrapolations. There is also experimental evidence that Ni-rich precipitates could appear at high fluence levels (the so-called “late blooming”), rapidly reducing fracture toughness margins. Under these conditions, performing thermal annealing[28] could be envisaged during LTO beyond 60 years. It is therefore necessary to understand the behaviour of annealed RPVs, as well as the potential impact of this remediation measure on the surrounding SSCs (i.e. concrete BS). Further, potential attenuation of RPV embrittlement through wall thickness should be further assessed as it could provide extra operational margins. Additional studies are also necessary to properly judge thermal ageing on the RPV over very long operating time frames (Busby et al., 2008).

28. Heat treatment applied to the inner wall of the RPV to restore its mechanical properties. This process can be performed in nuclear reactors both in wet and dry conditions. Dry annealing is usually more effective but requires specific tooling to be performed.

- **Ageing management for reactor vessel internals and welds**: Beyond 60 years of operation, reactor internals will also experience severe irradiation-induced phenomena, leading to microstructural changes and swelling, and increasing their susceptibility to corrosion. While significant research has been performed on IASCC, the underlying physical mechanisms are complex, especially over long operational lifetimes (Busby et al., 2008). Thermal ageing and the formation of a ferrite phase in CASS also requires additional evaluations. Welds and heat affected zones (HAZ) are also particularly sensitive to ageing. To be reliable over very long time frames, advanced simulation tools designed to accurately assess the residual stress in welds, and the development of new welding technologies for repair, could be useful.
- **Concrete and civil structure ageing management and degradation assessment:** For successful operation beyond 60 years, containments could benefit from materials properties data for long-term performance, improved predictive models (see Box 4.2), and global inspection and (NDE) methods. In terms of the concrete BS, simulations carried out by EPRI have shown that irradiation levels after 80 years of operation could be greater than 1 x 1 019 n/cm^2 (Bruck et al., 2019), requiring a better understanding of the long-term impacts on concrete at elevated temperatures and high irradiation.
- **Electrical cable ageing management guidance and condition assessment:** If design and material specifications during installation are respected, cables can also perform safely for long periods. Ongoing efforts are being made to develop multi-scale approaches (from microstructural to global polymer behaviour and measurements) to understand the kinetics of ageing in cables and assess the degradation state based on in-situ measurements and tests.

Co-ordinated research performed in the aforementioned areas over the last decade by EPRI, the US Department of Energy's (US DOE) Light Water Reactor Sustainability Program (LWRS) and the US Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research has provided the necessary technical basis to assess SSC degradation beyond 60 years, and develop dedicated ageing management approaches. The results indicate that if utilities implement enhanced ageing management programmes using the technical evidence already available, while performing the necessary repairs and replacements, LTO of LWRs until 80 years may not face any generic technical barriers. To date, six reactors in the United States have been granted with SLR, and more utilities are expected to file for SLR in the near future. These trends support the technical feasibility of LTO operations beyond 60 years. More recently, the NRC has been exploring the possibility of developing a new licensing framework, allowing US plants to run up to 100 years (NRC, 2021). Additional research will, however, be required to provide robust technical evidence supporting safe operation for longer periods.

4.1.4.SSC ageing in other reactor systems

Most ageing degradation mechanisms and considerations described in the previous sections for LWRs apply to all reactor types, particularly with regard to concrete and cable ageing. Depending on the system configurations and materials selected, some degradation mechanisms could nevertheless be accelerated (or attenuated), requiring different ageing management and replacement approaches. Life-limiting components could also change.

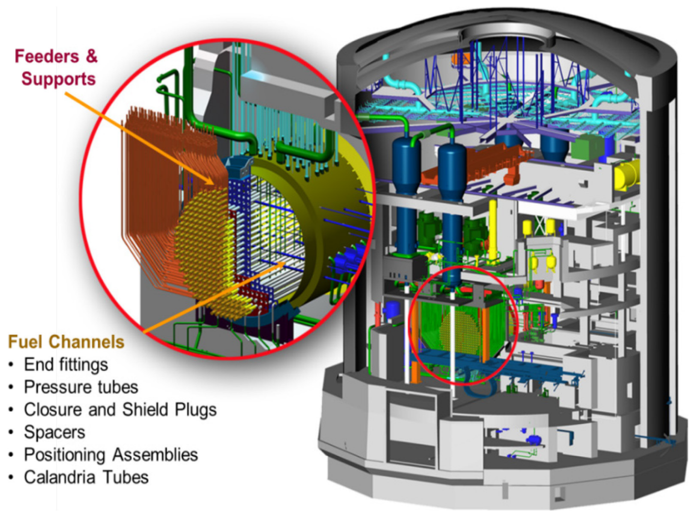
PHWRs

PHWRs use heavy water (or deuterium [D_2O]) as a moderator instead of light water, which enables the use of natural uranium. One of the most prevalent designs is the Canadian Deuterium Uranium (CANDU) reactor (see Figure 4.6). This reactor technology consists of horizontal fuel channels that pass through a sizeable calandria vessel that contains a large inventory of low pressure and temperature deuterium. Inside each fuel channel,[29] there is a string of natural uranium fuel bundles cooled by high pressure and temperature deuterium, which carries the

29. The fuel channels are formed of calandria tubes and pressure tubes in a coaxial configuration, and other components such as end fittings and spacers.

thermal energy through the feeders to four steam generators (SGs). Depending on their burn-up, the natural-uranium fuel bundles are replaced using online refuelling (without shutting the reactor down), which increases the availability of this type of reactor. More than 95% of the PHWRs in operation worldwide are CANDU reactors or an indigenous version of this design (e.g. India) (IAEA, 2021).[30]

Figure 4.6: **CANDU reactor design**



Source: Courtesy of SNC Lavalin.

In terms of ageing considerations, reactor assembly components in PHWRs will be subject to embrittlement, corrosion and stress corrosion cracking, erosion, fatigue and creep and stress relaxation (IAEA, 2001). In general, neutron embrittlement is less severe than in the case of LWRs because of the fuel channel materials[31] and the efficient shielding provided by D_2O. The main ageing issue involves the calandria tube rolled joint stress relaxation and calandria tube sag. The latter can deform under irradiation creep and enter in contact with the horizontal liquid injection shut-down unit nozzles, leading to fretting wear. This phenomenon has been successfully managed with routine inspections, but it may become a real concern if PHWRs are operated beyond 30 years, which corresponds to their initial design lifetime.[32] Consequently, LTO beyond 30 years in the case of PHWRs requires a full retubing to resolve this issue.[33] Stress corrosion cracking in SGs is also a concern in PHWRs, but experience confirms that with adjustments and remedial measures (i.e. active chemical control) they can operate safely until 60 years without replacement.[34] Cables and concrete structures will follow similar considerations as those described in Section 4.1.1.

30 Consequently, when referring to PHWRs in the present report, it is implicitly assumed that the reactor is a CANDU-type concept using horizontal pressure tubes. Atucha 1 & 2 units being operated in Argentina, however, are a type of PHWR developed by the German vendor Siemens-KWU using a vertical RPV configuration similar to LWR designs. Siemens-KWU PHWRs are not covered in present study.

31. Reactor assemblies in PHWRs are made of stainless steel and zirconium-niobium, which can withstand higher neutron fluxes before showing severe embrittlement.

32. The original design lifetime for PHWRs is not expressed in years but rather in operational hours, and it can be stated as 210 000 effective full power hours (EFPH), corresponding to approximately 30 years at a capacity factor of 80%. Operational experience confirms the existence of margins that enable a licence extension (without extensive refurbishment) to 225 000 EFPH or even to 300 000 EFPH, depending on the design and plant conditions.

33. For CANDU-6 reactors, this would mean the replacement of the 380 calandria tubes, 380 pressure tubes, 760 end fittings, 760 feeders, and various supporting and connecting components.

34. SGs can be replaced, and some operators may decide to perform in-situ SG replacement as part of the scope of LTO projects, depending on plant conditions (see Box 4.3).

Overall, the concrete containment and the calandria vessel are the only non-replaceable components that could ultimately limit the life of PHWR plants. Recent analyses suggest that a third life cycle of 30 years (thus 90 years of operation) may be technically feasible. It would, however, require a second retubing and certainly a more extended refurbishment, potentially including SGs. With regard to the calandria vessel, the low temperature and fluence environment under which it operates guarantees 90 years of safe operation. The inspections performed until present support these conclusions.

VVERs

VVER is the acronym of "*Vodo-Vodyanoi Energetichesky Reaktor*", a PWR design developed by Russia in the 1960s and then exported to several countries. As of 2020, there are 62 VVERs in operation in 8 countries and several projects under construction. Around 60% of the VVER fleet is older than 30 years. The main differences in relation to VVERs with respect to traditional PWRs include:

- horizontal steam generators;
- a different core configuration with triangle lattice, hexagonal fuel assemblies and relatively smaller cores with higher enrichment;
- an RPV with a lower diameter, no penetration in the bottom and two levels of coolant piping.

The physics between VVERs and traditional PWRs are essentially the same. The RPV and the concrete containment building remain the primary life-limiting components. However, the following specific ageing considerations should be mentioned:

- **RPV embrittlement**: the RPV materials of early VVER versions (built before the mid-1970s) contained high concentrations of copper and phosphor, which accelerated the embrittlement of the inner walls, reducing fracture toughness margins (NEA, 2012b). Mitigation measures implemented by the operators involved low-fluence fuel loadings, higher water temperatures in the emergency cooling system, and enhanced in-service inspections and NDE (Katona, 2011). Several RPVs have also been annealed to enable extended operation up to 60 years.[35] Various design improvements in subsequent VVER versions provide significant additional margins against RPV embrittlement.

- **SG performance**: the horizontal configuration of SGs in VVERs provides a large surface for evaporation with lower heat flux, thus reducing mechanical stresses and vibrations. Sediments (sludge) are lower compared to vertical SGs, and they deposit underneath the tube bundle. Also, horizontal SGs can be easily accessed for maintenance. The main ageing mechanism observed is outer diameter stress corrosion cracking (ODSCC) of the SG tubes. Operating experience has shown that it appears typically in the grid structure supporting the tube bundle. A series of modifications have slowed down the rate of ODSCC. The feed-water distributor has also experienced accelerated ageing due to erosion, and it has been replaced in some VVER reactors. All of these aspects, combined with the suitability of the SG tube materials, enable LTO without SG replacement.

4.2. The LTO programme

While a solid knowledge of ageing degradation mechanisms is key to enabling LTO, additional actions are often required to ensure that for a given SSC the associated safety functionality is available throughout the LTO period. A LTO programme is a systematic process that combines both technical evidence and organisational aspects to maximise the life of a nuclear power plant. Proven tools and procedures guide operators through the process, enabling the identification of potential replacements, as well as specific measures for life-limiting components. The governing frameworks associated with LTO programmes also allow for internal periodic re-evaluation and external peer reviews in order to identify potential shortfalls and provide access to the latest knowledge available and best proven international practices.

35. Around 15 VVER-440 RPVs were annealed between 1987 and 2017 (Kryukov, Rubtsov, 2017).

An LTO programme for a given nuclear power plant generally has three main stages: i) feasibility studies and preconditions; ii) LTO assessment; and iii) LTO approval and implementation (IAEA, 2008b).

4.2.1. *Feasibility studies and preconditions*

After 30 or 40 years of operation, the context in which a nuclear power plant operates may have changed considerably. A preliminary technical assessment can be performed to identify potential plant enhancements and replacements, and their economic feasibility based on current and projected market conditions and energy policies. Regulatory changes and their implications should also be assessed at this stage. Preconditions for LTO include quality assurance systems, as well as the availability of the latest safety analyses and associated assumptions.

4.2.2. *LTO assessment*

If the outcome of feasibility studies is favourable to the LTO option, it is then necessary to determine the scope of LTO activities in more detail. In this process, all relevant SSCs are analysed in order to define the best strategy to deal with ageing so as to enable LTO. In general, the following steps are considered:

- **Individual plant assessment (IPA):** Based on specific operating experience and plant conditions, all of the SSCs are screened and classified according to their importance to safety. Cost and reliability considerations are also taken into account in this assessment. At the end of the IPA, operators should have a clear understanding of the parts of a given plant which are:
  - *Non-critical* and can be run to failure and replaced without major implications in terms of safety and reliability.
  - *Critical but replaceable* and thus falling into the category of components that can be part of the LTO refurbishments (see Section 4.1.1). This is the case for most critical SSCs in nuclear power plants.
  - *Life-limiting* as they cannot be replaced for techno-economic reasons, and for which particular ageing management measures are required during LTO (see Section 4.1.1).
- **Ageing management reviews (AMRs):** Critical components are then subjected to detailed reviews in order to identify the main degradation mechanisms, and in which materials, areas and environments they are taking place. The technical evidence on materials ageing described in Section 4.1 is considered when performing AMRs.
- **Time limited ageing analysis (TLAA):** Using the information collected during the AMRs, specific time dependent safety analyses are performed in order to extrapolate the impacts of ageing mechanisms over the period of extended operations and assess operational margins.
- **Ageing management programmes (AMPs):** The issues identified by AMRs and TLAAs in critical SSCs are resolved through specific ageing management programmes. They usually cover understanding degradation mechanisms, as well as the prevention, detection, monitoring, mitigation and remediation of such mechanisms. Associated activities include maintenance, in-service inspection, and testing and surveillance. Inspections are typically supported by NDE involving numerous techniques, depending on the type of component being inspected. Radiographic (gamma or X-rays), magnetic and ultrasound methods are used to detect cracks in metallic components and welds. Eddy current techniques are used to check SG tubes and heat exchangers. Maintenance approaches may also vary depending on the AMP needs. Preventive maintenance is usually adopted as it allows for the replacement components before a failure occurs. Maintenance approaches can be further improved by harnessing risk metrics and data concerning the actual condition of components (i.e. condition-based maintenance). The emergence of new digital solutions and simulation tools offers new opportunities to improve maintenance, ageing management practices and the evaluation of safety margins in general (see Box 4.2 below). Several examples of ageing management measures for life-limiting components are provided in Section 4.1.1.

Box 4.2: **Enhancing ageing management approaches with digital solutions and simulation tools**

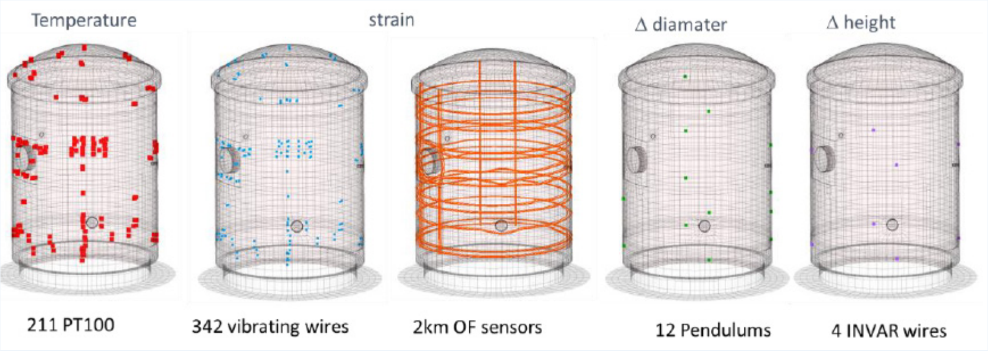
Several digital solutions are gaining maturity and could be rapidly deployed in the nuclear industry, leading not only to safety improvements but also to operation and maintenance cost reductions.

Digital twins

Digital twins are virtual and dynamic representations of physical assets. The data provided by sensors embedded in the real assets or by wearable and mobile devices carried by workers (e.g. cameras, tablets) during inspections are used to feed powerful predictive models that simulate the physical behaviour of the asset over time. As a result, digital twins close the loop between the physical and virtual realms to represent the current (and future) ageing condition of a given component almost in real time.

Nuclear operators are already developing these solutions to enhance their ageing management plans. One example is the VERCORS project led by the French utility, EDF. VERCORS aims at developing a digital twin of the concrete containment building of a French 1 300 MWe PWR (P'4 series). For the development of VERCORS, a one-third scaled mock-up of a P'4 containment building was built. Because of its reduced size, the concrete drying is around nine times faster than the larger-scale model, leading to accelerated ageing patterns that are monitored in real-time thanks to the numerous sensors inserted in the main structures of the mock-up (see Figure 4.7 below). Tests performed in 2016 validated the main ageing assumptions and models. In 2019, ageing in the VERCORS mock-up was greater than in actual P'4 containment buildings, allowing it to become a fully predictive tool. Thanks to VERCORS, EDF expects to increase its understanding of the leak-tightness evaluation in these types of containment vessels beyond 40 years, as well as to optimise maintenance strategies. EDF is also developing digital twins of SGs to better predict the evolution of corrosion and tube clogging and therefore increase the availability of the French nuclear fleet.

Figure 4.7: **Different types of sensors inserted in the VERCORS mock-up**



Source: Mathieu, Masson, 2018.

Integrated and unified information systems

Nuclear power plants already generate enough data to enable the proper assessment of ageing issues. Retrieving this information is nevertheless very time consuming for the most part since it is distributed across several isolated databases in different locations and formats, and with different access rights. The traceability of data changes is often lacking, hindering the identification of initial assumption and technical choices.

To overcome these issues, some operators are developing shared platforms, and integrated and unified information systems that provide quick access to relevant information during the elaboration of ageing management studies. This is the case, for instance, for the piping and component analysis and monitoring system (PAMS) developed by the Finnish utility, TVO (Smeekes et al., 2013). This tool consists of several interconnected databases and various modules allowing high levels of automation to be achieved when performing mechanical analysis of the piping. The new results are automatically synchronised, ensuring that the information in the databases is always up-to-date. PAMS has been successfully used to support the licence extension of Olkiluoto units 1 and 2, and could be easily extended to other types of components and technical studies.

Advanced analytics and machine-learning applications

The considerable amounts of data generated by sensors inserted in nuclear components can be used to feed advanced analytics models and machine-learning tools to enable condition-based maintenance plans and predict adverse situations. Evidence is being accumulated in the United States on the implementation of these types of tools by nuclear operators. In some cases, actionable faults have been predicted accurately more than three months in advance (Reuters, 2017; WNN, 2018). As a result, ageing management activities could be adjusted in real time, improving safety margins while streamlining resources. Enhanced or automated chemistry control for corrosion is also possible with these tools.

Improved simulation tools

Materials ageing analysis is a multidisciplinary approach resulting from the combination of irradiation history, thermal-hydraulic boundary conditions and mechanical properties. Initial design evaluations for Gen-II technologies were performed using simplified analytical models [36] based on bounding cases with penalised input data, accounting for uncertainties and thus leading to very conservative results. Improvements in computer power have enabled the use of more powerful simulation tools capable of performing three-dimensional, multi-physics and time-dependent simulations, which has resulted in a more precise assessment of actual safety margins today than in the past, and which supports LTO. In co-ordination with safety authorities, these new tools and methods have been qualified for use at an industrial scale. Examples include the utilisation of computational fluid dynamics for RPV integrity assessment and new simulation tools to accelerate the qualification of advanced NDE (MAI, 2018).

National and international experience on ageing management

With more than 30% of the global nuclear fleet already operating in LTO, there are numerous national examples of LTO programmes and related ageing management programmes (AMPs). At the same time, the experience accumulated by some countries represents an opportunity to improve ageing management worldwide by sharing best practices. International collaboration is also important to accelerate research and extend the knowledge basis in key areas. Organisations such as the International Atomic Energy Agency (IAEA) and EPRI have played a leading role in setting internationally recognised standards for ageing management and in creating the necessary platforms for collaboration and exchanges on LTO experience.

The IAEA International Generic Ageing Lessons Learned (IGALL) initiative was initiated in 2010 and is based on the US Generic Ageing Lessons Learned (GALL) approach. [37] The programme has facilitated the exchange of experience and the dissemination of best practices with regard to the identification, establishment and implementation of AMPs. The IGALL programme covers PWRs, BWRs, VVER, PHWRs and also advanced gas-cooled reactors. The main IGALL document is the Safety Reports Series No. 82 (IAEA, 2015), which is complemented by the publicly available "IGALL database", containing more than 2 000 line items in the AMR table, 76 AMPs and 27 TLAAs to support LTO assessments all over the world.

Peer reviews in selected countries are also a key element of the global governance of LTO experience. Every year since 2005, the IAEA organises Safety Aspect of Long Term Operation (SALTO) missions, gathering international experts and IAEA staff to review LTO activities and guide countries on the entire process. The scope of SALTO missions covers IPAs, AMRs, AMPs and knowledge management, which includes the review of written materials and databases, interviews with experts and nuclear power plant staff and direct observations on the nuclear site. The main outcome of the peer review is a report with recommendations and suggestions for improvement in areas where performance falls short according to international best practices. Some examples of issues identified thanks to SALTO missions include: lack of access to the design basis, incomplete scoping and screening of SSCs for LTO, inconsistency of databases, inadequate AMP for the containment and insufficient human resources for LTO activities (Nuclear Engineering International, 2014).

36. Typically one- or two-dimensional analysis with decoupled (non-interacting) physical models.

37. The nuclear power plants in the United States are, on average, five to ten years older than nuclear plants in Europe and Asia, and their operating experience and management philosophy has informed the development of the first set of AMPs required for licence renewal by the US NRC. These AMPs helped create the US GALL report, which became a starting point and forerunner for the IAEA IGALL initiative.

4.2.3. *LTO approval and implementation*

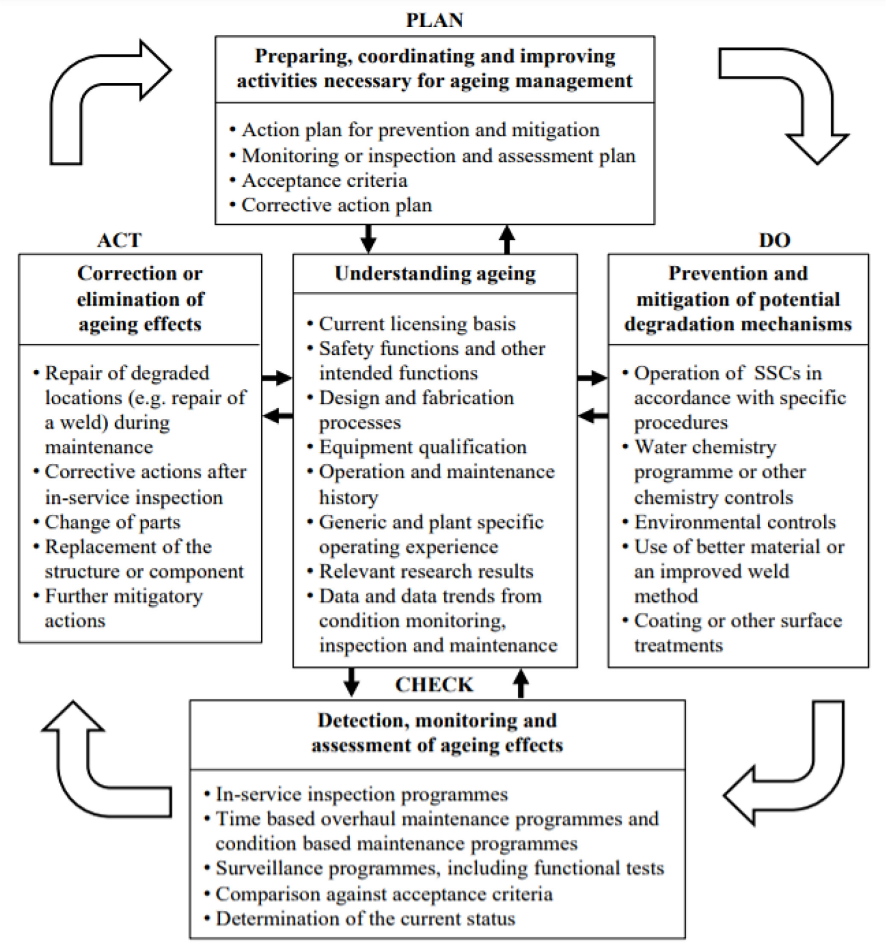
Once the LTO assessment has been performed, all of the related documentation and ageing management measures for the LTO period undergo regulatory review according to national and international standards. Depending on the regulatory framework, the scope of the LTO evaluation is identical to the periodical safety reviews imposed by regulators. In some cases, once the plant has reached its initial design lifetime, regulations may reinforce AMPs in life-limiting components. These aspects are further explored in Chapter 5.

During the implementation of an LTO programme, and according to the outcome of the IPAs and specific plant conditions, some components will be completely replaced (see Section 4.3.1) or follow specific AMPs. The success of the programme will rely on a systemic approach that:

- co-ordinates ageing management activities at all organisational levels;
- continually monitors programme effectiveness to identify potential shortfalls;
- screens international best practices and follows peer reviews;
- applies corrective actions as necessary.

These principles are those of Deming's continuous improvement and total quality management "plan-do-check-act" summarised in Figure 4.8 below. Extensive documentation is available to develop and implement LTO programmes.

Figure 4.8: **Systematic approach for ageing management**



Source: IAEA, 2018a.

4.3. Replacement, refurbishments and upgrades

The primary objective of LTO refurbishments is to compensate materials ageing, but experience shows that operators use the extended shutdown period [38] to implement additional plant retrofits. The objective is not only to update the plant to new safety standards but also to increase the overall economic attractiveness of the LTO business case. The LTO extension period ahead will heavily influence the return on investment of some of these solutions and thus the final scope of work.

4.3.1. *Scope of LTO refurbishments*

Most of the components of a nuclear power plant can be replaced. As part of LTO assessments, operators determine which components will be changed, as well as those that will follow specific AMPs, taking into account technical and economic considerations. The final scope is plant-specific, and is based on the design characteristics, operational experience and history, as well as previous refurbishments.

The typical scope of LTO refurbishments includes:

- **Mechanical equipment** – upper vessel heads, steam generators, turbines, pumps, motors, etc.;
- **Fluid systems** – service water piping replacement with corrosion resistance materials, independent core cooling system, large diameter piping, buried piping replacement with high-density polyethylene, etc.
- **Electrical equipment** – alternators, transformers, high voltage posts, electrical boards, etc.;
- **Instrumentation and controls –** control room, cables, sensors, etc.;
- **Civil works –** cooling towers, for example;
- **Post-Fukushima –** filter vents, emergency diesel generators, additional ultimate cooling systems, etc.;
- **Other –** fire protections, etc.

This list of components accounts for most of the overnight costs associated with LTO investment (see Chapter 6). It is important to highlight that LTO replacement and safety upgrades usually go together as both are evaluated by regulators to approve licence extensions. This is the case, for instance, for post-Fukushima safety upgrades. It could be argued that post-Fukushima measures are not an LTO expense per se as they do not directly relate to ageing. Nevertheless, under the current regulatory framework, no licence extension could be granted without complying with post-Fukushima standards. In addition, some safety improvements are also implemented on a voluntary basis by operators, and do not follow any regulatory demand. Some examples of the scope of LTO refurbishments for specific plants and designs are illustrated in Box 4.3.

38. Of several months or even years.

Box 4.3: LTO refurbishment examples

France (PWRs, Tricastin-1 case)

Tricastin 1 was the first 900 MWe unit to finalise the 4th decennial outage in late 2019 as part of the French long-term operation programme.[39] French regulations require an update of the licensing basis every ten years according to the most recent designs.[40] A significant part of the work was thus related to the implementation of post-Fukushima safety measures to ensure the management of severe, beyond-design-basis accidents. These measures included the installation of two ultimate emergency diesel generators, additional diversified emergency cooling systems for the secondary circuit, spent fuel pools and the containment, U5 filter vents, a corium stabiliser, reinforcement of the protection against earthquakes and an additional control room for operation under extreme events.[41] As part of periodic safety re-evaluations, stress tests (i.e. over pressurisation) were performed in the primary and containment buildings to verify their leak tightness. The RPV was also subjected to an overall inspection with cameras and automated NDE. Some replacements involved electrical equipment, the rotor of the alternators and the filters for the pumping station of the tertiary circuit (Payen, Willot, 2019).

Refurbishment work at Triscastin-1 took around 23 months[42] for a total investment of EUR 250 million. The final regulatory approval for extended operations beyond 40 years was granted by the end of 2020 with possible additional requirements by 2023, depending on the outcome of the regulatory oversight. Similar refurbishments will be executed in 21 additional 900-MWe units before 2025.

Argentina and Canada (CANDU-type PHWR, the case of Embalse, and of Darlington units)

To date, seven CANDU reactors worldwide have undertaken major refurbishments to extend operations for an additional 30 years. As indicated previously, this requires at least a full retubing (or replacement of calandria and pressure tubes, as well as related feeders and end fitting) of the plant. This activity typically represents more than 50% of the scope of work of LTO projects. Two CANDU refurbishments have been successfully finalised in recent years: Embalse in Argentina and Darlington-2 in Canada.

Embalse is a CANDU 6 reactor run by the Argentinean utility, NA-SA, since 1983. This unit was the third CANDU 6 plant to go through refurbishments, after Wolsong 1 in Korea and Point Lepreau in New Brunswick, Canada. After several years of planning, preparation and training, the unit was taken offline in December 2015 and returned to service around 3 years later in January 2019. The Embalse LTO project is the most extensive refurbishment of a CANDU 6 reactor executed to date, involving a series of upgrades throughout the station beyond full retubing, such as:

- steam generator replacement;
- control computer replacement;
- turbine and balance of plant refurbishment, for example a power uprate of 6%;
- diesel generator replacement;
- moderator heat exchanger and valve replacement;
- safety systems improvement and modernisation.

Because of its unique enlarged scope, the Embalse project faced various, first-of-a-kind challenges in CANDU refurbishments, in particular the interference of the retubing work with the steam generator replacement. The experience gathered provides valuable lessons for ongoing and future CANDU refurbishments taking place in Canada.

39. Other French reactors that have already completed their 4th decennial outages are Bugey 2 (February 2021) and 4 (June 2021) units.
40. In other words, a 900 MWe unit operated beyond 40 years must fulfil the requirements for EPR designs.
41. Other post-Fukushima measures for the entire French nuclear fleet include the establishment of a special force for rapid action (or FARN). In the case of a nuclear accident, this team is capable of offering assistance in less than 24 hours at any nuclear power plant on French territory and of mobilising portable cooling systems.
42. A total of 18 months with the reactor in operation, and 5 months of decennial outage.

The aforementioned aspects are also applicable to the larger CANDU9 units at the Darlington site. Its four units started operations in the early 1990s and supply 3 524 MW to the Ontario grid. Major LTO work has been scheduled to take place between 2016 and 2026. The first unit that was taken offline for refurbishment was Darlington 2, which resumed operations in April 2020.

The IPA performed on Darlington reactors confirmed that the calandria vessel and steam generators were fit for at least an additional 30 years of operations. Consequently, the refurbishment scope is essentially limited to retubing. The extended refurbishment outage nevertheless presents an opportunity to perform maintenance or upgrades on the turbine generator set and balance of plant equipment, including the cleaning of the steam generators and the installation of access ports to improve inspection capabilities. The ten-year period also allows for many extra activities to be performed, which are not directly related to unit refurbishments covering safety upgrades (e.g. installation of emergency power generators and filter vents), personnel training (e.g. full-scale control room simulator), enhanced operational flexibility and improved access to the plant (e.g. new highway interchange).

The six units at Bruce nuclear power plant will experience similar refurbishments between 2020 and 2033. Overall, LTO investments in Canada will represent CAD 24 billion for an additional 30 years of operation.

4.3.2. *Plant enhancements for LTO*

Typical plant enhancements executed during LTO outages include power uprates, I&C upgrades, flexible operations and plant modernisation. The latter two are real options for utilities in electricity systems facing increasing market pressures and grid constraints due to higher VRE penetration levels (see Chapter 2). Supply chain obsolescence is also forcing some operators to update the I&C systems of the plants.

Power uprates

A power uprate is an increase of the net electrical power of a nuclear power plant. These uprates usually vary between 2-7% of the nominal power and leverage on existing design margins enabling the accommodation of higher outlet temperatures and steam flows. More extensive power uprates (>20%) may require major plant modifications, affecting high-pressure turbines, condensate pumps and motors, main generators, and/or transformers (NRC, 2020). Power uprates result in permanent higher temperatures and neutron fluxes for the RPV and core internals, as well as higher fatigue, hence accelerating materials ageing. Since 1977, a total of 164 power uprates, ranging from 1% to 20% have been approved by the NRC in the United States, resulting in 7.9 GWe of additional generating capacity. While power uprates tend to reduce materials degradation margins, their impacts are well-known, measurable and predictable, and they do not hinder extended operations of nuclear power plants.

Flexible operations

Extensive operational experience exists in load-following mode for PWRs, emanating from France and Germany, among other countries (NEA, 2012a). More recently, some nuclear power plants have been operating in flexible mode in North America (Canada and the United States). Many of the existing LWRs in the above countries have been upgraded to improve their operational performances and manoeuvring capabilities. Retrofitting mostly involves the I&C system, the in-core measurement and monitoring equipment, the adoption of less absorbing control rods (grey rods) and the optimisation of fuel rods and pellets. Today, ramps of 1-5% power variations per minute can be performed with maximal changes in 30 seconds of 5-10%. Nuclear power plants participate in the primary and secondary frequency control, and some units follow a variable load programme with one or two large power changes per day. The implementation of flexible operation also requires specific ageing management approaches and personnel training. The necessary plant modifications to enable flexible operations in LWR and PHWR designs have been well documented by EPRI (2014).

The additional plant transients and cycling associated with flexible operations may induce wear, erosion, and fatigue in many systems and have implications on fuel management and fuel elements that need to be evaluated. Specific ageing issues reported for PWRs involve valves in the chemical and volume control systems, control rod drive mechanisms and the surge line in the pressuriser. Temperature transients may also impact secondary systems (erosion of pipes, ageing of heat exchangers). No impact to fuel reliability and fuel failures have been reported to date. Overall, all of these ageing impacts can be accommodated by existing operational margins and properly managed via reinforced inspections and maintenance approaches. More detailed information about the potential impacts of flexible operation on nuclear power plants and possible remediation measures is provided in the IAEA report entitled *Non-Baseload Operation in Nuclear Power Plants: Load following and Frequency Control Modes of Flexible Operations* (2018b).

I&C upgrades

Most of the Gen-II I&C systems are analogue [43] with a life cycle ranging between 30 and 40 years. Analogue systems have proven to be adequately designed and reliable enough to meet their intended function over their original design lifetime; however this has not prevented some operators from evaluating their replacement by digital systems for extended operations. In addition to the economic advantages associated with the adoption of digital devices, such as lower operational costs and a greater reliability and availability of the assets, technological obsolescence has become a real concern over the last years. Given unattractive market conditions, the main original equipment manufacturers (OEMs) have disappeared or have simply disinvested in I&C analogue equipment, leading to a loss of critical know-how and inhibiting timely replacement of these systems. In some cases, operators have been able to secure strategic stocks of critical equipment and devices that are periodically re-evaluated. Reverse engineering is also used by alternative suppliers to design similar analogue applications, which comes at a significant cost premium owing to the lack of economies of volume.

There are examples demonstrating that it is possible to replace analogue I&C by digital technology even for the highest safety class applications. In Sweden, for instance, a major digital upgrade on the Ringhals 2 PWR included the control room, reactor protection and control systems, and turbine control, as well as the installation of a new plant simulator. Project planning began in the 1990s, and major installation and testing was performed in 2009-2010 during a 10-month outage for a total cost of EUR 10 million. Similar projects have been carried out in Finland for the Loviisa units (i.e. LARA and ELSA projects) and in France for 1 300 MWe reactors (i.e. the M2C project).

Successful digital I&C refurbishment requires significant upfront efforts in terms of detailed definitions and planning, personnel training, and close co-operation between operators, suppliers and regulators. Qualification and licensing are often cited as the main obstacles for the adoption of digital applications in the nuclear industry. Some regulators may be reluctant to embrace these types of solutions because of potential black box effects [44] and increased vulnerabilities in terms of common cause failure and cybersecurity. Low IT maturity levels in some utilities can also prevent operators from taking advantage of the latest technology available and may need extra investment. The more frequent software updates related to digital applications can also be regarded as plant modifications and thus require safety review, increasing the overall cost burden. For these reasons, despite the recognised benefits of digital technology, plant-specific evaluations are needed to properly assess the return of I&C investments and the obsolescence strategy.

Plant modernisation

The ongoing digital transformation taking place in other industries provides a wide range of opportunities to modernise existing nuclear power plants. Rather than simply focusing on the introduction of new technologies, plant modernisation provides an opportunity to rethink the current value processes at nuclear power plants around advanced digital technologies in order to reduce operational costs and maximise the availability of the plant. Examples from other industries provide valuable lessons to accelerate this process while minimising overall implementation risks.

43. Some designs, such as the French 1 300 MWe and N4, as well as more advanced versions of CANDU reactors, integrate digital I&C systems to some extent. This is also the case for Gen III/III+ designs.
44. Difficulties in analytically linking the input of a system with its output.

Work conducted by EPRI in collaboration with the Nuclear Energy Institute (NEI) and DOE in the United States have identified at least 12 enabling processes that could be deployed in the nuclear industry (Barker, 2019). Immediate applications to save on costs involve condition-based equipment maintenance (see Box 4.2), integrated monitoring and diagnosis, mobile work execution, automated work planning and automated chemistry monitoring. Other technical areas cover wireless connectivity throughout the plant, risk-informed engineering and decision making, common information models, and continuous monitoring of radiation levels and real-time anomaly analyses in life-limiting components (EPRI, 2019a).

Similarly to I&C upgrades, plant modernisation faces challenges related to qualification, licensing, cybersecurity concerns and uncertainty around the effective return of investment. Early involvement with regulators could facilitate the licensing process, especially when important-to-safety SSCs are concerned. Moreover, most of these digital tools require robust IT infrastructures and effective change management (e.g. training of personnel) to deliver their full potential, requiring additional expenses that should not be neglected. In economic terms, initial estimates performed for US nuclear power plants suggest that many utilities can justify plant modernisation investment of more than USD 100 million. Justifiable investment for some US plants could reach USD 500 million for a 25% cost reduction and USD 1 billion for a 50% reduction (EPRI, 2019b).

Key findings

- Significant research has been completed on the identification and management of the main ageing phenomena in life-limiting SSCs in nuclear systems, providing a solid technical basis for safe, long-term operation, if the necessary replacements, maintenance and ageing management policies are performed.
- The technical knowledge base is complemented by ageing management programmes and robust governance models consisting of periodic re-evaluations, peer reviews and best practice sharing globally, which ultimately enables early detection of potential deviations and the application of corrective measures when necessary.
- Most of the components of a nuclear power plant can be replaced, and significant industry efforts can be carried out throughout plant life to refurbish the plant components and maintain or even improve plant material conditions.
- LTO refurbishments are also an ideal opportunity to upgrade the safety of the plant, as well as to implement additional plant enhancements, such power uprates, I&C upgrades (e.g. replacement of analogue equipment with digital one), flexible operations and overall plant modernisation. The objective is mainly to improve safety, but also overall plant economics through increased availability and reduced operating costs during the LTO period.

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5. Operational and human aspects

Countries evaluating the possibility to extend the operation of their nuclear power plants beyond their initial design lifetimes must understand the operational implications of such decisions. While the ageing of structures, systems and components (SSCs) will certainly determine the final lifetime of a nuclear power plant, it does not necessarily imply that safety or reliability concerns will be observed over the long term. As demonstrated in Chapter 3, nuclear operators have various options and approaches at their disposal to cope with ageing and to sustain safe operations during the long-term operation (LTO) period. These options and approaches include SSC replacements and technical advances, but also organisational improvements; all of which are carried out under permanent regulatory oversight, and in most cases, under the aegis of international peer reviews. Industry-led regulation activities may complement these approaches with the objective of achieving higher levels of operational excellence.

At the same time, the LTO of nuclear power plants is only possible if countries have the ability to ensure its success, which also requires access to a robust supply chain that provides high quality components at a reasonable cost, as well as the presence of a constant inflow of a high-skilled workforce at all levels. Increasing supply chain pressures and a loss of attractiveness in relation to nuclear activities are raising concerns in the nuclear sector. Concerted efforts among various stakeholders (e.g. governments, industry, research institutes and academia) are already underway to overcome these issues and to secure safe and reliable operations for longer periods.

5.1. Insights on the performance of nuclear power plants

Good performance in nuclear operations is represented through a combination of high safety and reliability (i.e. energy production) levels.[1] The evolution of the performance of a nuclear power plant over time will depend on several interrelated factors, from technical, organisational and governance perspectives:

- **Materials ageing**: Materials ageing is the main technical concern that could prevent SSCs from complying with their expected function during the LTO period. An extensive knowledge base already exists in terms of the main degradation mechanisms of critical components in a nuclear power plant and the evolution of their primary mechanical characteristics under a variety of conditions. Of particular importance is the ageing of life-limiting components, which could ultimately define the lifetime of the plant. These components require specific measures to mitigate the effects of ageing (see Chapter 3).
- **Replacements**: All of the components of a nuclear power plant can generally be replaced, except the reactor pressure vessel (RPV) and the containment building, the latter of which are life-limiting components. Cabling and RPV-internals can also be considered as life-limiting components, but their possible replacement is subject to economic considerations. The final scope of replacements necessary for LTO is not universal since it varies according to plant-specific conditions and regulatory requirements that are evaluated during the individual plant assessment for LTO.
- **Technical progress**: The nuclear sector has also benefited from continuous progress in materials development, engineering and computer science, among other disciplines.

1. In the present chapter, the term “performance” implicitly refers to both adequate safety and reliability levels, with safety being the overriding priority.

Advances in multi-physics simulation have expanded knowledge in relation to the complex interactions taking place within nuclear reactors and has allowed for a more accurate assessment of safety margins. Probabilistic safety analyses have been developed to enable the use of risk metrics, which are designed to improve maintenance strategies based on the criticality of systems and actual plant conditions. Today, the latter can be monitored, for example by means of sensors embedded in components and post-processing tools, which further increases the reliability of the plant. LTO refurbishments provide good opportunities to incorporate all of these technical advances and modernise existing nuclear power plants (see Chapter 3).

- **Operational experience**: The first years of operation of a nuclear power plant are typically characterised by lower availability levels. It is the so-called "running-in" period, during which personnel learn how the different systems work. Minor technical adjustments are also implemented to achieve smooth operations. After this period, performance levels tend to increase as the workforce has a better understanding of the facility and knows how to proceed under specific conditions, minimising potential downtimes. Today, nuclear operators and regulators have a better understanding than forty years ago of how nuclear reactors operate and age, which has a direct and positive impact on plant operation. As experience continues to evolve, only best practices are retained and disseminated among new personnel, thus sustaining good performance levels over time. At the same time, existing nuclear governing frameworks facilitate operating experience sharing among different plants and operators. Nuclear operators can hence adopt best safety and operating standards while identifying potential shortcomings in advance. In fact, younger plants can learn from older nuclear power plants in LTO in any part of the world and undertake the necessary actions in advance to avoid potential operational issues. These organisational dynamics explain, to some extent, the continuous improvement of global performance indicators in relation to existing nuclear facilities despite ageing (see Figure 5.2).

- **Governing framework**: Nuclear power plants operate under a governing framework with unique characteristics. First, nuclear power plants are subjected to the regulatory oversight of a competent and independent national authority that ensures that nuclear facilities comply with the required safety standards.[2] Second, the governing framework operates in continuous improvement logic at both the regulatory and operational levels. For instance, regulators periodically review the safety of nuclear power plants using the technical evidence provided by operators, and by carrying out on-site inspections. As part of the LTO-programmes, operators continually monitor ageing management practices for critical components to identify potential deviations. Third, international collaboration and experience sharing are at the core of nuclear activities. International organisations, such as the International Atomic Energy Agency (IAEA), the Nuclear Energy Agency (NEA), the Electric Power Research Institute (EPRI) and the European Nuclear Safety Regulators Group (ENSREG), among other organisations, periodically gather operators and regulators together to exchange on relevant safety- and operational-related topics. Peer reviews (e.g. IAEA SALTO, ENSREG)[3] involving different experts are usually undertaken as an effective way to check that the different strategies in place at a given nuclear power plant are aligned with international standards and best practices. Fourth, economic theory supports the existence of strong incentives for operators to internally regulate their activities in the nuclear sector. Given the high fixed costs of nuclear generation, operators will tend to maximise the availability of the plant and implement the necessary enhancements to reduce unexpected shutdowns. On the other hand, reduced availability can not only reduce potential revenues, but it can also undermine the reputation of the operator (and thus public perception) and even anticipate closure of the plant. Lastly, in the case of a major nuclear accident, the asset would be completely lost, leading to a significant

2. This means that any nuclear power plant currently in operation has approval from the national authority to operate since it complies with existing regulations; if not, the plant would be taken off-line and forced to implement the necessary corrective actions.

3. ENSREG performs topical peer reviews (TPRs) every six years (i.e. European Nuclear Safety Directive) and the topic examined is always a different one. The TPRs are carried out per country and not per nuclear power plant, as is the case for IAEA SALTO missions or their equivalents by WANO.

financial impact and jeopardising the global nuclear business as a whole (Lévêque, 2014). All of these aspects have pushed nuclear operators to create organisations such as the Institute of Nuclear Power Operators (INPO) in the United States and the World Association of Nuclear Operators (WANO), which today make significant contributions to improve nuclear operations worldwide (see Box 5.1).

- **Safety upgrades**: In most regulatory frameworks, the safety of the nuclear power plant is periodically reviewed, and operators must implement new safety upgrades in order to comply with the latest safety standards (see Chapter 5). The most recent example is the introduction of post-Fukushima safety measures to reinforce protection against extreme events potentially requiring accident management in harsh environments, extended loss of power and/or loss of cooling functions, and accidents simultaneously affecting multiple units (NEA, 2012b).

Box 5.1: **The role of INPO and WANO in the operational excellence of nuclear power**

INPO

Internal regulation of the nuclear industry started in the United States with the creation of INPO in 1979 – nine months after the Three Mile Island (TMI) accident – based on the recommendations of the Kemeny Commission. It was clear for US nuclear operators that the reputational risks associated with TMI could have important economic implications on the nuclear business, and that the industry should work together to achieve higher levels of safety and reliability. As a non-governmental organisation that operates on a non-profit basis, the mission of INPO is to promote excellence in the operation of the US commercial nuclear fleet. The core of its activity is to conduct on-site peer reviews called plant evaluations. The outcomes of these peer reviews are distributed among INPO members (note that the name of the plant is not typically included) as a way to share best practices and common weaknesses. Since 1980, INPO has carried out nearly 1 200 plant evaluations, meaning that each plant in the United States has been inspected at least 16 times, once every two years on average.

The success of INPO was not guaranteed when it was established in the 1980s. This type of industry-driven endeavour does not escape from the "free-rider" problem (Lévêque, 2014). In theory, some operators tend to be bad performers to avoid investments, benefiting nonetheless from the good image projected by INPO's good performers. However, INPO has somehow overcome these issues through peer pressure that drives change (Pate, Ellis, 2011).[4] Another powerful incentive provided by INPO to promote operational excellence comes from INPO ratings, which are used by the industry's collective insurance company, also known as Nuclear Electric Insurance Limited (NEIL). Since TMI, every operator requires an insurance from NEIL and, in turn, NEIL considers INPO membership as a condition for insurability. Depending on plant evaluation ratings, some operators may be subjected to higher insurance premiums, thus undermining the profitability of the plant.

WANO

Similar to INPO, WANO is a not-profit, international organisation with a mission to maximise the safety and reliability of the world's commercial nuclear power plants. It was established on 15 May 1989 after the Chernobyl accident, and its members operate 203 nuclear power plants in over 30 countries (WANO, 2020a). The organisation enables members to provide mutual support, exchange on safety knowledge and operating experience, and share best practices so as to improve performance through five main programmes: peer review, performance analysis, member support, training and development, and corporate communications.

The peer review programme provides a critical assessment of plant performance by an experienced team of global industry peers using nuclear industry standards of excellence as defined by the WANO performance objectives and criteria. A significant milestone was reached in 2009, with every commercial nuclear power plant in the world peer reviewed at least once.

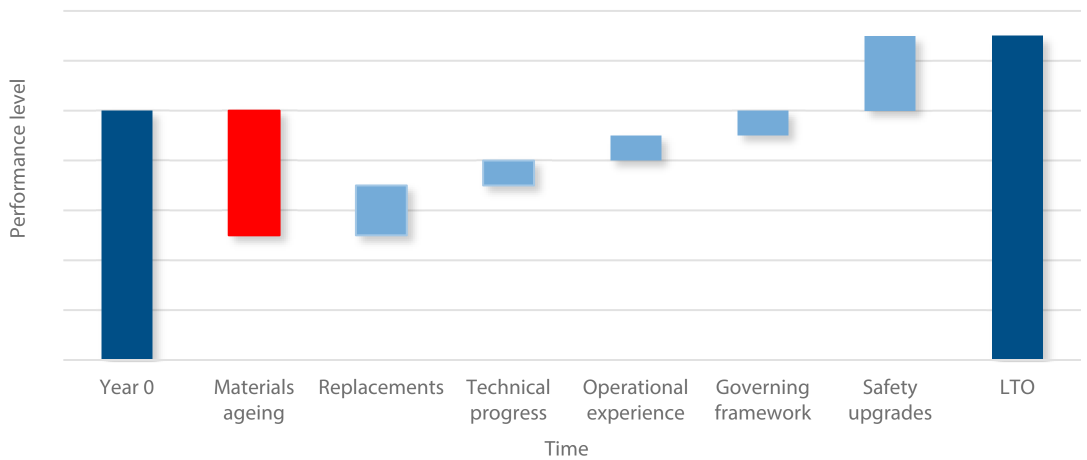
4. INPO's influence has led some operators to implement specific safety upgrades. In one notable case, a company's Board of Directors made changes in its executive leadership in response to escalating concerns pointed out by INPO concerning their corporate management's lack of responsiveness.

The performance analysis programme collects, screens and analyses operating experience and performance data, providing members with lessons learnt and industry performance insight reports, using an international electronic information exchange system. If particular concerns become evident, a special operating event report (SOER) is prepared and distributed among members. A SOER was prepared, for instance, six days after the Fukushima accident, and responses from WANO members were received within two months.

Overall, the benefits of regulation via the nuclear industry through organisations such as INPO and WANO are acknowledged. Countries fostering similar initiatives as part of their nuclear governing framework could observe safety and reliability gains for the existing fleet. To increase its effectiveness, internal regulation must be performed independently and in a complementary manner to the external oversight carried out by national regulatory oversight.

As a result, despite the negative effects of materials ageing, the combination of replacements, new technical progress (including enhanced ageing management programmes), an expansion of operational experience and additional safety upgrades may all lead to the restoration – or even enhancement – of overall performance levels during the LTO period (see Figure 5.1). The governing framework ensures that all these measures are implemented in a timely manner and are reviewed according to best international standards in order to continuously improve operations at the plant from a technical and organisational point of view. Existing Gen-II reactors can therefore be seen as evolving assets that are periodically retrofitted and enhanced for regulatory and economic reasons. In this sense, performance levels should not abruptly decline as long as the necessary investments and improvements continue to be carried out as part of the LTO programme.

Figure 5.1: **Qualitative evolution of the performance level of a nuclear power plant over time**



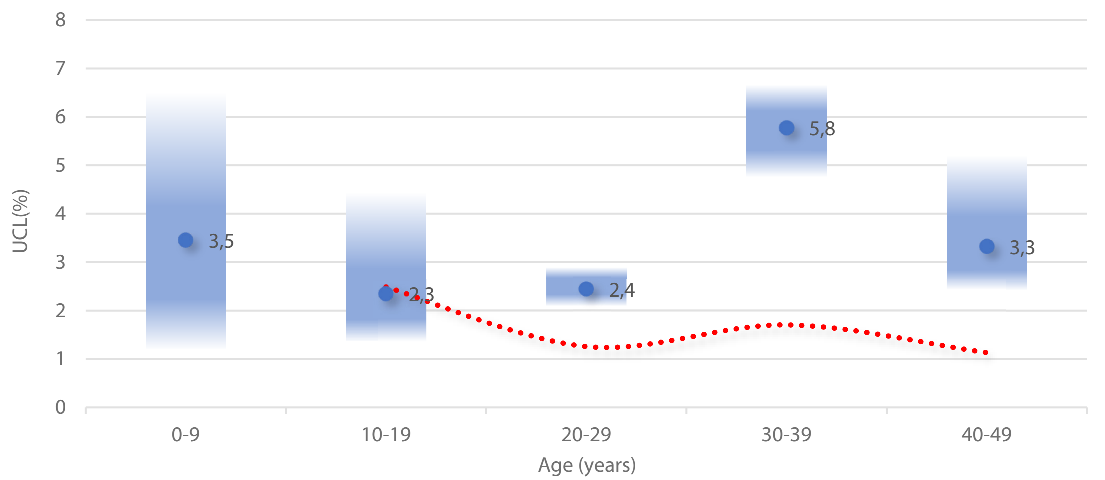
Furthermore, global performance indicators support the aforementioned trends and provide additional insight into the interplay between materials ageing and technical, as well as organisational, improvements in nuclear power plant operations (see Figure 5.2). Of particular importance is the evolution of the unplanned capability loss (UCL) factor[5] over time. UCL levels

5. Unplanned capability loss factor accounts for the energy that was not produced during a given period because of unplanned shutdowns, outage extensions or unplanned load reductions resulting from causes under plant management control. Energy loss is considered to be unplanned if it is not scheduled at least four weeks in advance (IAEA, PRIS).

for young plants are typically high and large variations can be observed. These variations are a result of the running-in period of the facility, during which several systems and procedures are progressively fine-tuned before reaching steady-state operating conditions. As operational experience develops, UCL rapidly declines and stabilises at a lower level. From 30 years of operation, ageing mechanisms tend to prevail over operational experience, driving UCL levels up again. Thanks to major replacements and plant enhancements taking place in preparation for LTO, performance levels beyond 40 years once again become close to those of 20 years before. The reliability of nuclear power plants may therefore follow a somewhat sinusoidal behavioural pattern, driven by SSC ageing, replacements and growing operational experience. Reactors entering LTO after major retrofits should observe lower unplanned outages (Kang, Krivanek, 2017).

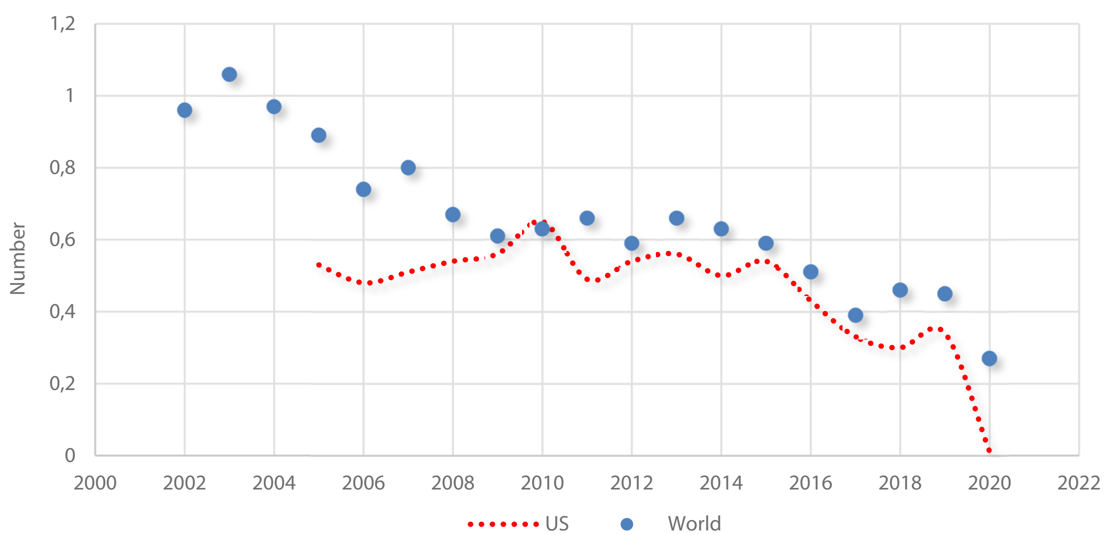
Figure 5.2: **Evolution of global performance indicators for the existing nuclear fleet, 2020**

Unplanned capability loss factor



Note: Each column captures the variability of UCL between 2015 and 2020 for a given age range. The point corresponds to the average value observed during this period.

Unplanned scrams per 7 000 hours critical



Source: OECD/NEA, using data from IAEA, 2021.

Similarly, the number of unplanned scrams per 7 000 hours critical provides indirect indications of how well a plant is being maintained and operated. According to the IAEA PRIS database, this parameter can be defined as the number of unplanned automatic/manual scrams normalised to 7 000 hours of critical operation. Its purpose is to monitor performance efforts to reduce the number of unplanned reactor shutdowns.

The decreasing trend for both indicators (see Figure 5.2) suggests that the factors presented in Figure 5.1 contribute to improvements in performance levels despite ageing. A comparison with US values – the oldest nuclear fleet in the world, with an average age of 40 years and showing similar patterns – reinforces this conclusion (see Figure 5.2). Similar trends can also be observed in WANO's global performance indicators (WANO, 2020b). More detailed evaluations considering actual plant conditions, as well as managerial and human aspects, may be needed to draw similar conclusions for individual plants.

5.2. The role of the supply chain

Utilities make continuous efforts to refurbish and modernise their nuclear power plants over the entire lifetime of the plant so as to meet regulatory requirements and to improve plant performance and economics. LTO therefore requires utilities to have access to a robust and reliable supply chain, capable of delivering high quality components and services. Thus far, the nuclear suppliers have proven their capabilities, with more than 30% of the existing fleet already operating beyond the initial design life (see Chapter 2). However, supply chain challenges like SSC obsolescence or difficulties of finding new suppliers are of rising concern, especially in those countries with a small installed nuclear capacity. Several strategies exist to mitigate supply chain risks and new approaches can be developed with the approval of regulators to sustain market opportunities while meeting stringent standards.

5.2.1. *The characteristics of the nuclear supply chain*

A unique characteristic of the nuclear supply chain is the high level of quality assurance and qualification efforts required to produce nuclear SSCs. Only the aviation sector works with a similar level of stringency and scrutiny. The quality and equipment qualification standards for SSCs are directly correlated with the safety requirements of the nuclear industry. SSCs in nuclear reactors must remain reliable under normal operation, plant transient conditions (e.g. reactor start-ups or shutdowns) and even design-basis accidents (DBAs). Depending on their functions and their significance for plant safety,[6] SSCs can be classified in three different safety classes (SC) (IAEA, 2014):

- SC1: any SSC for which failure would lead to consequences of "high" severity;
- SC2: any SSC for which failure would lead to consequences of "medium" severity;
- SC3: any SSC for which failure would lead to consequences of "low" severity.

Safety-classified SSCs are subject to specific nuclear codes and standards (NC&S). They define, in a comprehensive manner, the requirements for the design, manufacturing, installation, commissioning, operation, and maintenance of safety-classified SSCs in accordance with their expected level of safety and performance. According to NC&S, SSCs are referred to as "nuclear grade".

The first NC&S were developed in the 1960s-1970s since conventional industry standards in those days were not adapted to meet the requirements of the nuclear industry, in particular in terms of quality control (QC) and quality assurance (QA). A number of countries with domestic nuclear power programmes developed NC&S (sometimes for specific reactor designs)

6. This includes, for instance, their capabilities to prevent accidents and/or limit the radiological consequences of accidents should they occur.

to primarily serve their national industrial needs. Some examples include Boiler and Pressure Vessel Code (BPVC) Sections III and XI of the US American Society of Mechanical Engineers (ASME), and the French "Règles de Conception et Construction" (RCC) series, developed by AFCEN.[7] In some countries, specific NC&S are mandated by national nuclear regulations (e.g. ASME BPVC in the United States and Slovenia).

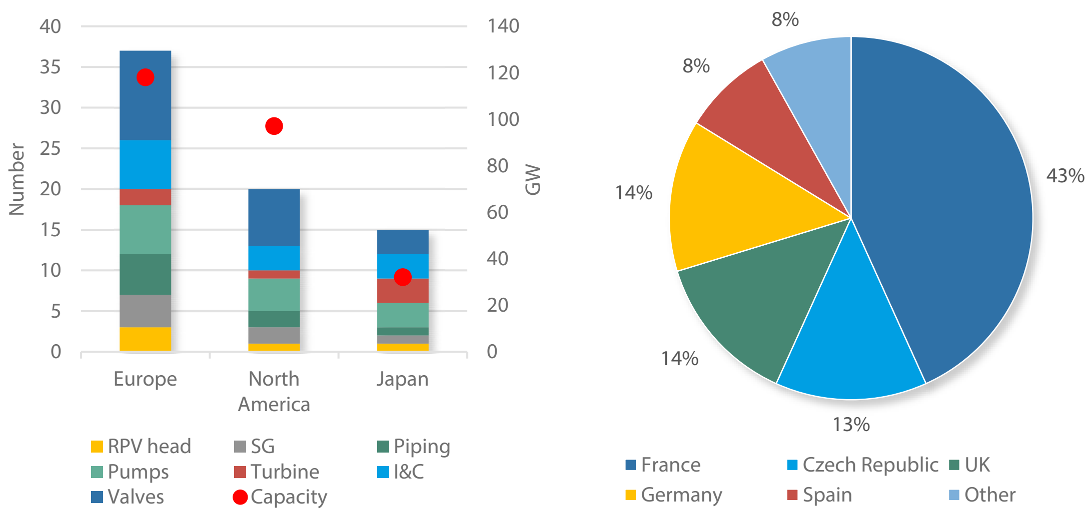
At the same time, supplying nuclear-grade SSCs requires the supplier to establish a nuclear QA programme (e.g. ASME NQA-1) with the corresponding certification. In some cases, this certification needs to be renewed periodically (e.g. in the United States). This results in significant qualification efforts for the suppliers, which require a sufficiently large order book over time to become economically attractive.[8]

The diversity of NC&S poses a challenge for the nuclear industry. Running a nuclear QA programme for a specific NC&S allows the supplier to only produce SSCs that comply with one specific set of rules, which artificially limits the available pool of suppliers.

5.2.2. *Global trends and challenges for LTO*

The nuclear industry is composed of more than 100 companies, providing key nuclear SSCs worldwide (WNA, 2020). A significant number of suppliers produce nuclear-grade valves, pumps, I&C systems and piping. These SSCs can also be found in other industrial sectors, which increases market opportunities for suppliers. Companies supplying heavy conventional SSCs (e.g. turbines) and SSCs for the nuclear steam supply system (e.g. vessel head, steam generators) are less numerous, resulting from both a need for economies of scale and lower demand prospects for such specific components. Over time, competitive pressures have led to higher levels of consolidation and localisation in the nuclear supply chain (NEA, 2015). Europe, Japan and the United States represent together more than 65% of the world's nuclear fleet (IAEA, PRIS) and these regions still have local suppliers for all of the key SSCs. The size of the industry is also proportional to the installed capacity (see Figure 5.3). While the industry remains weighted towards domestic markets, most of the leading vendors are internationally diversified in terms of corporate make-up and supplier structure.

Figure 5.3: **Main nuclear suppliers by region and component versus installed capacity (left) and distribution of main suppliers in the European region (right), 2020**



Source: OECD/NEA, using data from WNA (2020).

7. "Association française pour les règles de conception, de construction et de surveillance en exploitation des matériels des chaudières électro-nucléaires".

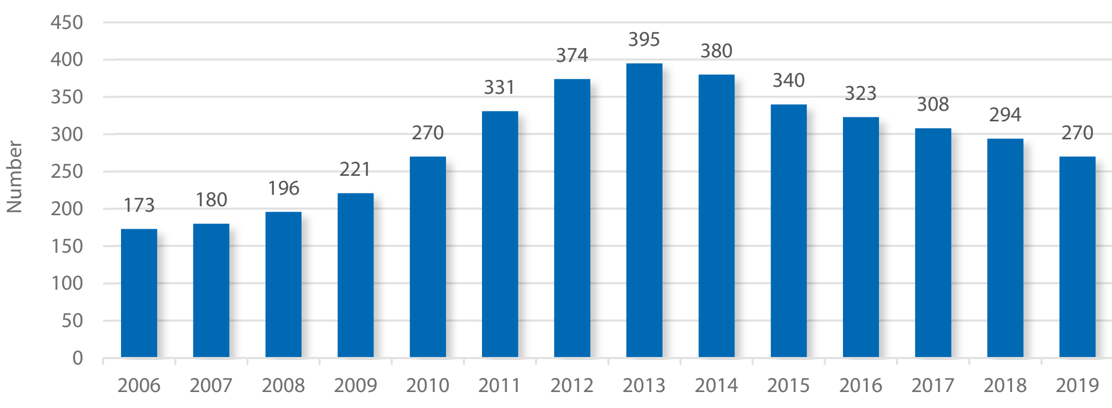
8. Experience from the United States after the Three Mile Island accident shows that suppliers can drop their QA programme in the absence of favourable market prospects.

Thus far, this industrial base has enabled LTO for more than 30% of the existing nuclear fleet and provided a constant inflow of components for regular maintenance. This volume of activity has also served to develop significant industrial capabilities for LTO projects, which has led to a low risk profile that increases the economic attractiveness of LTO projects (see Chapter 6). Around 140 reactors are projected to undergo licence extensions, representing USD 4 billion of investments per year on average (i.e. 30% of the total nuclear investment levels as of 2020) until 2040 (WNA, 2020). These projections will positively contribute to sustaining industrial capabilities over time.

Some regions are nevertheless facing reduced market perspectives (i.e. early capacity retirements) that, combined with the high qualification needs and policy uncertainties, are increasing nuclear supply chain challenges in two ways:

- **SSC obsolescence**: A significant number of original equipment manufacturers (OEMs) have stopped producing nuclear-grade SSCs or have even left the nuclear sector altogether. For some critical SSCs, the OEM may even no longer exist. This is the case in particular for analogue I&C systems of nuclear power plants. (IAEA, 2016). Consequently, utilities are increasingly confronted with obsolescence issues that could become more critical in the near term, in the absence of strategic measures and with an increasing number of reactors being operated for longer periods.
- **Reduced pool of qualified suppliers and the difficulty to find new suppliers**: There were about 400 companies holding an N-type certificate from ASME in 1980, mostly in the United States. Today, most N-type certificate holders are found outside the United States, and the overall number has been in steady decline by about 5% per year since 2013, from 395 to 270 in 2019 (WNA, 2020). Furthermore, the regulatory hurdles to adopt modern state-of-the-art technologies for safety-classified SSCs in nuclear power plants poses a barrier to entering the nuclear sector for the suppliers of such technologies. Modern state-of-the-art technologies may only be deployed for safety-classified SSCs after extensive qualification and their inclusion in existing NC&S.

Figure 5.4: **Companies holding an N-type ASME qualification, 2006-2019**



Source: OECD/NEA, using data from WNA (2020).

These supply chain challenges are forcing nuclear operators to postpone replacement and to choose "elaborative maintenance" and repairs of installed SSCs as the preferred strategies. If "elaborative maintenance" is not possible, operators need to replace installed SSCs, preferably as like-for-like replacement, which could involve reverse engineering, if necessary. Replacement with modern SSCs of improved functionality (not like-for-like) could be an option if this leads to additional benefits in terms of functionality and costs. This option normally requires lengthy design modification and associated equipment qualification processes.

It is important to highlight that not all countries are equally affected by supply chain challenges (Martin, Abbt, 2020). Depending on the configuration of their nuclear fleet in terms of installed capacity and standardisation levels, a great variety of situations, strategies and even specific opportunities exist (see Box 5.2).

Box 5.2: **The role of the size of the nuclear fleet and standardisation levels in the supply chain: Overview of national opportunities and challenges**

Existing nuclear capacity was developed through the adoption of different national strategies that may have consequences in the supply chain today. Those countries that envisaged large nuclear programmes had strong economic incentives to build domestic capabilities as a way to reduce costs while boosting the national economy. Around 45% of nuclear suppliers in Europe are from France (see Figure 5.4), the country with the largest nuclear fleet in Europe. At the same time, building large numbers of the same reactor is an opportunity to harness the benefits of standardisation. Standardisation is an industrial strategy aimed at increasing the efficiency of the supply chain through the homogenisation of design and transactions. Productivity and quality levels are thus substantially increased by the greater volume of production of identical components. Qualification needs are also limited to a unique standard, which enables the development of a larger pool of suppliers, as well as long-term contracting.

On the other hand, countries with reduced nuclear construction plans found it more convenient to take advantage of foreign supply chains with more developed capabilities. While this provided a clear economic advantage by avoiding the huge costs associated with the development of domestic nuclear power plants, these countries became dependent on technology suppliers and their NC&S.

In general, countries with low installed capacity, involving different reactor designs and/or single-unit nuclear power plants, are the most vulnerable to supply chain risks. In contrast, countries operating large nuclear fleets of standardised reactors are far less affected. In these countries, orders are larger in volume, more frequent and more predictable. Experience shows that high levels of standardisation offer significant business opportunities for suppliers. Two bounding cases can be found, with a variety of national realities and strategies in between:

- Small nuclear programmes mainly with single-unit nuclear power plants and different reactor designs. Examples are Switzerland (LWRs) and Argentina (PHWRs).
- Large nuclear programmes with multi-unit sites having the same or similar reactor designs. Examples are France (PWRs) and Canada (PHWRs).

Small nuclear programmes mainly with single-unit nuclear power plants and different reactor designs

Switzerland (LWRs)

As of 2020, Switzerland operated four nuclear reactors at three sites, representing a total of 3 GW of installed capacity:

- Gösgen: Siemens-KWU PWR 1 100 MWe;
- Beznau units 1 and 2: Westinghouse, PWR 2 Loop 2 x 365 MWe;
- Leibstadt: GE, BWR 6 Mark III, 1 220 MWe.

Swiss reactors respresent different LWR designs from different vendors. Gösgen nuclear power plant was designed and built according to German KTA standards, which were no longer developed following the nuclear phase-out decision in Germany. Beznau and Leibstadt were designed according to the American ASME Boiler and Pressure Vessel Code (BPVC). Consequently, Switzerland is a country where a small number of reactors of different designs and NC&S cohabit, creating a challenging context for the supply chain.

Existing, preventive maintenance strategies and procurement processes are facing increasing obsolescence issues, which is requiring more efforts than in the past. In most cases, the original equipment can be procured, but reverse engineering approaches have already been used in the past for specific SSCs.

Swiss regulations also allow for the use of non-nuclear industrial standards for SC3 components as long as the original design is based on such standard. Further, industrial experience already exists with these types of approaches. The use of alternative NC&S to ASME BPVC and KTA standards for SC1 and SC2 SSCs could also be envisaged, but it would require additional efforts to demonstrate the compliance with design rules. Swiss utilities have also adopted a common supply chain management strategy with the objective of increasing bargaining power, economies of scale and scope, and of enabling more competitive orders.

Argentina (PHWRs)

Argentina has three PHWRs, Atucha I, Atucha II (both Siemens-KWU) and Embalse (CANDU reactor), run by the state-owned company, Nucleoeléctrica Argentina S.A. (NA-SA). One of the most recent projects was the licence extension of the Embalse unit for 30 additional years. Since its inception, the Argentinian nuclear energy programme has promoted high levels of local participation, despite the reduced number of projects. The Embalse LTO project was thus essentially designed to be executed using local capabilities.

The main challenge was to convince local suppliers to qualify their processes so as to produce nuclear-grade components, especially after a 12-year hiatus from nuclear construction. The Argentinian government rapidly introduced an attractive policy framework that encouraged suppliers to ramp up nuclear capabilities based on new, future perspectives. At the same time, NA-SA adopted a project strategy that included the qualification process in the contracts with the main suppliers. The selected companies were required to obtain a certificate of authorisation to start the manufacturing of nuclear components (ASME from the United States or TSSA from Canada). Throughout the process, the suppliers were technically assessed by the design provider as part of the technology transfer agreement, which was surveyed by the owner with permanent QC at the shop, and audited by the regulator during key milestones. The project also benefited from experience gained in the construction of the Atucha II reactor.

As a result, activities such as steam generator and moderator heat exchanger replacements and balance-of-plant modifications were implemented with less than 15% of foreign support specialists. The personnel were also trained using 1:1 scale mock-ups, and supervised by NA-SA for critical welding and tubing conforming processes. These localisation efforts increased the overall costs of the project compared to other PHWR refurbishments, but they should bring long-term benefits for future nuclear projects (e.g. LTO of Atucha II).

Large nuclear programmes with multi-unit sites having the same or similar reactor designs

France (PWRs)

In total, France has 56 reactors in operation with an installed capacity of 61.3 GW. One of the unique characteristics of the French nuclear fleet is its high level of standardisation, with the development of three generic PWR series[9] of 900 MWe (32 reactors), 1 300 MWe (20 reactors) and 1 450 MWe (4 reactors). Different designs cohabit within each series, but the differences are very limited (i.e. position of the turbine hall), which ensures the overall standardisation of the series.

The French regulatory framework imposes an in-depth periodic safety review (PSR) every ten years to renew the operating licence. PSRs typically require new safety studies and the implementation of safety upgrades, which results in a significant amount of work that is easily predictable by the suppliers, thus mitigating supply chain risks.

Furthermore, most of the reactors in the 900 MWe series are set to operate until 50 years upon the requirements specified by the French regulator (ASN, 2021), with additional LTO investments already undertaken. Work to secure a 10-year licence from 30 to 40 years of operation for the 1 300 MWe series is also underway. EDF decided to structure all these activities under a specific programme called the “Grand Carénage” (i.e. the “Major Refit”), gathering around 20 projects with a total investment of EUR 49.4 billion (EDF, 2020). This programme takes full advantage of the standardisation benefits in relation to the French fleet thanks to:

- generic studies and proposals for modifications by series;
- generic regulatory oversight by series, complemented by on-site verifications and authorisations for each unit;
- long-term contracts with key partners for several units.

9. A fourth series is under development with the construction of the first EPR, Flamanville 3.

The Grand Carénage is also an opportunity to boost the national economy while also benefiting from the skills and expertise developed by the French nuclear industry over many years. EDF engineering centres place orders with local or nationwide industrial partners, establishing long-term partnerships with these contractors. [10] Given the size of the internal market, EDF can also adopt strategies aimed at finding a compromise between sustaining domestic capabilities while increasing competition to reduce costs. In fact, French companies often bid alongside foreign suppliers for EDF offers.

Canada (PHWRs)

As of 2020, Canada had 19 nuclear reactors in operation, representing an installed capacity of 13.5 GW. These reactors are distributed among four main nuclear sites. The Canadian nuclear programme is based on the domestic PHWR CANDU design. The two biggest nuclear power plants in the country in terms of capacity are the Darlington (3.5 GW) and Bruce (7.8 GW) nuclear power plants. Both host CANDU reactors with power outputs between 750-900 MWe and with important levels of design standardisation.

Both nuclear power plants are planned to undergo major refurbishment in order to enable operations for 30 additional years, for a total cost of CAD 24 billion. Works started at Darlington unit 2 in 2016 and are scheduled to finish by 2026 with unit 4. Refurbishment at the Bruce nuclear power plant will take place between 2021 and 2033 and will involve six units. The period of highest stress for the supply chain corresponds to 2021-2024, with five reactors simultaneously undergoing major refurbishment. The two main nuclear operators in the country, Ontario Power Generation and Bruce Power, have already expressed their shared desire to work in a co-ordinated manner so as to enhance supply chain performance and minimise potential risks (Bruce Power, 2016). Areas of collaboration include sharing lessons learnt on retubing activities, leveraging economies of scale through joint procurement, the creation of shared tooling for CANDU refurbishments, and scheduling and critical resource planning optimisation to avoid supply bottlenecks.

5.2.3. *Enhancing supply chain capabilities for LTO*

Increasing nuclear supply chain challenges could seriously hamper the ability of some countries to ensure the LTO of nuclear power plants. International safety standards such as those developed by the IAEA already include guidelines to effectively deal with the obsolescence of safety-related SSCs (IAEA, 2018). As part of the LTO-programme, operators can also adopt a programmatic approach, allowing for the identification of obsolete SSCs and the implementation of maintenance, engineering and supply chain management strategies. Their objective is to increase the pool of suppliers and drive costs down through keener competition, while maintaining (or even increasing) the quality and reliability of SSCs. The selected approaches may vary depending on the safety class (and thus the QA standards) of the SSCs, as well as on the situation of the country, as described in Box 5.2.

Increasing the number of industrial/commercial grade components

A growing number of utilities are using commercial components and equipment to operate as safety-classified SSCs, thanks to the introduction of commercial-grade dedication (CGD). This process provides reasonable assurance that the commercial item (i.e. the industrial-grade component or equipment) delivers its safety function when used in a nuclear facility. The dedication process is normally performed by the utility or a competent third-party organisation acting on behalf of the utility. [11] CGD enables companies that normally do not produce nuclear-grade items to supply the nuclear sector, without the need to run a costly nuclear QA programme, hence increasing the pool of suppliers for utilities. Table 5.1 provides an overview of QA requirements for nuclear-grade items versus commercial items.

10. The tube heat exchangers installed at the Tricastin-1 unit as part of its fourth decennial outage were manufactured, for example, using a new high-tech alloy developed in Lyon. A factory located in Mantes-La-Jolie was in charge of the production of several nuclear-grade pumps that were replaced in the reactor.

11. Typically, reactor vendor companies running a nuclear QA programme.

Table 5.1: **Potential classification of nuclear components according to their quality assurance requirements**

Nuclear-grade components		Industrial-grade components
Safety-classified items	**Safety-significant items**	
Enhanced quality assurance programme is mandatory.		Quality assurance programme may be required.
Production process is subject to inspection verification or testing. Defects or non-compliance must be reported and corrected.		Good commercial practice required. Analysis of past performance required.
Performance testing according to specified codes or standards is required.	Performance testing according to special codes or standards is required.	Performance testing according to specified codes or standards may be required.

Source: Adapted from NEA, 2015.

The Slovenian utility, NEK, operating the single-unit Krško nuclear power plant, is a good example to demonstrate the benefits of a well-established CGD process.[12] Utilities and licensees in the Czech Republic, Finland and Sweden are currently implementing CGD and running the corresponding pilot projects in close interaction with regulators (see Box 5.3 below). Swiss utilities (see Box 5.2) and the Belgian utility ENGIE-Electrabel have also undertaken some CGD trials in the past for a limited number of SSCs. These initiatives provide valuable experience for utilities seeking to enhance their supply chain capabilities for LTO through CGD processes. It is nevertheless important to highlight that CGD requires regulatory approval, and existing nuclear regulations may need to be adjusted in most countries before CGD becomes a common practice in the nuclear industry.[13]

Box 5.3: **The KELPO project**

As part of the discussions on the necessary preconditions for LTO in Finland, in 2018 the industrial consortium led by the Fortum, TVO and Fennovoima utilities launched the KELPO project. Its main objective is to reinforce national supply chain capabilities by developing new procedures to license and qualify high-quality industrial SSCs for nuclear installations, based on the experience of other industries (Fortum, TVO, Fennovoima, 2019). This initiative benefits from the approval of the national Finnish regulator, STUK, also participating as an observer.

The KELPO project consists of three phases. Phase 1 was finalised in 2018 and led to a potential redefinition of responsibilities with regard to the supervision of the manufacturing and QC/QA of safety-classified SSCs as shown in Table 5.2. While the regulator, STUK, will continue to have a leading role at the plant and system levels for SC1 and SC2 SSCs, the proposed framework encourages utilities to take a more active role in the process, especially for low SC SSCs and at the device level. For SC3 devices and components, the utility could be fully responsible with the option of involving a specialised third-party organisation.

12. NEK has been successfully using CGD processes since 1995. It follows EPRI guidelines consistent with US practice and other international nuclear industry groups dealing with SSC obsolescence and searching for dedicated solutions. As a result, NEK has considerably mitigated supply chain challenges, despite operating only a single unit nuclear power plant.
13. The use of non-nuclear SSCs for low SCs may be possible after additional specific testing (e.g. seismic standards), but higher SCs will continue to require additional efforts.

Table 5.2: **Proposed new roles for regulatory approvals of plant-, system- and device level design and manufacturing oversight for nuclear SSCs according to the KELPO project**

	SC1	SC2	SC3
Plant level	STUK	STUK	STUK
System level	STUK	STUK/Utility	STUK/Utility
Device level	STUK	AIO/Utility	Utility or third party

Note: The authorised inspection organisation is an organisation that conducts tasks related to the conformity assessment, and approval of the design and manufacturing of components and structures in nuclear facilities on behalf of the regulator, which in this case is STUK.

Source: Martin, Abbt, 2020.

Additional outcomes of Phase 1 include measures such as:

- Increasing collaboration among national utilities (similar to the Canadian case in Box 5.2);
- Avoiding duplications;
- Utilising common approvals;
- Defining common and coherent documentation for safety-classified SSCs;
- Developing a qualification and dedication process with a focus on SC2 and SC3 SSCs.

The aim of phases 2 and 3 is to prove the viability of the new qualification and dedication process in relation to a number of selected components, such as a valve (i.e. mechanical component), a battery (i.e. electrical device) and pressure transmitters (i.e. automation devices). The experience gained should then be used to develop a common qualification and dedication process for all Finnish utilities. Moreover, the evidence collected by STUK throughout the different phases of the KELPO project could inform potential adjustments in terms of Finnish regulations.

Lastly, the KELPO project also represents a great opportunity to engage with other interested countries (e.g. Sweden) and make additional contributions towards more harmonised licensing practices at the EU level.

Since CGD processes shift dedication activities away from the supplier to the utility, or to a third-party organisation, some upfront investment by utilities may be required to build the necessary skills for their adoption. These efforts should nevertheless be outweighed by the benefits over the long term. Another possibility is to perform CGD processes for individual components and equipment in a collaborative and cross-border manner, involving utilities from different countries. This could include, for instance, the joint issuing of technical specifications for SSCs to be procured and data sharing of qualification and dedication tests.

Lastly, the use of high-quality, non-nuclear industry standard components and equipment for safety-classified SSCs in nuclear installations could bring benefits for nuclear safety. Risks and additional costs for first-of-a-kind designs could be avoided as suppliers are allowed to use the industry standards and manufacturing methods with which they are most familiar. The possibility of common cause failures could also be reduced given the potential opportunities to deploy commonly used components and equipment with long-term experience from other industries. More importantly, the timely and correct replacement of SSCs could be facilitated, reducing the number of unexpected shutdowns and improving the overall safety and reliability of nuclear power plants.

Higher collaboration and harmonisation levels

Utilities planning to undertake major refurbishments should consider working closely with key suppliers from the early stages of the LTO programme as a way of anticipating and mitigating supply chain risks. Recent experience from countries like France (see Box 5.4) and from new nuclear build[14] show that collaboration between utilities and suppliers is a key factor of success, especially for companies that are new to the nuclear industry. Contracts between utilities and suppliers can be designed with the right incentives so as to drive the performance of all the involved parties and not simply to primarily protect the individual interests of the companies when issues arise (e.g. quality flaws). The commercial interests of stakeholders also need to remain aligned throughout the project in order to avoid adverse impacts on delivery.

In parallel, greater collaboration can be pursued as a way to increase the competitiveness of the supply chain, particularly for high SC SSCs. Utilities in different countries could explore, for instance, the joint cross-border qualification of suppliers in order to avoid any duplication of efforts. SSCs with a good operational record should be easily transferable to other countries (if they technically fit into the plant system configuration) with fewer extra qualification efforts, which could ultimately result in several NC&S being used in the same country or even in the same nuclear power plant. While mixing various NC&S is, in general, not considered good practice, there may be no other option in some cases.[15] The use of different NC&S is something already being done in Belgium, and the corresponding regulatory guidance exists. At the same time, the adoption of SSCs that have been produced with alternative NC&S is not formally forbidden in most countries. Extensive work, however, is likely to be required to prove to regulators that alternative NC&S can deliver similar SSC quality and reliability without compromising safety (Martin, Abbt, 2020).

Another option involves increasing harmonisation levels of existing NC&S through international collaboration. In general, the different NC&S are similar in scope but differ in the detail of and emphasis on certain items. At the same time, there is a general understanding that each NC&S is a complete set of rules on its own basis, whose sections are interrelated and interdependent. In this sense, complete harmonisation may be unrealistic – and in some respects, undesirable. It is possible, however, to identify some areas where meaningful common positions can be achieved. Three major, ongoing international harmonisation initiatives include:

- **Cooperation in Reactor Design Evaluation and Licensing (CORDEL)**: Since its creation by the World Nuclear Association in 2007, this initiative has made significant efforts to benchmark existing NC&S and identify potential areas of harmonisation. CORDEL also works closely with the Standards Development Organisations Convergence Board[16] to achieve greater convergence of existing NC&S.
- **CEN Workshop 64**: This project is run under the umbrella of the European Committee for Standardization (CEN)[17] with the purpose of making recommendations on the further evolution of AFCEN codes (i.e. the French RCC series) and the required underlying research. The CEN Workshop 64 opens up the development of the AFCEN codes to the nuclear stakeholders of other EU member states in order to achieve higher levels of versatility.
- **Nuclear Quality Standard Association (NSQA)**: Founded by Bureau Veritas and Framatome (formerly AREVA NP) in 2010, NSQA efforts have resulted in the publication of ISO 19443. This standard provides specific requirements to suppliers of safety relevant SSCs in relation to the application of ISO 9001 (Naden, 2018) and combines the best practices in quality management, including ISO 9001:2015, IAEA GSR part II and ASME NQA-1. ISO 19443 also harmonises a minimum level of requirements, covering many regulatory, industrial, national and international rules. As most companies are familiar with the ISO 9000 standards family, the qualification process and subsequent audits are accelerated. In order to achieve wide applicability of ISO 19443, further efforts may be needed in the accreditation process of certification bodies, implementation oversight among different tier suppliers and the definition of a wider set of criteria for qualification. Management of this process by the industry, with the endorsement of regulatory bodies, is a key element for the possible implementation of the quality management standard.

14. This is the case, for instance, for the Hinkley Point C EPR project in the United Kingdom (Owen, 2018).
15. For example, if the nuclear power plant design is based on a NC&S that is no longer maintained. This is the case of German designs using KTA standards.
16. An assembly of standard development organisations, including ASME and AFCEN.
17. The acronym represents the French *"Committee European pour Normalisation"*. This organisation is in charge of developing and maintaining European standards.

Supply chain management considerations

Supply chain management starts at the nuclear power plant operator level. Maintenance and procurement services should include processes and methodologies to continuously evaluate existing stocks of spare parts for critical SSCs, identify and track obsolete components and renew suppliers when necessary. Good practices also cover the development of strategic contracts to sustain the capabilities of key suppliers, and securing a hoarding stock by buying appropriate quantities of key items if the supplier plans to cease production.

A single player in the market, operating just one or two nuclear reactors, may find some difficulties in generating enough demand to create attractive market conditions. This low bargaining power could potentially lead to higher prices, and thus the overall competitiveness of the company is undermined. Under such circumstances, various utilities can join forces to develop a common supply chain strategy in order to avoid work duplication, streamline processes and set new standards for supply chain management, as well as reduce costs and share risks through economies of scale[18] and scope.[19] Joint supply chain strategies have been developed in Canada (see Box 5.2) and are one of the key findings of the KELPO project to overcome supply chain issues (see Box 5.3).

Reverse engineering and plant modernisation

When the specific SSCs created by the original equipment manufacturers (OEMs) are no longer available in the market and/or the aforementioned measures do not yield the expected results, utilities can also envisage two additional strategies: reverse engineering and plant modernisation.

According to EPRI, reverse engineering can be defined as "the process of developing technical information sufficient to duplicate an item by physically examining, measuring, or testing existing items; reviewing technical data; or performing engineering analysis". Guidelines already exist on how to perform reverse engineering in nuclear power plants (EPRI, 1998). The process starts in a similar manner as that of procuring any other item (e.g. choosing a supplier, defining technical and quality requirements), but requires close collaboration between vendors or suppliers and operators to collect high-quality information concerning the component so that it can be reverse engineered.[20] If this information is not available, additional exams and measurements may be needed. Therefore, replacements based on reverse engineering approaches typically cannot be considered as like-for-like replacements, and additional item equivalency evaluations are necessary (IAEA, 2016). For these different reasons, reverse engineered components may come at an important cost penalty for one single nuclear power plant. The emergence of new manufacturing and digitalisation technologies (e.g. additive manufacturing) is also increasing the attractiveness of reverse engineering approaches. In the Krško nuclear power plant in Slovenia, a 3D-printed impeller for a fire protection pump was manufactured using design data collected through the examination of obsolete components (WNN, 2017).

In some cases, the most cost-effective alternative for operators is to undertake major modernisation programmes in order to introduce new components consistent with the latest state-of-the-art technology, which provides more functionality and is supported by a larger pool of suppliers (e.g. replacing analogue by digital I&C). As highlighted in Chapter 3, plant modernisation approaches can also bring cost and reliability benefits. Proposals should consist of solid economic justifications and risk assessments associated with the introduction of the new technology.

18. Reduction of the unit cost of a product or a service based on the inverse relationship between the volume of production and fixed costs per unit in a company. Utilities undertaking a common supply chain strategy can reduce the incidental cost for both the contractor and the purchaser as a result of an increased demand of products and services. The specific tooling and machinery necessary for LTO refurbishments can also be developed jointly and amortised through a greater number of projects. The higher volume of joint orders also increases the bargaining power of utilities, potentially leading to more attractive prices for SSCs.

19. Economies of scope occur when producing a wider variety of goods or services in tandem is more cost effective for a firm than producing less of a variety, or producing each good independently. Utilities can share the costs of developing diversified suppliers, providing the variety of products necessary for LTO.

20. Typical information includes the original procurement specification, drawings, historical performance data, operating environment conditions and interfaces with other systems.

The use of modern, state-of-the-art technologies (e.g. additive manufacturing, advanced analytics) for safety-related applications is only possible if these technologies are already covered by the applicable NC&S, or have undergone an extensive qualification process. Their adoption may be easier for low SC SSCs not belonging to the nuclear island (Martin, Abbt, 2020).

5.3. Nuclear workforce and competence assessment

Supply chain concerns related to the production of safety-classified SSCs can also be extended to the nuclear workforce. Similar to the aforementioned high qualification needs, excellence in nuclear skills requires time, investment and training. While operators and regulators have been somewhat successful in planning and replacing an ageing workforce,[21] attracting and retaining the best talent is becoming more difficult given increasing political uncertainty and degraded perspectives in the nuclear sector. The situation could worsen as longer operational lifetimes are being envisaged, ultimately undermining the ability of operators to sustain operational excellence and economic performance. Again, aspects such as the scale of the nuclear programme can facilitate human resource management. However, the particular characteristics of nuclear knowledge need specific long-term strategies at all levels to ensure the timely availability of a skilled workforce. Many international organisations have been active over the years, attempting to foster collaboration in nuclear human resource planning, knowledge management and building robust international academic networks.

5.3.1. Nuclear knowledge and knowledge management

Working in the nuclear industry is a knowledge-intensive activity. A significant amount of training, specialised studies, experience and managerial skills is required in order to perform at the highest levels of safety and quality expected by the industry, regulators and the public. Operating and modernising a nuclear power plant, in particular, involves considerable skills and interrelated disciplines[22] that, in most cases, require long time frames to be properly mastered.[23] The high level of technical and managerial skills is not limited to the nuclear power plant itself, and must be extended to regulators and suppliers that ensure excellence throughout the entire value chain. A closer look at the different types of education, qualification and skills needed in the nuclear energy sector leads to the following classification of the nuclear workforce (see Figure 5.5):

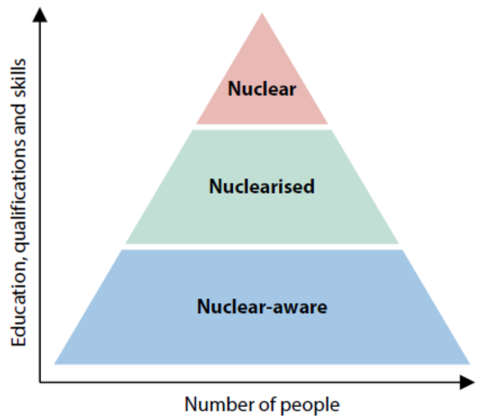
- **Nuclear-aware**: generic skills gained through vocational training or professional qualifications;
- **Nuclearised**: a tertiary education in science, technology, engineering and mathematics (STEM) disciplines;
- **Nuclear**: specialists who have a tertiary education qualification in nuclear energy and nuclear-related subjects, and who possess specialised skills that take a considerable amount of time to acquire. These specialists include leading experts who have developed broad knowledge and experience in the nuclear field and are able to tackle challenges and resolve problems, as well as steer and lead organisations.

Efforts are required at all levels of the pyramid to sustain nuclear capabilities over time. The long cycles associated with nuclear knowledge are, moreover, particularly unique and need specific planning. A nuclear power plant engages a local community for around one century, with the operating phase representing 60 years[24] or more, if LTO is undertaken. This time frame is longer than the professional career of a single person. Human resource planning and knowledge management thus become critical at some point in the life of a nuclear power plant.

21. Similar to supply chain issues, countries with a small nuclear fleet, with an uncertain policy and market context, may generally face more difficulties in replacing an ageing workforce.
22. Fundamental and nuclear physics, plant operation, fluid mechanics, thermo-dynamics, chemistry, materials science, electricity, electronics, etc.
23. Nuclear experts generally hold high-level qualifications, such as an MSc or PhD.
24. Including the preparatory and infrastructure development phases (10-15 years), construction (5-10 years), operation (60 years) and decommissioning (15-20 years).

According to the IAEA (2012), knowledge management is "the integrated, systematic approach for identifying, managing, sharing and transferring an organization's knowledge and enabling persons to create new knowledge collectively and thereby help achieve the objectives of that organization." One of the main challenges of transferring knowledge is that most of this knowledge is generated in a tacit[25] manner within organisations (Dudézert A. et al. 2012). Tacit knowledge is the result of experience, trial and error, human interactions and work practices, and thus it is inseparable from individuals and difficult to transfer. When personnel leave an organisation, the loss of human capital can lead to operational disruptions and lower performance. Consequently, those organisations that rely heavily on knowledge are more vulnerable and require a critical mass of activity that ensures a constant inflow of skilled workers in order to minimise the risks associated with turnover (NEA, 2020). Countries with large nuclear programmes may face less difficulties in maintaining an adequate volume of work to sustain skills. Knowledge management can also be used to properly mobilise people, technologies and processes to effectively transfer tacit knowledge to new staff.

Figure 5.5: **Pyramid of competencies and skills for the nuclear industry workforce**



Source: NEA, 2020.

5.3.2. *Global trends and challenges*

As a general trend, the workforce in the nuclear field is ageing. Personnel that gained unique experience during the commissioning and operation of the nuclear fleet in the 1970s and 1980s have already retired or are close to retirement. The majority of the workforce is older than 40 years of age, and it is estimated that around 20% of the workforce will retire in the next 10 to 20 years (NEA, 2020b). Retirement, however, is not specific to the nuclear power industry, as it affects every industry and can be properly managed if planned in advance. What requires specific attention in the case of the nuclear sector is the high reliance on knowledge across the value chain, which may exacerbate operational issues induced by retirement.

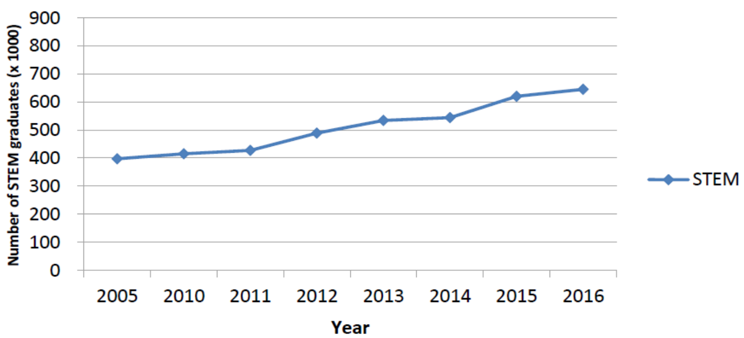
To date, there is evidence suggesting that the nuclear industry has been capable of renewing its personnel and transferring knowledge generated over the years. A survey performed by the Nuclear Energy Institute (NEI) in 2015 for the US nuclear industry showed a broadening of age distribution, with the number of employees in the 48- to 57-year-old range in continuous decline (Reuters, 2015). In France, EDF has also been successful in overcoming retirement issues by assessing workforce ageing over the past 15 years and by ensuring active recruitment and training (Fillon, 2019). In parallel, global performance indicators continue to improve (see Figure 5.2), indirectly supporting these trends.

25. Conversely, knowledge can also be explicit. Explicit knowledge is codified in books, archives, drawings, etc., and it is easily storable, retrievable and reproducible. Nuclear organisations have thus far been successful in making knowledge more explicit.

The main issue for the nuclear industry is related to the capability of the sector to attract and retain the best talent. Some nuclear operators have reported a reduction in the number of applicants for a given position of more than 60% compared to 2010 levels (Fillon, 2019). The lack of nuclear graduates has been a growing concern since 2000. However, a detailed quantitative analysis at the OECD level is difficult to find (NEA, 2020b). Such patterns arise from a combination of several factors. First, the legacy of nuclear accidents in public acceptance and difficulties encountered in recent new build projects have contributed to creating a bad reputation for nuclear power. At the same time, strong policy support to other low-carbon technologies has resulted in nuclear energy being perceived as an outdated technology. Second, the increasing political uncertainty following the Fukushima accident, and reduced market perspectives induced by nuclear phase-out in some countries, makes it more challenging to recruit new personnel. Third, increasing market pressures are forcing utilities to reduce the budget associated with building internal competence and proposing more attractive job offers. The situation is not uniform across all NEA countries, and depends to a great deal on the national context.

On the other hand, the number of STEM graduates is steadily increasing (see Figure 5.6), and therefore the potential pool of young professionals willing to pursue a career in the nuclear sector. In the United States, the number of nuclear graduates has also been growing since 2000, suggesting that it is possible to sustain the talent pipeline with specific, co-ordinated efforts between industry, government and academia (NEA, 2020b).

Figure 5.6: **Evaluation of the total number of STEM graduates in NEA/OECD countries**



Source: OECD, 2018.

Lastly, attracting and retaining the best talent in the nuclear sector will also require a better understanding of generational issues. In the coming years, the global workforce will essentially be formed by millennials (i.e. the generation Y [26]), followed by an increasing number of generation Z staff [27]. Compared to their predecessors, these generations change jobs more frequently. According to a survey from Deloitte (2018), 43% of millennials expect to leave their organisations within two years. Only 28% plan to stay beyond five years. These numbers get worse with younger generations, with only 12% of generation Z indicating that they would be likely to stay in an organisation beyond five years. Evidence from the United Kingdom suggests that, while a high salary remains central in attracting young professionals to the nuclear industry, job satisfaction and progression are the main motivations to stay in a given company (YNPF, 2018). The higher turnover rates associated with generations Y and Z personnel are however inconsistent with the long timescales required for the development and transfer of nuclear knowledge. New technologies that would enable the enhancement of knowledge management approaches and provide more sophisticated and rapid training could help to overcome these issues.

26. People born in the 1980s and the beginning of the 1990s.

27. Young professionals born in early 2000s.

5.3.3. *Building skills for LTO*

Nuclear organisations have at their disposal a series of strategies to systematically assess their internal human capabilities so as to minimise potential performance risks. These approaches are based on rigorous human resource development and management practices, investments in communication and modern technologies, and knowledge management practices. Additional efforts may be required at the national level with governments, industry and academia working together to create a functional framework for workforce development, including R&D investments, attractive university and training programmes and apprenticeship opportunities. All of these measures can be supported with national plans, providing the right incentives to the nuclear industry to invest in their personnel and reinforce international collaboration.

Human resource development and management

Human resource development strategies involve different aspects that are common to every company, such as workforce planning, career management, remuneration, recruitment, training and talent development. All these dimensions have to be taken into account to attract not only the necessary resources but also the best talent to meet the high levels of excellence in the nuclear industry. Each nuclear organisation and facility should set up specific management systems to identify any growing performance risks associated with the loss of critical skills, and then trigger the necessary countermeasures in due time. Early planning, proactive recruitment and reinforced education and training can be effective measures and should be supported with continuous monitoring. In parallel, companies can also invest in soft skills such as leadership (NEA, 2019), as well as talent identification and promotions that consider the motivations of younger generations.

Similar approaches can be adopted at the national level, with the elaboration of human resource plans for the entire nuclear sector. These government-led programmes can be created in consultation with industry and academia in order to properly address specific long-term capability needs. France is a good example of this type of nationwide endeavour (see Box 5.4 below).

Box 5.4: **Building nuclear capabilities at the national level: The case of France**

Nuclear knowledge and skills require long-term planning and strategies. In light of the potential shortage of skills for new build projects and LTO, France has been undertaking concerted efforts at all levels of the nuclear value chain – involving the government, industrial key players and academia – to secure these skills in future.

Sustaining capabilities through national, industrial planning

The nuclear sector in France consists of around 2 600 companies, 50% of which have export activities, and generates 220 000 direct and indirect jobs. In order to provide a stable policy framework consistent with the energy strategy, the main French representatives from government and the nuclear industry signed a nuclear sector deal[28] in January 2019, which includes reciprocal commitments in four key areas (Conseil National de l'industrie, 2019):

- jobs, skills and training;
- digital transformation of the nuclear sector;
- research and development and the circular economy (i.e. back-end activities);
- international market opportunities.

The deal also includes specific mechanisms to boost the development of small and medium nuclear enterprises. The initiative followed the creation of the French nuclear industry platform called GIFEN[29] in 2018. GIFEN gathers key nuclear industry players and other associations with the objective of co-ordinating industry

28. Contrat Stratégique de la Filière Nucléaire Française.

29 The acronym GIFEN stands for Groupement des industriels Français de l'énergie nucléaire, or in English, Group of French nuclear energy industrialists.

efforts in areas such as: skills and training, nuclear safety and quality, digital transformation and R&D, development perspectives of the sector in France and abroad, European and international affairs and communication with the public.

Reinforcing nuclear curricula and R&D efforts

Since its creation in 1956, the public higher education institution, Institut national des Sciences et Techniques Nucléaire (INSTN), has been training young engineers, researchers and technicians to support the development of the French nuclear programme. The INSTN is administered by the French Alternative Energies and Atomic Energy Commission (CEA) and works in close collaboration with the industry in order to support its workforce needs. As a result of this long-standing dialogue, the International Master of Nuclear Energy was created in 2009 with the objective of sustaining the talent pipeline, providing a specialised nuclear cursus to French and foreign high-level students in the following subject areas: fuel cycle, nuclear reactor physics and engineering, nuclear plant design, operations, decommissioning and waste management. Nuclear industry professionals from EDF, Framatome and CEA also participate in the teaching. This master's degree takes full advantage of a unique partnership between academia and industry to provide on-site specific training in nuclear power plants and research laboratories, as well as attractive job offers in the most prestigious nuclear companies for students willing to perform their career in the French nuclear sector.

Another success story of national and international industrial collaboration is the creation of the Materials Ageing Institute (MAI). Founded by EDF in 2008, MAI regroups nuclear operators, reactor vendors and research institutes[30] from all over the world to accelerate research in nuclear materials ageing. The main R&D areas include all of the life-limiting SSCs and associated ageing phenomena covered in Chapter 3 of the present report. The mission of MAI is to improve materials ageing simulation, bringing together materials scientists, modellers and nuclear operators with actual operational data to improve the accuracy and accelerate the development of advanced simulation models and tools. Another key activity of the institute is to provide training on materials ageing to students and young nuclear professionals (MAI, 2020).

Engaging young professionals through apprenticeships

Around 5 000 apprentices today receive hands-on training in nuclear organisations during their studies in France. These students have access to offers through a dedicated apprenticeship web portal that includes the offers of approximately 2 500 companies. Around 25% of jobs offers in nuclear companies are filled by apprentices (RGN, 2017).

Communication and job advertisements

The difficulties faced by the nuclear industry in attracting new talent can be explained, to some extent, by limited advertisement efforts and the use of outdated communication approaches. Countries that are willing to pursue the nuclear option could advertise the role of nuclear power in their countries through public talks and visits to nuclear facilities as part of school education. The boom of social media is also an opportunity to revisit current communication strategies so as to update them with more modern, fresh and targeted content to increase the interest of young graduates in nuclear jobs. In parallel, companies could participate more actively in local, national and international job events. When organised locally, these events can strengthen the relationship with local communities and provide opportunities to better communicate the benefits of nuclear activities in the local economy.

Know-how and know-why transfer

A starting point of any knowledge transfer plan is the elaboration of a comprehensive knowledge map within the organisation to have a clear picture of who does what and anticipate potential critical skills shortfalls. Specific knowledge management programmes can then be built around critical knowledge areas, including activities to make knowledge more explicit (e.g. through the

30. MAI membership currently includes: EDF (France), TEPCO (Japan), EPRI (United States), Rosenergoatom (REA, Russia), EDF Energy (United Kingdom), China General Nuclear Power Group (CGN), Kansai Electric Power Company (Japan), Mitsubishi Heavy Industries Ltd. (MHI, Japan), Central Research Institute of Electric Power Industry (CRIEPI, Japan), CEA (France), Framatome (France), as well as a robust scientific network of universities across these countries.

generation of expert documents and video recorded interviews), as well as the creation of specific training, mentoring and communities of practice[31] to properly handle tacit knowledge.

Also, it is important to differentiate "know-how" from "know-why" when transferring knowledge. While the former is limited to the generative processes of a given phenomenon, the latter requires a deep understanding of the underlying physical principles. Know-how can therefore be effectively transferred through training and knowledge management efforts as it involves a "nuclear-aware" workforce and, to some extent, nuclearised personnel. However, know-why transfer requires complementary efforts in higher education in order to replace nuclear specialists (see Figure 5.5).

Research and development, and higher education activities

Nuclear research contributes to building the knowledge base necessary for safe nuclear operations over longer periods. Key areas of research to support LTO are materials ageing and plant modernisation (see Chapter 3). Research laboratories and industry can combine their forces to accelerate research in these areas, combining scientific advances with actual plant data. In 2008, MAI was created in France with the mission to develop more accurate predictive models (see Box 5.4). In the United States, the Light Water Reactor Sustainability Program (LWRS) regroups utilities, regulators, universities, nationals and other international organisations to develop the scientific basis, and science-based methodologies and tools, for LTO (LWRS, 2020). The technical evidence generated by LWRS has been used to support the safety cases of recent subsequent licensing renewals (SLRs) in the United States.

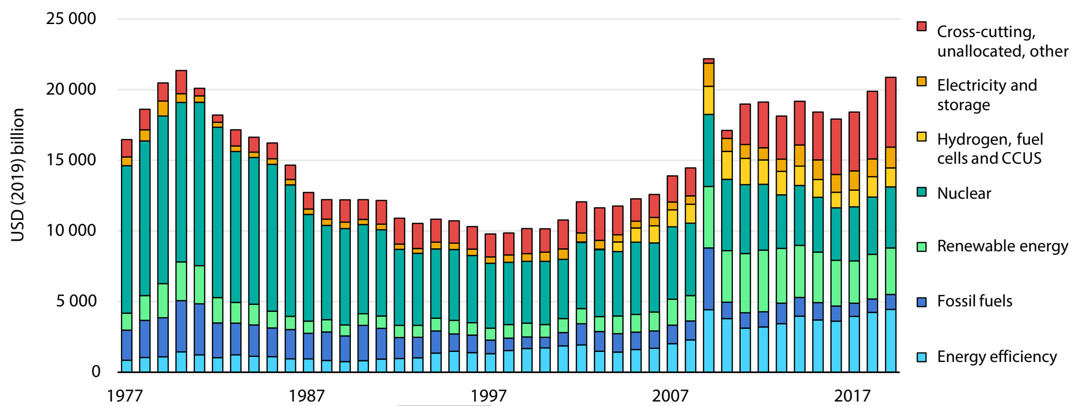
Moreover, research activities in combination with higher education programmes are essential to provide highly specialised nuclear professionals (see Figure 5.5). Since the 1970s, R&D investment has been steadily declining, suggesting decreasing academic activity[32] and nuclear expertise in some areas (see Figure 5.7). The industry and academia can work together to establish a specific nuclear cursus that leverages existing research and nuclear facilities (e.g. on-site training, talks to nuclear professionals) to provide high-quality and attractive educational experiences. Some examples include the creation of the Master of Nuclear Energy at the INSTN in France (see Box 5.4) and the European Master in Innovation in Nuclear Energy (EMINE, 2020) at the European level. Post-doctorate schemes can be set up around the most complex technical issues to reinforce capabilities. In countries that are planning to phase out nuclear power in the near or mid-term, R&D and education become the main levers to sustaining nuclear capabilities given the expected lower commitments from industry. Germany, for example, has not reduced R&D efforts in nuclear activities[33] despite its nuclear phase-out. In 2019, investments in nuclear R&D represented 22% of the total budget, with similar amounts allocated to energy efficiency and renewables (IEA, 2021).

31. Networks of people who work on similar processes or disciplines, and who come together to develop and share their knowledge in that field for the benefit of their organisation and themselves (IAEA, 2012). A key advantage of communities of practice is that knowledge is managed collectively and thus is less vulnerable to the turnover of its members.

32. Nuclear R&D budgets in IEA member countries represented in 2019 22% of the total R&D investment compared to 75% in 1974 (IEA, 2021).

33. The main research areas include: nuclear safety, waste management and disposal, basic sciences and non-power applications, such as materials behaviour and fusion energy.

Figure 5.7: **Public energy technology R&D and demonstration spending by IEA member country and by technology, 1977-2019**



Note: Nuclear R&D includes nuclear fission and fusion activities. CCUS = carbon capture, use and storage.

Source: IEA, 2020a.

Apprenticeship opportunities

Apprenticeships are an efficient approach to mobilise both industry and education centres so as to secure the necessary nuclear workforce in a mutually beneficial way. On the one hand, apprenticeship contracts provide graduates with hands-on experience to complement their academic background, which can also help to attract new students. On the other hand, companies benefit from additional and inexpensive resources that will be fully operational if apprentices are selected for full-time jobs. Apprenticeships can be adapted to any type of degree and qualification (from higher education to vocational training) and recourse to such an option varies from one country to another. In France, recruitment after a successful apprenticeship period is a common practice in the nuclear industry (see Box 5.4).

Industry development plan and international collaboration

The opportunities are significant to build a competent nuclear workforce at the industry and academic levels. However, factors such as policy risks and public perception can make this task more difficult and can only be properly addressed by governments. This situation has pushed several countries to create nationwide nuclear industry policies in an attempt to guide industry and academic efforts while creating a stable policy framework to face potential the LTO challenges ahead. In June 2018, for example, the government of the United Kingdom released its "Nuclear Sector Deal" with a strong, joint commitment to developing a highly skilled workforce (BEIS, 2018). Similar joint endeavours were published in France in January 2019 (see Box 5.4). These types of agreements also provide positive policy signals to address public perception issues among young generations and help industry to sustain its capabilities.

At the international level, several organisations are contributing to nuclear human workforce development in various ways. The IAEA has represented the reference in terms of knowledge management methodologies and guidance for the nuclear sector since the early 2000s. The organisation also provides knowledge management services to members that need specific assistance (IAEA, 2020). In Europe, organisations such as the European Nuclear Education Network (ENEN) and the European Nuclear Energy Forum (ENEF) support nuclear knowledge preservation, higher education and training. The European Commission (EC) Joint Research Centre (JRC) hosts and manages the European Human Resources Observatory for Nuclear (EHRO-N). This initiative was set up by ENEF with the aim of monitoring supply and demand for nuclear human resources in the European Union and making recommendations on specific policies to address potential gaps (EHRO-N, 2020). The NEA has also assisted member countries in addressing issues associated with nuclear workforce capabilities (NEA, 2000; 2012a). The NEA Nuclear Education, Skills and

Technology (NEST) Framework, for example, recently entered into force in February 2019. The main objective of this initiative is to foster nuclear skills capacity building, knowledge transfer and technical innovation in the international context (NEA, 2020).

Key findings

- Globally, nuclear power plants have steady improvements in safety and reliability levels despite an ageing nuclear fleet. The explanation for such improvements can be found in replacements of structures, systems and components (SSCs) during plan refurbishments, increasing technical progress and operating experience, combined with governing frameworks that foster continuous improvements and the adoption of best international practices.
- The nuclear supply chain remains robust and mature after more than one hundred LTO projects around the world. From a technical and managerial perspective, LTO projects are simpler than new build projects, contributing to their overall low risk profile. SSC obsolescence and supply chain issues, however, are a rising concern as a result of increasing policy risks, degraded market perspectives and high qualification needs. The severity of these issues varies from country to country depending on the size and standardisation of the nuclear programme. Several strategies can be adopted to reduce supply chain risks associated with the procurement and qualification of critical structures, systems and components, including the introduction of commercial grade dedication and higher collaboration and harmonisation levels across countries. Some countries are undertaking national initiatives in this direction, in co-operation with regulators.
- Recent experience shows that the nuclear industry has sufficiently planned and managed the retirement of a significant share of its workforce. Attracting and retaining talent nonetheless remains a major concern. The industry and academia can join forces to increase the attractiveness of the sector, but governments are key in addressing public perception issues that could hamper nuclear workforce development. National nuclear industry policies provide a functional framework to properly guide joint undertakings among government, industry, research institutes and academia.

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6. Economic aspects

The economics of nuclear power have been the subject of intense study and scrutiny in past years given the importance of understanding the cost and risk drivers of this technology so as to adhere to sustainable development capacity scenarios. Economic trends observed in recent new nuclear build projects within OECD countries have also nourished general policy and public perceptions that all nuclear investments should be expensive and risky, even those that concern existing reactors currently in operation. However, actual evidence from most nuclear power plants operating around the world today does not confirm these perceptions.

While new build and long-term operation (LTO) are related to the same technology, the associated investments are significantly different from an economic perspective. The LTO of a nuclear power plant requires brownfield investments on assets that are already built and, to a large extent, amortised. The extent and complexity of the technical work is also less significant compared to building a new facility. The results of the present report confirm that LTO remains the most competitive, low-carbon technology option in many regions around the world, and that refurbishment costs are predictable and well-contained. A closer look at LTO economics reveals that cost and risk breakdown patterns can help to explain why policymakers should regard LTO as an independent and separate solution in the low-carbon technology portfolio.[1] The 2020 edition of *Projected Costs of Generating Electricity* (IEA/NEA, 2020) thus introduces for the first time LTO investments.[2]

Like any other low-carbon technology, existing nuclear reactors nevertheless have sizeable fixed costs that can make them more exposed to market risks. Challenges in existing market designs, amplified by regional conditions (e.g. abundant cheap fossil fuels), is pushing some operators to cease operation earlier than expected, particularly in the United States. Around 25% of early closures between 2011-2025 resulted solely for market reasons, and another quarter of these closures have been influenced by electricity price prospects that may not guarantee the return of the necessary LTO investments (see Figure 1.2). The present economic analysis therefore encompasses both cost and market dimensions in order to provide a full picture of the economic conditions in relation to the existing nuclear fleet worldwide, as well as of the areas where effective policy action could enable LTO.

6.1. The generation costs of LTO

6.1.1. Breakdown and cost metrics

The generation costs of nuclear power, similar to any other electricity generation technology, fall essentially into four main categories: i) capital costs; ii) operation and maintenance (O&M) costs; iii) fuel costs;[3] and iv) decommissioning costs. Capital costs can be split, in turn, into overnight construction costs (OCCs) and financing costs.

1. Other low-carbon technologies with long lifetimes, in particular hydro-electric plants, could be similarly attractive for such LTO investments (IEA/NEA, 2020).
2. A shorter version of the LTO economic analysis developed in this chapter is presented in Chapter 8 of IEA/NEA (2020).
3. O&M and fuel costs can be grouped together, and considered as operational expenditures (OPEX).

The OCC represent all of the expenses necessary to design, build and commission the plant. For the particular case of LTO, the OCC cover the investments necessary to sustain operations for a given period. The OCC metric assumes that all of the investment is disbursed at once (i.e. overnight), and consequently, it does not capture any time-related effects in the form of financial interests or discounted payments. These costs are typically reported in US dollars (USD) per installed kWe. In essence, the OCC reflects the intrinsic cost of a given technology and enables cross-technology comparison, independently of financial conditions.

The different cashflows associated with each of the aforementioned cost categories (i.e. investment, O&M, fuel and decommissioning) can then be evaluated over the expected lifetime of the asset, discounted and levelised through electricity generation over the same period according to an expected capacity factor to compute the LCOE.[4] The LCOE can be interpreted as the minimum average price of electricity needed over a lifetime for the investment to reach the break-even point, and it is typically expressed in USD per MWh (or cents per kWh). System costs (i.e. balancing, grid and profile costs[5]) and other externalities beyond decommissioning and waste management (i.e. air pollution cost) (see Chapter 2) are not captured via the LCOE calculation. Additional explanations of the different cost categories involved in the calculation of the nuclear power LCOE can be found in IEA/NEA (2020) and NEA (2020).

The LCOE methodology was originally developed to assess baseload technologies operating under rate-regulated and stable electricity prices. After the deregulation wave of the power sector initiated in the 1990s, this can no longer be considered the case. At the same time, the penetration of higher shares of variable renewable energy (VRE) generation is progressively reducing the window of the LCOE to adequately reflect the economic performance of a technology in the electricity market. Aspects such as systems costs and dispatchability attributes (e.g. capacity credit, flexibility) need to be properly accounted for in the metrics to ensure a proper comparison between VRE resources and conventional generators. For this reason, new complementary metrics such as the value-adjusted LCOE (VALCOE)[6] are being used to provide a fuller economic picture (IEA/NEA, 2020).

The Nuclear Energy Agency's Ad Hoc Expert Group on Maintaining Low-Carbon Generation Capacity through Long-Term Operation (LTO) of Nuclear Power Plants: Economic, Technical and Policy Aspects (EGLTO) acknowledged the limitations associated with the use of the LCOE in the current and future energy context, but concluded that this cost figure should be at the core of the economic analysis of LTO for two main reasons:

- The simplicity and transparency of the LCOE makes it a well-understood metric that is still widely used today in energy modelling and policy making.
- It is important to be consistent with the approach used in IEA/NEA (2020), enabling rapid cost comparisons among technologies, countries, and past and recent studies.

Other metrics that may be relevant from a policy and utility perspective include CO_2 emissions abatement costs, net present value (NPV), payback time and internal rate of return. While in practice these may be important in the overall LTO decision-making process, most of these metrics are outside of the scope of the present study.

6.1.2. ***Economic and methodological considerations***

LTO costs have the particularity of applying to existing assets (i.e. brownfield investments in contrast to new construction or greenfield investments), which means that they can be conditioned by the operational and investment history of the plant. In addition, some assumptions may be required to deal with past investments that have not been fully depreciated. After reviewing the existing literature and several industrial cases, the EGLTO

4. The exact formula can be found in IEA/NEA (2020), page 35.

5. System expenses resulting from an increase in the generation costs for the rest of the electricity system, in response to the variability of VRE output, and the sub-optimal use of residual dispatchable capacity.

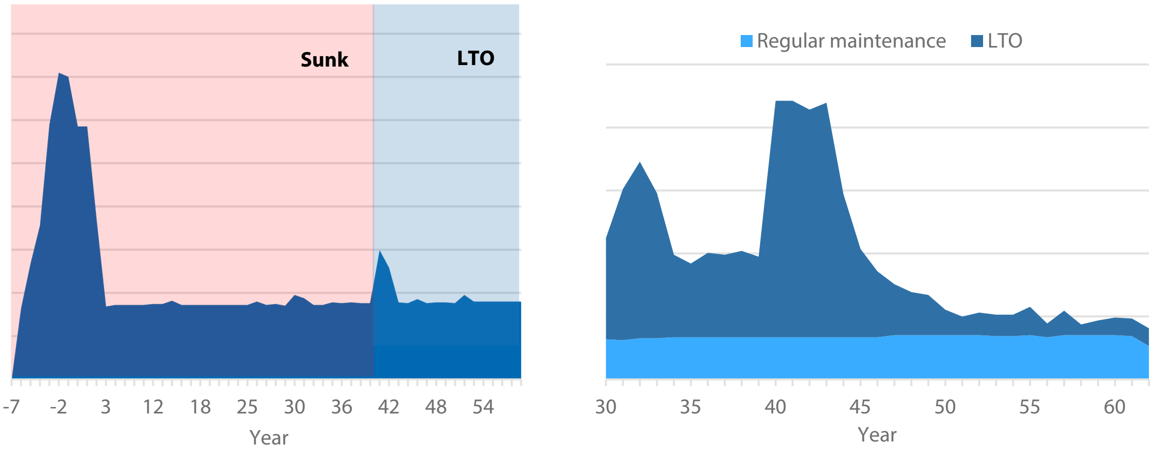
6. Introduced in the 2018 edition of the International Energy Agency's (IEA) *World Energy Outlook* (IEA, 2018), VALCOE incorporates all traditional plant-unit cost elements, but also adds three categories of the value in power systems: energy, flexibility and capacity. Combining these costs and value measures provides a stronger basis for comparisons between VRE and conventional generators.

drew upon several economic and methodological considerations for the evaluation of costs associated with any LTO project. The purpose is to provide a consistent and conservative estimate of the LTO costs while ensuring a certain degree of freedom to adapt to the specific conditions of each project.

OCC

As illustrated in Figure 6.1, once a nuclear power plant is built, generation costs are low and stable. However, as the end of the initial design lifetime approaches (i.e. typically around 30-40 years for light water reactor technologies), investment patterns tend to increase rapidly as operators start to undertake the necessary replacements and modifications for LTO of the plant for a defined period.[7] These expenses correspond to the LTO OCC costs (or LTO investments) and the evaluation of such costs is not always straightforward.

Figure 6.1: **Generic distribution of costs (left) and LTO investments (right) over the operating time frame of a nuclear power plant**



Source: NEA, 2015.

Source: Courtesy of CEZ.

One of the first difficulties arises from the definition of the exact envelope of the LTO investment. LTO investments are those specifically incurred to extend operation of the plant and are therefore different from regular and maintenance investments that can be assimilated to fixed O&M (see Figure 6.1, right). Three main categories can be identified:

- **LTO programme**: These expenses cover all the necessary studies and inspections required to define the scope of the LTO programme (e.g. individual plant assessments, time limited ageing analysis, as shown in Chapter 3), and the management of the regulatory and licensing interfaces. They can largely be considered as indirect costs. They can also cover additional ageing management programme activities (i.e. monitoring, testing, in-service inspection, maintenance) that could eventually lead to a re-evaluation of the O&M costs during the LTO period.
- **Replacement of heavy components and other works**: This category usually represents the bulk of LTO investments and includes the replacement of mechanical and electrical equipment, fluid systems, instrumentation and controls (I&C) and civil works. Additional

7. These investment trends are quite specific to nuclear power as they are, to some extent, aligned with the regulatory calendar of the LTO review process of each country. This is not the case, for instance, for other technologies, for which LTO expenses do not spike in accordance with regulatory decisions and can simply be assimilated as fixed O&M costs. The specific trends of nuclear investment on existing assets support the treatment of LTO as a different "technology" from an economic perspective.

details of the specific nuclear power plant components typically being replaced during LTO refurbishment is detailed in Chapter 3. Both the direct costs of the components and the necessary equipment and labour for their installation should be accounted for in this category, as well as project management and other engineering services.

- **Post-Fukushima**[8]: These are the investments necessary to meet the post-Fukushima safety standards. They cover extensive plant upgrades and the installation of new, redundant systems. Some examples are presented in Chapter 5 of the present report.

While this categorisation can be considered consistent from a technical and economic perspective, in practice it may face some shortcomings. First, operators usually perform additional plant enhancements and safety upgrades alongside LTO refurbishments. Accounting rules used by utilities may not differentiate LTO expenses from other expenses, making LTO cost data difficult to retrieve. Second, these categories are not identical from one company to another, which inhibits the application of standard cost categories for more transparent data collection and comparison across projects.

The analyses carried by the EGLTO experts also concluded that, rather than determining a single cost figure for LTO, it would be more convenient to define a cost range, covering with a high degree of confidence the typical envelope of LTO expenses. While most utilities will roughly devote the same number of resources to define the extent of the LTO programme, the scope of the components to be replaced, as well as of post-Fukushima safety upgrades, can vary considerably from one project to another. The final LTO OCC will essentially be conditioned by various factors, as confirmed in the findings of *The Economics of Long-Term Operation of Nuclear Power Plants* (NEA, 2012):

- specific design characteristics;
- operational experience and history;
- previous investments and retrofits already implemented at the plant;
- the regulatory framework;
- potential safety upgrades or plant enhancements performed by operators on a voluntary basis.

Another challenge lies in the time distribution of LTO investments. In fact, the application of the LCOE methodology requires the treatment of all LTO expenses as an overnight cost that is discounted over time. For brownfield investments, previous investment should be considered as sunk (see Figure 6.1, left).[9] However, this may not be a realistic representation of the actual expenditure patterns for LTO as most of the capital costs are continuous and incremental rather than upfront at the age of 40 years (see Figure 6.1, right). As such, it is possible to identify some nuclear power plants for which the actual LTO investments at the end of the original design lifetime are very low since operators had been investing on a continuous basis in order maximise the lifetime of the asset. In this situation, LTO OCC costs can be estimated by defining a baseline of regular investments to sustain plant operations[10] and then by identifying any excess investment that could be attributable to LTO over a given period. This approach is illustrated in Box 6.1 below.

Among the different LTO projects examined in this report, some of them reported upfront OCC and others reported yearly investments over a defined period; the reality for most plants

8. EGLTO experts have argued that post-Fukushima investment cannot be considered as an LTO cost per se since it is not related to the ageing of the plant. In fact, if the Fukushima accident had not taken place, post-Fukushima measures may not have been necessary. However, there was an overall consensus among EGLTO experts that no LTO authorisation or approval would be granted by regulators today without complying with post-Fukushima safety standards. It is, however, to be noted that the scope of the modifications related to a "post-Fukushima" upgrade can highly differ from plant to plant.

9. From an economic point of view, it is possible to include some sort of depreciation term in the LCOE so as to account for past investments. Such an approach is not considered in the present economic analysis to be consistent with the methodology used in IEA/NEA (2020).

10. This baseline corresponds, for instance, to periodic maintenance investments for more short-lived systems, structures and components (SSCs), and these can be assimilated to fixed O&M costs.

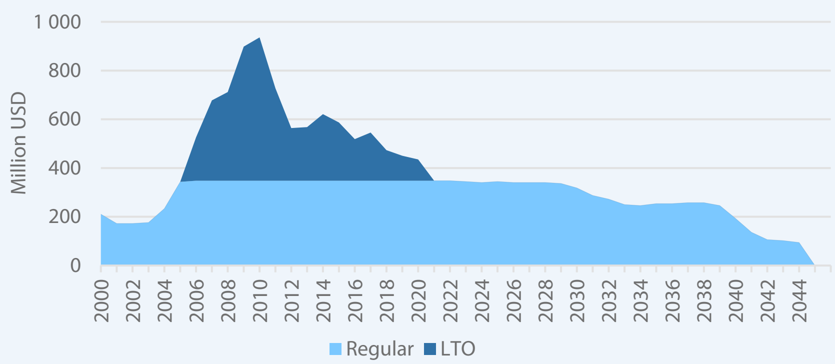
being somewhere in between. The evaluation of the LTO OCC must therefore be undertaken on a case-by-case basis, considering whenever possible annual investment patterns and making the necessary adjustments to isolate LTO investments and treat them as actual OCC. This process should be conservative, for instance, by not discriminating LTO expenses from other plant enhancements and/or safety upgrades, and therefore leading to overestimated (but conservative) LTO figures (see Box 6.1 below).

Box 6.1: **Estimating LTO overnight costs: The Swedish case**

In 2016, the consultancy firm, SWECO, prepared a report as an input to assist the Swedish government in its economic evaluation of the different technology options (SWECO, 2016).[11] The SWECO report provides data on annual yearly investments for the entire Swedish nuclear fleet[12] from 2000 to 2045, reconstructed from publicly available sources such as yearly income statements from the utilities (see Figure 6.2 below).

The baseline shown in Figure 6.2 indicates the annual volume-aggregated investments for all Swedish nuclear power plants as being in the order of USD 350 million per year.[13] This is the investment level in the plateau from 2020 and 2030. The investment volume beyond 2030 gradually falls below this base level, which can be expected when approaching the last years of operation. For the period between 2005 and 2020, higher volumes of investment above the base level are observed. These greater expenses can be attributed to the major safety improvements required by the regulator that are carried out in combination with ageing management measures, and in some cases, power uprates. A major, additional safety upgrade finalised in 2020 was the design and construction of complementary independent core cooling systems as part of post-Fukushima measures (NucNet, 2020), which explains why the total investment volume exceeds the regular baseline between 2016 and 2020. Investment levels in the period 2000-2004 are, on the other hand, exceptionally low, which may be attributed to minimised investments on the part of operators during this period as a result of high political uncertainty regarding the future of nuclear power, as well as increasing market pressures following the deregulation of the electricity market in Sweden in the late 1990s.

Figure 6.2: **Yearly investments in the Swedish nuclear fleet, 2000-2045**



Note: These investment projections include Oskarshamn units 1 and 2, and Ringhals 1 and 2, which in the end did not pursue LTO.

Source: OECD/NEA, adapted from SWECO (2016).

11 The original title of the report in Swedish is “Ekonomiska förutsättningar för skilda kraftslag”.

12. Note that these cost figures include investments undertaken in the Oskarshamn units 1 and 2, and Ringhals 1 and 2, which in the end did not pursue LTO. These investments were made prior to the intention of considering LTO. In fact, these reactors operated slightly beyond 40 years.

13. Considering 10 GW of installed capacity in Sweden, this corresponds to USD 30-40 million per kWe, which is consistent with the typical investment levels (or volume of work) that can be engaged during normal outages in a nuclear power plant.

The SWECO report indicates that the aggregated annual investment between 2005 and 2014 is on average around USD 680 million, which corresponds to a total excess investment over ten years of USD 3.3 billion that can conservatively be attributed to LTO, as shown in the above figure. Considering a total installed capacity of 10 GW, and assuming all expenses as overnight, this yields USD 330 per kWe. A total of USD 60-120 million per reactor should furthermore be taken into account during 2016 and 2020 as part of post-Fukushima measures, leading to an additional USD 105 per kWe.[14]

In conclusion, the LTO OCC in Sweden can be estimated to be around USD 440 per kWe. Actual LTO OCC are, however, less significant since most of these expenses cover safety upgrades engaged since 2005, as well as power uprates for some reactors that are not necessarily related to LTO. The most direct LTO-specific investments involve LTO-verification and justification (including time limited ageing analyses [TLAAs]) of the reactor pressure vessel, environmental qualification, ageing-related turbine/alternator replacements, as well as the management of obsolescence in relation to spare parts for I&C components.

O&M costs

O&M and fuel costs represent operating expenditures (OPEX), which, for nuclear power, remain low and stable (see Figure 6.1), which explains why this technology is well-fitted for baseload generation. It is, however, necessary to provide some insight into factors that could drive up (or down) OPEX over time (or before and after LTO refurbishment), as well as some justifications in relation to this type of expenditure, and to which extent, it can be assumed to be similar to recent Gen III/III+ reactors.

In terms of O&M trends, in D'haeseleer's *Synthesis on the Economics of Nuclear Energy* (2013), the author illustrates how O&M costs vary significantly across countries, which can be explained by the different accounting conventions. O&M costs are often divided into a fixed and a variable part, but most of the time it is not clear what is included in each part. In practice, the fixed O&M part may correspond to the regular baselines illustrated in Figure 6.1 and in Figure 6.2, capturing the refurbishments associated with short-lived components. Overall, the final baseline can be set at different levels according to different rules, but from an LCOE perspective, the result will essentially be the same.

The fixed part of O&M can also be lowered thanks to economies of scale and on-site multi-unit and nuclear fleet standardisation effects, which can spread fixed charges across various reactors. At the same time, it can be argued that maintenance costs may increase over time due to ageing. However, as illustrated in Chapter 4, there are other drivers that should be considered, such as operational experience and technical progress that can contribute to containing (or even reducing) O&M costs. In fact, lower O&M costs can be observed following major plant modernisation efforts that have been carried out during LTO refurbishments.

In light of these trends, EGLTO concluded that the evolution of O&M costs during extended operations may not always be evident. Considering the O&M costs of Gen III/III+ new build for the calculation of LTO figures could be a good approach, therefore, and would be consistent with the conclusions of D'haeseleer (2013).

Fuel costs

Fuel costs can be separated into front-end (i.e. mining, enrichment and manufacturing of the fuel assemblies) and back-end (i.e. reprocessing, conditioning and final waste disposal) costs, covering the whole fuel cycle. These costs can vary depending on the type of fuel cycle chosen (open or closed cycle) and on the course of fissile material prices. For existing reactors, it is possible to improve front-end fuel economics with optimised fuel loading and the adoption of fuels that allow for higher burn-up. The consideration of front-end cost data for new build nevertheless remains a robust approximation.

14. Only the remaining six reactors in operation, accounting for a total capacity of 6.9 GW, are considered in this case.

At the same time, it is necessary to account for the costs of managing the radioactive waste generated during the LTO period. EGLTO acknowledged that these expenses could vary significantly depending on country-specific conditions. In some cases, for instance, at the moment that LTO is being considered, most of the infrastructure to store any additional waste generated is already available, which would mean no major re-evaluation of back-end costs. Conversely, other countries may require new interim storage facilities and/or may introduce new regulations that could potentially lead to higher back-end costs during the LTO period. These aspects can be conservatively addressed by considering cost data for new build, an approach consistent with D'haeseleer (2013).

Lastly, when assessing fuel back-end costs, it is important to distinguish between the economic and the financial perspectives. In fact, postponing the closure of a nuclear power plant can bring some financial benefits [15] (e.g. waste management trust funds will be able to generate returns for a longer time frame than initially planned, reducing the provisions that need to be allocated to the funds) and therefore the LCOE (see Box 6.2). Conservatively, these aspects are not included in the calculations presented in the present report.

Refurbishment period

One of the key characteristics of LTO refurbishments is that some of the work can be executed while the plant is in operation. The LTO work, for example, in the LWR unit Triscastin-1 in France took a total of 23 months: 18 months with the reactor online and a long outage of 5 months with the reactor shut down (Payen, Willot, 2019). EGLTO made a conservative estimate of two years (with the reactor completely shut down) as the refurbishment period for the calculations of LWR LTO LCOE. It is important, nevertheless, to highlight that the refurbishment period can vary depending on the envelope of the LTO work, and the technology. For instance, given the larger volume of activity associated with "retubing" [16] of a pressurised heavy water reactor (PHWR), four years would be the estimate for these types of reactors (see Box 6.3).

LTO period

For LWRs, the LTO period varies between 10 and 20 years according to the existing regulations in most countries. [17] For PHWRs more specifically, the LTO period considered is 30 years. Additional technical and regulatory insights on these numbers are provided in Chapters 3 and 5, respectively.

Decommissioning costs

With regard to decommissioning costs, evidence from the Loviisa project in Finland indicates that an increase of the operational lifetime of a nuclear power plant has no significant impact on decommissioning costs (NEA, 2016). For this reason, decommissioning costs can be considered as almost independent and invariant in relation to the operating life of a nuclear power plant. The potential cost increments associated with the dismantling and handling of contaminated components during LTO refurbishment are very low and generally directly included in LTO investments. As such, initial decommissioning costs can be considered as having been fully provisioned during the initial lifetime period (IAEA, 2018), with no additional cost during the LTO period.

Similar to the back-end fuel costs, delaying decommissioning cost outlays would translate into a negative cost (benefit), and it will therefore not be considered in the present calculations (see Box 6.2 below).

15. Assuming that inflation and potential cost escalations do not outweigh these benefits.
16. For the CANDU 6 PHWR design "retubing" means the replacement of the 380 calandria tubes, 380 pressure tubes, 760 end fittings, 760 feeders, and various supporting and connecting components (see Chapter 3).
17. In some countries, 30 years are granted for VVER designs.

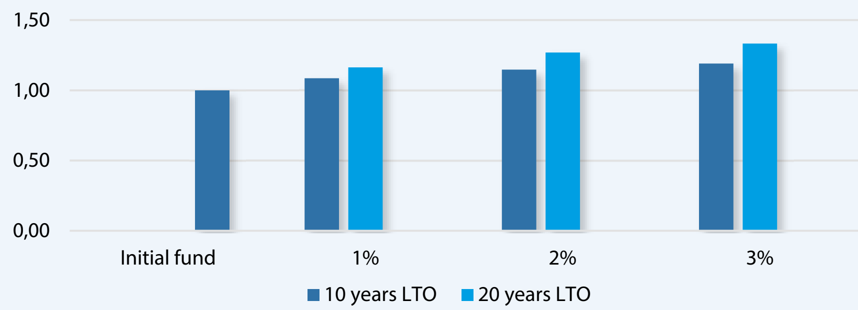
Box 6.2: **Quantifying the financial benefits of delaying the closure of a nuclear power plant**

Before evaluating the value of delaying the closure of a nuclear facility, it is important to distinguish economic treatment from the actual financial implications of decommissioning and waste management (D&WM) costs for nuclear power plant operators. In general, and according to the "polluter pays" principle, D&WM costs are fully internalised. The LCOE formula uses two cost components to internalise D&WM costs: i) decommissioning costs (i.e. for the actual dismantling, handling and storage of irradiated components); and ii) back-end fuel costs (i.e. fuel removal, interim storage and final waste disposal) integrated into the overall fuel cycle costs. In the present study, for instance, fuel cycle costs are estimated at USD 9.33/MWh, with back-end fuel costs representing USD 2.33/MWh (IEA/NEA, 2020).

In practice, however, the internalisation of D&WM costs is carried out in a different manner. Operators make annual contributions to dedicated funds through an allocation of provisions or through specific fees levied from the operators' revenues during the operation of the plant. The amount of these annual contributions is calculated based on estimates of D&WM costs that are periodically re-evaluated. The process, as well as the organisations responsible for managing these funds and the repartition of liabilities, are aspects that vary from one country to another, and thus are out the scope of the present study.

The fact that operators make annual contributions to a dedicated fund as long as the plant is running brings direct financial benefits[18] if LTO is pursued. These benefits can be quantified in two ways. First, the returns of the dedicated fund continue to grow every year. Assuming a discount rate of 2%, the total available fund can increase by 15% for a LTO period of ten years. The longer the LTO period, the greater the benefits (see Figure 6.3 below).

Figure 6.3: **Evolution of the decommissioning fund as a function of the LTO period and the discount rate**



Note: The decommissioning costs allocated to the fund are assumed to be disbursed five years after the last operational year, for a duration of decommissioning work lasting ten years (IEA/NEA, 2020)

Second, the plants will continue to provide annual contributions to the fund during the LTO period. Assuming that the necessary funding remains constant, LTO can significantly reduce the number of annual contributions, thus improving the profitability of operators. In Spain, adding ten years of operations can reduce fees by around 50% (MITECO, 2018). Similarly, in an audit on the evaluation of the decommissioning costs performed in France, government experts estimated that an extension of the operating time frame from 40 to 50 years could lead to a reduction of the required provisions for decommissioning of the existing fleet by approximately EUR 3.2 billion (DGEC, 2015).

Overall, the financial benefits of delaying the closure of a nuclear power plant increase almost linearly with its operating time frame. Its value could be captured in the LCOE formula as a negative cost (benefit), leading to lower LCOE values. In the present study, however, this effect has not been taken into account in order to increase the degree of conservatism of the LTO cost figures and to be consistent with the methodology employed in IEA/NEA (2020). In addition, these results show that LTO will make a positive contribution to ensuring the adequacy of funding for D&WM activities (see Box 2.4).

18. This example abstracts from inflation and escalation effects, as well as new regulations that could potentially offset these benefits.

6.1.3. *Evaluation of LTO generation costs*

LTO OCC and LCOE analysis

Given the considerations described in the previous section, as well as various case studies, EGLTO concluded that an average overnight LTO investment for LWRs [19] in OECD countries would range from **USD 450-950 per kWe**. This variability can largely be explained by the differences in the scope of LTO investments for reasons previously indicated (e.g. operating experience, previous investment in the plant, regulatory framework, See Section 6.1.2). Moreover, these numbers have been estimated in a conservative manner as they treat all plant enhancements as LTO expenses. [20]

Table 6.1: **LTO LCOE values for LWRs as a function of the LTO period, discount rate, overnight costs and the capacity factor**

Overnight LTO investment costs (USD/kWe)	LWR LTO LCOE (USD/MWh)					
	LTO period = 10 years			LTO period = 20 years		
	Discount rate			Discount rate		
	3%	7%	10%	3%	7%	10%
	Capacity factor = 85%					
450	29.4	31.2	32.6	26.4	28.6	29.7
700	33.4	36.1	38.3	28.7	31.4	33.8
950	37.4	41.1	44.1	31.0	34.7	38.0
	Capacity factor = 75%					
450	31.9	33.9	35.5	28.4	30.5	32.2
700	36.5	39.5	42.0	31.0	34.2	36.9
950	41.0	45.1	48.5	33.6	37.9	41.6
Min	**29.4**			**26.4**		
Max	**48.5**			**41.6**		

Note: These values have been computed assuming a refurbishment period of two years, fixed O&M costs of USD 85/kWe, variable O&M costs of USD 1.5/kWe, front-end fuel costs of USD 7/MWh and back-end fuel costs of USD 2.33/MWh, consistent with the values for new build projects considered in IEA/NEA (2020). The overnight LTO investment cost includes other plant enhancements beyond LTO and 5% of contingencies. Decommissioning costs are not included as they have largely depreciated during the initial design lifetime.

A closer look into the structure of the LTO OCC confirms that most investment consists of the replacement of heavy components and other work, including the labour necessary for their installation. The indirect costs associated with project management, regulatory and licensing interfaces and the initial engineering efforts necessary to evaluate the extent of LTO refurbishments (i.e. LTO programme) are not negligible and typically account for 20-25% of the total investment. The updated review of the costs associated with Fukushima upgrades for several projects shows that they can vary considerably, depending on the project, but they could represent in some cases 20-25% of the total OCC. This represents an increase compared to preliminary estimates of 10-17% in NEA (2012), which does not threaten the overall competitiveness of LTO investments. Table 6.1 above shows the LTO LCOE for different overnight costs, real discount rates, capacity factors and LTO periods. [21] The assumptions are summarised at the bottom of the table. The table is intended to cover all of the expected LCOE associated with LTO of LWR in OECD countries. [22] The case of a capacity factor of 75% captures the short-term economic penalty associated with higher shares of variable renewables in the electricity system. Taking into account

19. LWRs represent roughly 85% of installed nuclear capacity worldwide.
20. This means that power uprates, safety upgrades and other types of plant enhancements not associated with licence extension for LTO of the plant are included in the overnight costs of LTO considered in the present study.
21. The LTO periods presented in Table 3.1 (i.e. 10 and 20 years) are the typical values considered for LWR reactors in most countries. Other technologies, such as PHWRs and VVERs, take into account 30 additional years of operations.
22. For instance, country values for France, Sweden, Switzerland and the United States included in IEA/NEA (2020) fall into the results presented in Table 6.1.

all of these aspects, LTO LCOE is expected to fall into the range of **USD 25-50 per MWh**. A similar analysis for PHWRs is presented in Box 6.3. Overall, these results confirm that the LTO of nuclear power plants remains one of the most competitive options of low-carbon electricity generation, in line with recent IEA (2019) and IEA/NEA (2020) findings.

Box 6.3: LTO OCC and LCOE analysis for PHWRs

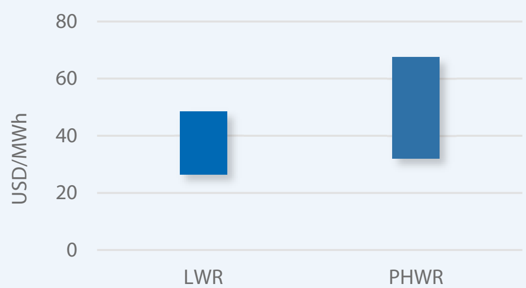
According to Ontario Power Generation (OPG, 2015), refurbishment work for four CANDU units at the Darlington nuclear power plant are estimated to cost USD 7 billion leading to an OCC of around USD 2 000 per kWe.[23] The scope of PHWR refurbishment is significantly larger than for LWRs because of work related to the retubing of the reactor. These activities represent more than 55% of the scope of the replacement of heavy components. The estimated share of indirect costs is consistent with other LTO projects, representing 27% of the total overnight investment.

Additional, relevant economic considerations differing from LWRs include:

- *LTO period*: PHWR refurbishments are meant to cover 30 years of additional operations, which also explains its larger technical scope;
- *refurbishment period*: Recent experience has shown that the work can take around three to four years to complete;[24]
- *capacity factor*: Online refuelling enables higher load factors, which can on average be close to 90%;
- *fuel costs*: the use of natural uranium provides savings in front-end fuel costs of around 40% (i.e. no need for fuel enrichment; NEA, 2013), but it has the drawback of requiring deuterium production facilities.[25]

Based on these considerations, EGLTO experts determined that a conservative estimate of the LTO OCC for PHWRs could be in the range of **USD 2 000-2 500 per kWe** with an associated LCOE between **35-70 per MWh**. These LCOE values show that PHWRs are practically in the same competitiveness range as LWRs (see Figure 6.4) and remain one of the most cost-competitive, low-carbon options in the countries in which they are operating. Similar to LWRs, a sensitivity analysis performed by OPG (2015) underscores the importance of the load factor (or future production prospects and electricity prices) in the economic performance of extended operations. However, the discount rate and potential uncertainties also have a noticeable impact on the final LCOE, given the greater size of LTO investments in PHWRs.

Figure 6.4: **LTO LCOE comparison between LWR and PHWR technologies**



Note: These values have been computed assuming overnight costs of 2 000-2 500/kWe, a load factor ranging between 75-90%, a refurbishment period of four years, fixed O&M costs of USD 85/kWe, variable O&M costs of USD 1.5/kWe, front-end fuel costs of USD 4.2/MWh and back-end fuel costs of USD 2.33/MWh, consistent with the values for new build projects considered in IEA/NEA (2020). The front-end fuel costs do not take into account enrichment costs corresponding approximately to 40% of the total cost of front-end fuel activities (NEA, 2013). The overnight LTO investment cost includes other plant enhancements beyond LTO and 15% of contingencies. Decommissioning costs are not included as they have largely depreciated during the initial design lifetime. Maximum and minimum values for LWR come from Table 6.1.

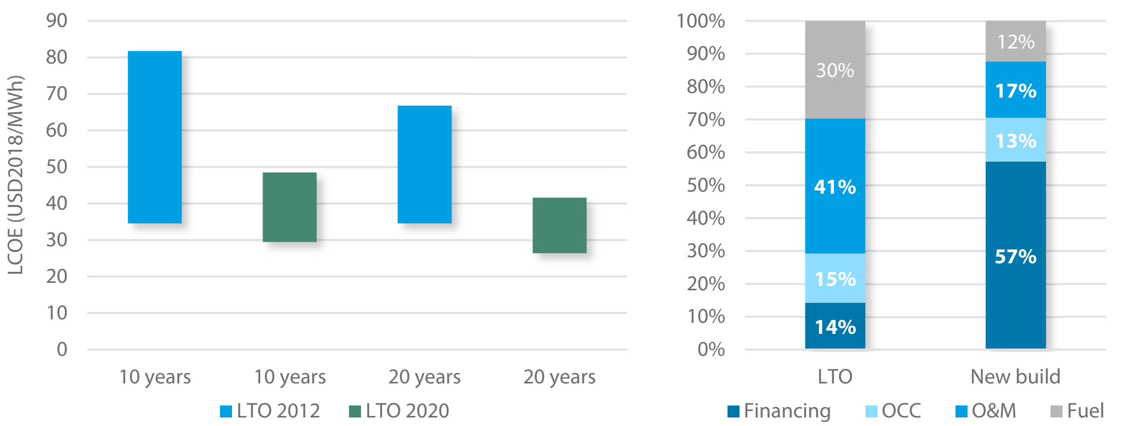
23. This value does not consider any contingency, interest or cost escalation.
24. These estimates do not take into account potential programme and learning effects at the Darlington or Bruce sites in Canada, which could reduce the overnight construction costs and lead times for the refurbishment of individual plants.
25. In the present analysis, the cost associated with these facilities is considered as sunk.

Insights on risks and financing

From a technical and managerial perspective, the scope and complexity of LTO projects is less significant than for new build projects. Refurbishments do not need the same number of critical components and engineering studies, and have neither the same number of contracts and suppliers to co-ordinate nor the same volume of manpower to be managed on-site. As of end 2020, more than 100 reactors worldwide were older than 40 years, meaning that the learning curve of LTO is at quite an advanced stage and supported with a sufficient volume of projects that are contributing to sustaining industrial capabilities and reducing the costs and delivery times (see Figure 6.5, left). All of these aspects contribute considerably to reducing the real and perceived construction risks of LTO refurbishments. This situation, combined with the small size of LTO investments compared to new build projects, allows nuclear operators to carry these projects in their balance sheets with limited financing costs (see Figure 6.5, right).

While project risks are low and market risks manageable, fixed costs still represent a significant share of the expenses of existing nuclear reactors (70% compared to the 85% for new build). In countries where market and policy uncertainties are significant, the resulting risk premium can challenge the economic viability of some plants.

Figure 6.5: **Evolution of LTO LCOE for different LTO periods (left), and the cost profile of LTO versus new nuclear build (right)**



Note: LTO 2012 values from NEA (2012) have been computed for overnight costs ranging from USD_{2010}500 to USD_{2010}1 090 per kWe, discount rates of 3% and 8% and a capacity factor of 85%. LTO 2020 values represent the results presented in Table 6.1.

Note: Overnight costs of USD 700 and USD 4 500 per kWe for LTO and new build, respectively. Real discount rate of 7% at a capacity factor of 85%. The operational expenditure assumptions are detailed in Table 6.1.

Sensitivity analysis

The sensitivity analysis presented Figure 6.6 provides additional insight into the expected economic performance of LTO under existing market conditions. Existing nuclear power plants will be, by large, primarily affected by plant availability downturns or, on the revenue side, low electricity prices. The IAEA report, Economic Assessment of the Long Term Operation of Nuclear Power Plants: Approaches and Experience (2018), arrives at the same conclusion, with a similar analysis based on the net present value (NPV) metric at the plant level.[26] This pattern explains the early closures of some reactors observed in the United States for market reasons, and to a lesser extent, in Sweden. The dominance of parameters governing the revenue side over the costs also indicates that operators have a strong incentive to perform power uprates (or any other plant enhancement that increases the availability of the plant) during LTO projects as this will directly improve the attractiveness of the business case.

26. In fact, the LCOE corresponds to a net present value equal to zero.

The discount rate is the least dominant factor, given a cost profile essentially dominated by operational expenditures (70% of the generation costs, see Figure 6.5, right). This cost structure is somehow similar to that of fossil fuel plants, which confers a certain economic advantage to better withstand market shifts and improves the economic rationale for flexible operations, which increases the overall value of LTO of existing fleet (IEA/NEA, 2020).

The thinner LTO bands compared to new build reflects the higher predictability and lower project risks of LTO refurbishments. Potential cost overruns and shorter operating time frames can be absorbed more easily than reductions in the plant's availability and/or electricity prices. Longer LTO periods tend to improve the overall economics but do not change the main trends.

O&M and fuel cost variations are more unlikely to happen given the stability of operation expenditures in nuclear power (see Figure 6.6, left). Nevertheless, this does not prevent nuclear operators from undertaking continuous efforts to reduce OPEX and improve the overall economics of plants.

Figure 6.6: **Sensitivity analysis of the LCOE of new build, and LTO of nuclear power plants**

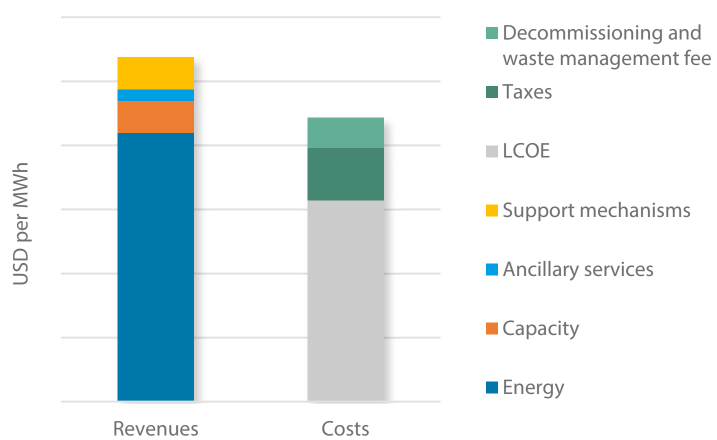
Source: OECD/NEA, using data from IEA/NEA (2020).

6.2. Recovering the costs of LTO

Despite LTO being one of the most cost-competitive, low-carbon technology options, this does not necessarily mean that it recovers all of its generation costs under all circumstances to remain profitable. In some regions, nuclear power plants close prematurely for market reasons. Enabling LTO thus requires a comprehensive economic analysis that assesses both the technology costs and revenue trends or market prospects (see Figure 6.7). It is the combination of both of these dimensions, under regulatory compliance of course, that will trigger the final investment for LTO of a nuclear power plant.

On the other hand, current electricity markets are designed to adequately reflect over time the value of the system through marginal cost pricing mechanisms. The system value includes the volume of electricity generation and the delivery of electricity where needed at any moment, satisfying certain quality standards (i.e. frequency). In this sense, generators are both energy (i.e. energy-only markets) and grid service providers (i.e. system adequacy and ancillary services). In order to be sustainable and maximise social welfare, the electricity and the associated grid services must also be low-carbon and resilient. In theory, current market designs ensure, in the short term, optimal dispatch at the lowest cost for the customer while providing the right signal to ensure, over the long-term, optimal capacity adequacy. In practice, markets face some difficulties reconciling all of these system features and require support mechanisms to guide low-carbon investments, especially in the long-term. As a result, those power markets encompassing a series of measures to promote long-term decarbonisation, affordability and security of supply will more likely benefit LTO.

Figure 6.7: **Qualitative representation of the system value and technology cost for LTO**



6.2.1. *Insights in the decision-making process for continuing operation*

In the decision-making process to continue (or completely cease) operations of an existing nuclear power plant, many interrelated factors (i.e. policy, technical, regulatory and economic) come into play. The different chapters of the present report cover all of these factors and provide an overall appreciation of the holistic approach necessary to assess LTO decisions. From an economic perspective, the following key criteria can be considered (NEA, 2012):

- existing production and asset portfolio of the country;
- energy policy of the country, including aspects such as taxes, carbon policy and security of supply aspects;

- new availability factor of the plant after refurbishment and the predictability of future electricity prices;
- need for equipment upgrades and replacements, associated overnight costs and LCOE;
- other risks and uncertainties related to the site, the political situation, and financial and/or regulatory aspects.

The costs, therefore, do not provide the full picture, and utilities usually include their evaluation price projections and policy factors[27] in different scenarios to account for all potential risks and adjust their strategy accordingly. Depending on the timescale, the expenses that can effectively be managed by the utility are, in addition, not the same, which directly influences operational decisions.

Short term

In the short term, the operation of a power plant is justified if at least the marginal costs are recovered. The marginal costs are essentially fuel costs and variable O&M costs that vary depending on the technology. When electricity prices are low, fossil-fired plants, which are dominated by fuel costs, improve their economics by reducing the power output or even by mothballing their production until prices can be recovered. For high fixed cost technologies such as nuclear power, the economic optimum is to operate as baseload power. However, in a very long-term perspective, even fixed costs become variable.

Long term

In the long term, all of the expenditures (i.e. fixed and variable) are included in the decision-making process of continuing operations. LTO investments are evaluated in the context of a long time frame because they need several years (or even decades) to be completely amortised. LCOE (see Table 6.1) and/or NPV-based approaches are commonly used to inform the final decision. Revenues play a central role in the economic outcome (see Figure 6.6), and they are usually estimated using electricity price and other derivative[28] forecasts under different conservative scenarios. If the LCOE is too high (or the NPV is negative in most scenarios), the company may decide to cease nuclear operations completely. It is therefore necessary to understand the main factors governing electricity market trends in the long term, as well as the main regulatory and policy strategies that can be harnessed to address potential challenges.

6.2.2. *Market trends*

Energy-only markets and their emerging shortcomings

Energy-only markets are the main revenue source for all power generators in current electricity systems. There are essentially two types of energy-only markets: regulated and deregulated. In regulated markets, vertically-integrated utilities centralise and co-ordinate investment decisions in the entire value chain.[29] The overall economic viability of the investment is ensured by regulated electricity tariffs set by market regulators. In the 1990s, on the other hand, a number of regions and countries (e.g. Europe and some states in the United States) initiated the deregulation of electricity markets, unbundling the value chain and introducing competitive markets in generation and retail activities.

At the generation level, this implies that all dispatch and investment decisions in new capacity are strictly commercial and properly incentivised by electricity prices. In the short term, generators participate in day-to-day bids according to their marginal costs, balancing demand and supply over different time frames (i.e. marginal price-setting mechanisms). The resulting price ensures optimal dispatch at the lowest cost for the final consumers, while at the same

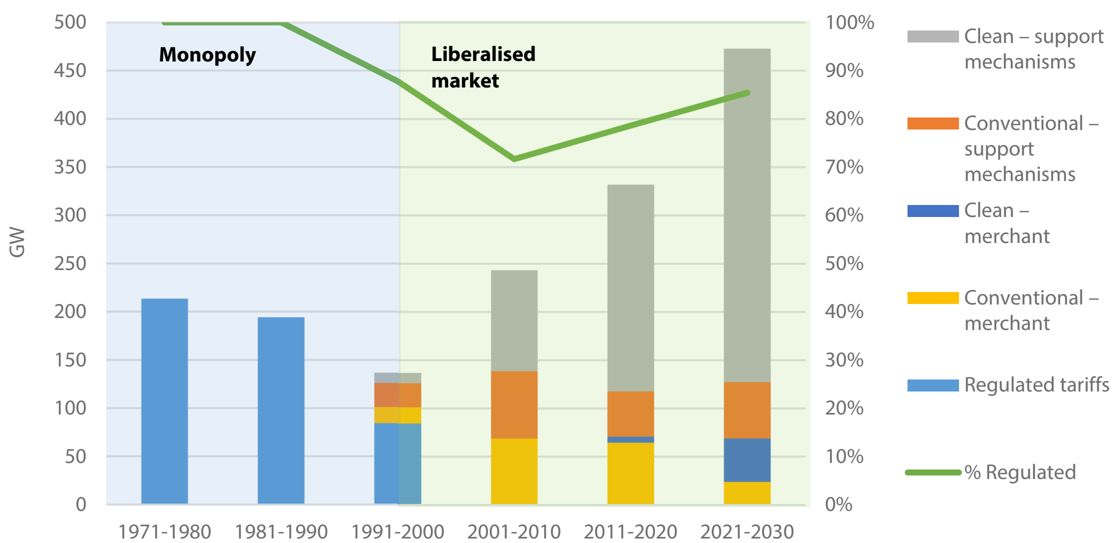
27. Through higher risk premia, for instance.
28. Especially if the utility hedges future income to a large extent.
29. The electricity value chain is formed by the generation, transport, distribution and retail of activities.

time fostering innovation. In the long term, electricity prices should trigger the necessary investments to guarantee optimal capacity adequacy in the system.

Empirical evidence indicates, however, that current deregulated electricity markets may suffer from a "missing money" problem, with prices that do not adequately reflect the value of new capacity investments to meet customer expectations and a reliable electricity supply (NEPP, 2016; Hogan, 2017). This is particularly the case for low-carbon capacity, since the high-fixed cost structure of this type of asset requires long-term price stability to become economically attractive for investors. Over the last ten years, most of the investments in deregulated markets have not been incentivised by the market but rather by specific regulations, subsidies or additional long-term payment mechanisms not emanating from energy-only markets (see Figure 6.8). Only a small share of total investment is merchant, as utilities prefer to undertake investments under support mechanisms to reduce their exposure to merchant risk, reflecting the limits of current deregulated markets to attract capital-intensive, low-carbon investments relying solely on market price signals.

These trends are set to continue over the next decade with significant, low-carbon investments needed to meet the emission targets set by the Paris Agreement. In practice, deregulated electricity markets may become more hybrid, combining deregulated mechanisms to ensure optimal dispatch in the short term, with some sort of public intervention and planning to properly guide investment trends and maximise system value and social benefits in the long term (Roques, 2017).

Figure 6.8: **Capacity additions in Europe by market regulatory framework**



Source: OECD/NEA, adapted from Roques (2021).

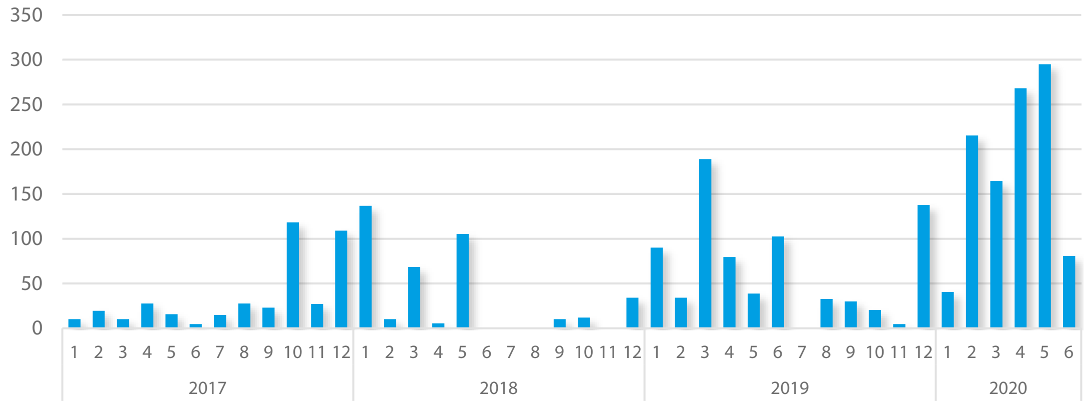
In order to properly assess the recovery of LTO costs over a given period, it is necessary to understand the main drivers influencing the formation of wholesale electricity prices in electricity markets.

The irruption of massive amounts of variable renewables (mainly wind and solar photovoltaic) over the last decade, underpinned by governmental support (see Figure 6.8) is pushing wholesale electricity prices down. Given the very low or zero marginal costs associated with VRE, they are dispatched ahead of any other technology, setting the final price at a lower marginal cost (i.e. the merit order effect). At high levels of VRE generation (and protected by out-of-the-market support mechanisms), VRE can become marginal units[30] and bid at zero or even negative prices. Episodes of zero or negative prices have been rising in Europe over the past years (see Figure 6.9) and could continue in the absence of measures to improve system flexibility in the short term and/or the implementation of more structural market reforms. This situation forces conventional generators such as nuclear power plants to further rely on uncertain and more volatile periods, when capacity is scarce, to recover their fixed costs, increasing overall risks and undermining their economic viability. In some regions, such an approach may not be politically feasible since price spikes may give rise to public concerns about market powers calling for administrative measures such as price caps (NEPP, 2016) or additional taxes.

Gas prices (or fuel costs) also play an important role in the formation of wholesale electricity prices as gas plants are usually marginal units. The decline of global gas prices that has been observed since 2012 has certainly contributed to lowering average wholesale electricity prices (EC, 2018). At the same time, strong geographical variations in gas prices exist, with gas transportation costs being higher than oil transportation costs. This results in three primary, segmented markets, with the United States presenting the lowest gas prices,[31] Asia the highest and Europe somewhere in between. While increasing liquified natural gas (LNG) exports may contribute to homogenising gas prices around the globe, gas market segmentation is also reflected, to some extent, in electricity prices which are set at different levels depending on the region.

Other factors influencing wholesale electricity prices include electricity demand growth and carbon pricing trends (IEA, 2019). Their relative importance varies from one country to another.

Figure 6.9: **Number of negative, hourly wholesale prices on selected, day-ahead trading platforms**



Note: The selected trading platforms are: N2EX, EXAA/EPEX-AT, APX-NL, SEMO-IE, CROPEX-HR, BSP-SI, OTE-CZ, DK1 west, BPX-BE, PNX-FR and EEX-DE.

Source: OECD/NEA, adapted from EC (2020).

As a result of the above factors, wholesale electricity prices have experienced various years of steady decline, thereby undermining the economic viability of LTO in some regions. Since 2012, 11 nuclear units in OECD countries have been retired purely for market reasons, more than 50% of them in the United States. In Europe, because of the higher gas and carbon prices, the overall number of early closures for economic reasons is more limited, with some isolated cases in Sweden (see Box 6.4 below). Overall, around 50% of the plant closures by 2025 will be directly

30. The marginal cost of the last unit of electricity produced, which sets the final electricity prices for a given period.

31. Following the shale gas revolution.

motivated by the plant economics (i.e. market and techno-economic factors; see Figure 1.2).[32] Based on the positive attributes of LTO in terms of decarbonisation, affordability and security of supply (see Chapter 2), this could lead to a net loss in the overall value of the system – and for the society as a whole. Different options exist to address the existing shortcomings of deregulated energy-only markets and foster the development of low-carbon systems in the long term, including LTO. In some particular cases, revenue diversification might also be an option to be explored in order to improve the economics of existing nuclear power.

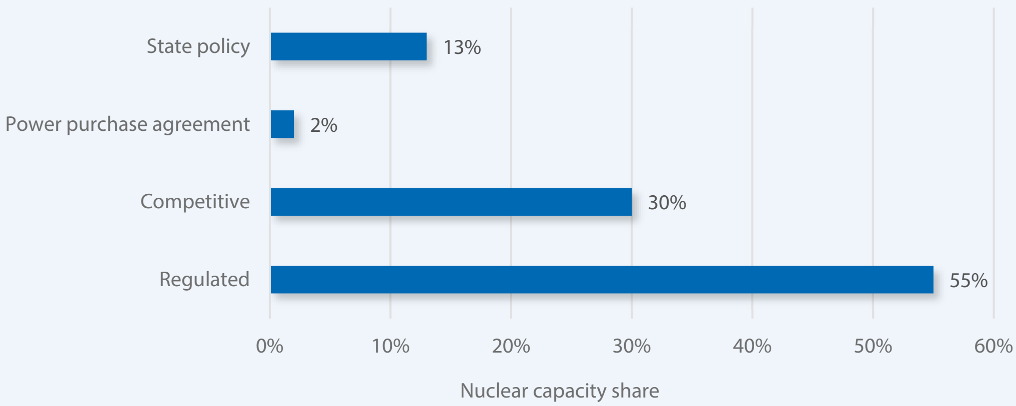
Box 6.4: **The impact of market conditions on LTO**

The market is one the main causes of early closures of nuclear power plants following policy decisions. Trends vary geographically, with the United States the country with highest number of closures for market reasons. Operators around the world have made significant efforts to achieve more efficient operations and reduce production costs. Nevertheless, in some cases, these efforts have been insufficient to offset the fall in power prices, and additional policy measures and regulations are thus required to enable competitive LTO.

United States

Between 2008 and 2015, wholesale electricity prices dramatically dropped in the United States: around 36% in the Midwest and 46% in the Mid-Atlantic regions (Haratyk, 2017). This low USD 30 per MWh range has been typical for electricity prices in recent years, resulting mainly from stagnant electricity demand since the 2008 financial crisis, combined with the shale gas boom in 2010 and the penetration of higher shares of VRE. Gas prices have more than halved since 2008, and they are 60% lower compared to prices in Europe, leading to more severe market pressures for nuclear reactors in the United States (IEA, 2019). In the face of such challenges, twelve plants have been taken off the grid since 2013, eight of them essentially based on negative market prospects, with five additional reactors to be retired by 2022[33] for similar reasons.

Figure 6.10: **US nuclear operating capacity by market type, 2019**



Source: EIA, 2019.

32. Note that, indirectly, positive market trends improve the economic case of LTO and enable more extensive refurbishment than would otherwise not have made economic sense under more degraded market conditions.

33. Palisades, Byron 1 and 2 and Dresden 2 and 3. According to the nuclear operator Exelon, Bradwood and LaSalle, nuclear power plants are also at risk of early closure for market reasons (S&P Global Platts, 2021a). Diablo Canyon units will be retired by 2025 for policy reasons (NEI, 2020).

The US market landscape is also quite heterogeneous in terms of market design, and mechanisms vary from one state to another. In general, US reactors operate either in regulated or competitive markets. Two nuclear power plants are selling their output under power purchase agreements, and some states support continuing operations with specific state polices (see Figure 6.10 above). More specifically, around 30% of the installed capacity performs under competitive markets and relies solely upon market signals to determine whether the plant should close or continue operations. These "merchant" plants are of course more exposed to market shifts and have a higher risk of shutting down prematurely than those owned by a regulated utility or a public power company.

The total production cost of the US nuclear fleet has fallen on average by almost 32% since 2012. Current generating costs are on average USD 38/MWh for single units and USD 28/MWh for multi-unit sites (NEI, 2020). Nevertheless, as of 2017, around two thirds of the nuclear fleet were still unprofitable, based on negative revenue gaps,[34] with the Midwest, California and Texas the most challenging market environments for nuclear energy (Haratyk, 2017; INL, 2017). The revenue gaps were on average USD 3.5-5.5/MWh, suggesting that most of these closures could be avoided at a cost lower than subsidising VRE and other support mechanisms. Recently, zero-emission credits (ZECs) have been approved in some states to support the continuing operation of nuclear power plants, based on their low-carbon attributes (see Box 6.5).

Sweden

Four plants (i.e. Oskarshamn units 1 and 2, and Ringhals units 1 and 2) were retired in Sweden in 2015 for market reasons. Nordic bidding zones observe structurally lower wholesale electricity prices than the rest of Europe, given the abundance of hydro and wind power and the stagnating electricity demand. In addition, these closure decisions were taken at a time when the nuclear capacity tax of EUR 8 per MWh was in place, but this tax was completely abandoned in 2018 as part of the parliamentary energy agreement reached in 2016. In fact, at the time that this tax was introduced (before the 1990s) power prices were high enough to ensure sufficient profit margins. However, because of falling power prices, the overall tax burden ended up representing around 30-40% of total revenues for nuclear operators. More recently, Swedish wholesale electricity prices have been steadily increasing (i.e. since 2016), partly as a result of the EU Emissions Trading System (ETS) reform, further improving the competitiveness of the remainder of the nuclear fleet in the country (IEA, 2019).

Energy-only market reforms

As illustrated in the previous section, energy-only markets have some limits in terms of sending long-term price signals that would ultimately enable the system to encompass value features, such as capacity, flexibility (i.e. dispatchability) and low emissions. The former two are becoming increasingly important in light of massive additions of VRE and uncertain prospects for the large-scale deployment of low-carbon, flexible solutions (e.g. storage, demand-side response, sector coupling). A range of additional remuneration mechanisms have been introduced to address the shortcomings of energy-only markets and foster low-carbon capacity investments in future. Their type, design and revenues vary according to national regulatory frameworks, energy policy objectives and system-specific constraints. While some of these mechanisms are quite straightforward and could rapidly support LTO in most unfavourable markets, questions remain concerning whether these additional remuneration mechanisms are to be a transitional measure or whether more structural market reforms may be needed to build and efficiently operate the clean energy infrastructures of tomorrow.

- Capacity remuneration mechanisms

Capacity remuneration mechanisms provide additional revenues to operators that ensure that a certain level of capacity will be available at a given point in time according to the system's needs, and dictated by national transmission system operators to meet peak demand. There are essentially two types of capacity mechanisms: strategic reserves and capacity markets.

34. The difference between the electricity prices and total generating costs of a nuclear unit.

Strategic reserves are meant for capacity that is expected to run a few times per year and that would be unprofitable otherwise without this type of special support. Its establishment is quite straightforward and has a limited impact on competitive energy-only markets.[35] On the other hand, capacity markets remunerate capacity that will be used more frequently, for instance to accommodate power fluctuations associated with high shares of VRE in the system. Typically, dispatchable technologies such as nuclear power, with its high-capacity credits[36] (approximately 95%), are eligible to bid in capacity markets.

Over the last years, a number of regions (e.g. some countries in Europe and states in the United States) have introduced capacity payments to overcome existing shortcomings in energy-only markets so as to ensure long-term system adequacy. The introduction of capacity markets should lead to an increase of installed capacity and enhance the ability of the system to meet peak demand at all times. In general, the revenues from capacity markets remain low compared to energy-only markets. The share of nuclear power in overall capacity eligible for capacity payments is typically lower percentage-wise than the share for gas plants (Jenkin et al., 2016; Ofgem, 2020). Such aspects largely depend on the specificities of each electricity system. In some cases, ill-designed capacity markets may encourage over-investments and distort cross-border trade and competition, especially if different national initiatives are developed in an uncoordinated manner (NEPP, 2016).[37]

- Direct support mechanisms

The feed-in tariff, feed-in premium, contract for difference and production tax credit are some examples of direct support mechanisms. In their design, these instruments either isolate low-carbon generators from market prices by guaranteeing a fixed revenue per unit of output, reduce the exposure to market risk or provide a tax credit for every MWh produced. In principle, they can be applied to any low-carbon technology and are the result of various policy motivations seeking to: i) support a specific technology; ii) recognise the economic disadvantages of low-carbon generators in current electricity markets; or iii) compensate low-carbon electricity generation (IEA/NEA, 2020). Thus far, these support mechanisms have been very effective in fostering the deployment of VRE and lowering their production costs (Figure 6.8). The protection that they confer from market shifts, however, have also induced some market distortions (e.g. generators bidding at negative prices in some countries, system costs not properly internalised) that have underscored the limits of current energy-only markets.

To date, the introduction of support mechanisms for LTO of nuclear power plants has been very limited. This can be explained by the competitiveness of this technology option, as well as by policy reasons. In the United States, where market pressures are significant, ZECs have been the privileged solution to sustain low-carbon capacity from nuclear power (see Box 6.5). While ZECs have proven to be an effective measure in the short term, additional efforts and more structural reforms may be necessary to support widespread LTO in the United States.

35. Strategic reserves cannot participate in the regular wholesale market but are activated by grid operators upon demand.
36. The capacity credit indicates how much a technology is relied upon to meet peak demand from a planning perspective (IEA/NEA, 2020).
37. This is typically the case in Europe.

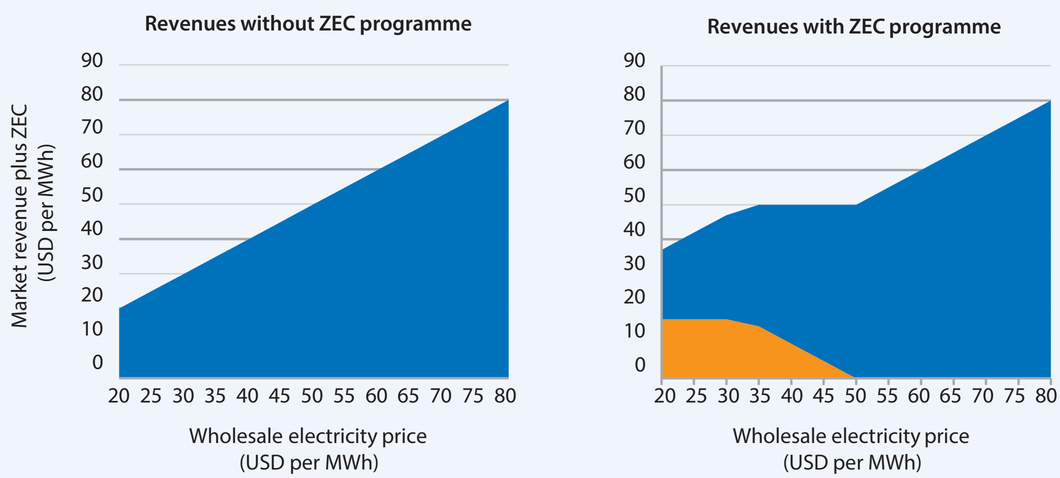
Box 6.5: **Pricing emission avoidance for nuclear power through ZECs: The US experience**[38]

Zero emission credits (ZECs) are payments that electricity generators receive to compensate for the valuable attribute of not emitting greenhouse gases during the production of electricity. ZECs work similarly to renewable obligations that support renewable energy production in many US states. Similar to renewable energy credits (RECs) that are generated by wind and solar generators and sold to utilities, ZECs are sold to utilities that are required to purchase a certain number of these credits from low-carbon generators. The utility then rolls the cost of the credits into electricity customers' bills, similar to the increase in retail electricity prices that would be expected through the introduction of a carbon tax or an emission trading system. From the point of view of a nuclear plant owner, ZECs provide a source of revenue for the service of reducing climate change-inducing greenhouse gas emissions, which had previously been provided free of charge. Some state air regulators and public health advocates have recognised these clean-air benefits, without anyone directly paying for these benefits directly. At the very least, ZECs internalise the service of low-carbon power production.

Since the idea of a ZEC is to provide the incentive to preserve non-emitting generation, the price of the ZEC should be related to the value of the avoided emissions. Initial ZEC programmes in New York and Illinois used the social cost of carbon (SCC) as the starting point for determining credit value. The SCC indicates the long-term economic impact of emissions. A central estimate of the SCC was established at USD 42 per tonne of CO_2. On this basis, regulators converted the SCC into a USD-per-megawatt-hour value by multiplying the SCC by the average emissions generated by plants running on natural gas or coal. For instance, New York set the value of the ZEC at USD 17.48/MWh. This is higher than the revenue gap observed in most US plants (INL, 2016).

How the basic ZEC framework operates is illustrated in Figure 6.11. Without ZEC, there is a one-to-one relationship between the market price of electricity and the final value received by the nuclear generator, as would happen in standard electricity markets. When a ZEC is introduced, the wholesale electricity price directly increases from a pre-set level. When electricity prices exceed a certain threshold, the value of a ZEC decreases based on a phase-out provision. In other words, in current designs, ZECs act as a price floor that is gradually removed as market prices rise, demonstrating the extent to which current ZEC programmes are temporary expedients to compensate for low electricity prices.

Figure 6.11: **Operation of the ZEC framework**



Source: IEA/NEA 2020.

38. Most of the content of this box is taken from IEA/NEA (2020) and it is based on a personal contribution by Mathew P. Crozat, Senior Director, Business Policy, Nuclear Energy Institute (NEI), United States.

While ZECs are an innovative policy instrument to remunerate low-carbon producers for the service of emission avoidance, they also impose an added cost on utilities, and to the extent that the latter can pass them on, to electricity consumers. ZEC programmes have thus been challenged in federal courts. It is also widely accepted that more widespread carbon pricing would be a more robust solution to these state-by-state solutions. From an economic point of view, it would be preferable if the contribution to emission avoidance by nuclear power, renewables and hydro were correctly valued at the SCC in a comprehensive carbon management policy framework. However, carbon pricing prospects seem remote in a US context. Overall, the ZEC programme could constitute a blueprint for remunerating emission avoidance in nuclear power, and the US experience could be useful for other countries.

- Carbon pricing

Carbon pricing mechanisms internalise the negative externalities of burning fossil-fuels (e.g. climate change, air pollution) by setting a price on carbon and making carbon-intensive generation less competitive. There are two primary means of establishing a carbon price: i) governments can impose a carbon tax to encourage a switch to less carbon-intensive production or consumption; or ii) they can introduce a cap-and-trade system (e.g. in Europe, the EU Emissions Trading System [EU ETS]). Hybrid approaches can also be adopted. The potential advantages and disadvantages of each mechanism are out of the scope of the present study, but these are discussed in more detail in IEA/NEA (2020).

As of April 2020, 20% of the global greenhouse gas emissions were covered by 61 carbon pricing initiatives: 31 using market-based emission trading systems and 30 using carbon taxes. Carbon prices vary widely across schemes, from less than USD 1 per tonne of CO_2 equivalent (tCO_2-eq) to USD 127/tCO_2-eq (i.e. the Swedish carbon tax). Since 2017, carbon prices in Europe have been steadily increasing after a reform limiting the number of carbon allowances. In May 2021, carbon prices in Europe reached 50 per tCO_2, a tenfold increase compared to price levels prior to the reform. Overall, carbon prices remain low, meaning that they have a modest impact on driving electricity prices up. Most of the initiatives set carbon prices lower than USD 30 per tCO_2 with only 5% being consistent with Paris Agreement pathways (IEA, 2020).[39]

Regarding the potential effects of carbon pricing, it is possible to identify different timescales. In the short term, the increase in the generation costs of carbon emitters will favour fuel switching (e.g. coal to gas). In the mid to long term, capital investment and demand patterns could change, as could technology deployment trends. In all situations, nuclear power and the existing fleet will directly benefit from carbon pricing approaches given its low-carbon emissions. At the same time, the distributional effects of carbon pricing[40] should not be neglected as they can raise social equity and acceptance concerns. There are indications that subsidising emission avoidance through support mechanisms is considered a politically more sustainable solution in a number of OECD countries (IEA/NEA, 2020).

In conclusion, both support and carbon pricing mechanisms are aimed at reducing emissions and properly recognising low-carbon emitters, but the policy and distribution implications are not the same. Thanks to a greater understanding and growing experience with these mechanisms, governments have a solid base to design packages encompassing both solutions in order to find the right balance between economic efficiency, emission reductions, and social equity and acceptance.

39. Explicit carbon price levels consistent with the Paris Agreement should be at least USD 40-80 tCO_2-eq by 2020 and USD 50-100 tCO_2-eq by 2030 (IEA/NEA, 2020).

40. Welfare transfers between different types of generators, as well as between electricity consumers, generators and governments, amount to USD billions annually (IEA/NEA, 2020).

Flexible operations

From a technical perspective, nuclear power plants are dispatchable generators, and extensive operational experience exists on their ability to provide services to the grid in terms of inertia, frequency control and load following. The dispatchability attributes of nuclear reactors can be enhanced, and some operators might consider implementing plant retrofits for flexible operations if the economics are sufficiently attractive (see Chapter 3).

The value that could be captured by nuclear reactors operating more flexibly, however, remains bounded by the characteristics of the system. The high fixed costs of nuclear make this technology economically suitable for baseload operation. Any variation in the capacity factor resulting from flexible operation will come at a significant economic penalty. On the order hand, more frequent and longer periods of zero or negative wholesale electricity prices in an electricity system with high shares of VRE may push utilities to perform load variations so as to stabilise prices and explore additional revenues arising from arbitrage considerations (i.e. saving fuel for periods with high electricity prices). The associated economic case for flexible operations in such contexts must be sound – and most likely supported by specific market regulations. Otherwise, baseload operations will naturally emerge as the most economic option for existing reactors.

Non-electric applications

Existing nuclear power plants can provide products other than electricity, which could help to diversify their revenues and better withstand electricity market changes after some plant adjustments. These products include heat production for district heating applications and the production of hydrogen, as well as the generation of radioisotopes. Such applications are not a novelty as they have already been implemented in the past in some operational reactors, in particular district heating and radioisotope generation applications.[41] The first pilot projects for hydrogen generation in existing reactors are under development in the United States.[42] The need to decarbonise hard-to-abate sectors and the associated market opportunities are reviving interest in nuclear non-electric applications.

The economic case for these types of applications relies on an opportunity cost assessment, the principle being to use the power generated in the core for other purposes when electricity prices are not attractive. The different opportunities currently being assessed are either pilot projects or are limited to specific plants close to demand or niche applications. Their economic viability and widespread deployment to support LTO remains uncertain, and is strongly subject to the competitiveness of other alternatives, especially for heat and hydrogen production.[43] In the case of radioisotopes, the impact on power output is negligible and can be considered as a co-product, directly improving the plant's revenues. The safety evaluations necessary for the implementation of non-electric applications should not be neglected as they entail licensing costs and additional investments that may not be recovered over the LTO period.

41. For instance, the two units of the Beznau nuclear power plant in Switzerland have operating in co-generation mode since 1985, supplying the Refuna district heating grid with 80 MWth. CANDU reactors take advantage of their online refuelling capabilities to ensure the generation of radioisotopes on a reliable basis, especially for medical radioisotopes that have to be supplied just-in-time given their short lifespans (e.g. molybdenum-99).

42. Various utilities, in collaboration with national laboratories and the US Department of Energy, are exploring the economic potential of hydrogen generation with low-temperature proton exchange membrane electrolysers and high temperature electrolysis at some specific plants. The technical and safety cases are making good progress. Currently, all of the hydrogen being produced serves the exclusive demand of the individual plants, but the objective in future is to scale-up the electrolysis facilities in order to improve the economics and sell hydrogen to nearby industrial customers (e.g. refineries, cement production facilities) (S&P Global Platts, 2021b).

43. Radioisotope generation can be considered as a niche market with a tight supply. These conditions significantly improve the business case.

Key findings

- Most LTO costs fall into three main categories: i) LTO programme; ii) the replacement of heavy components and other works; or iii) post-Fukushima costs. These categories can face significant shortcomings in practice, however, given the variety of accounting conventions and project scopes, which usually include expenses not strictly related to LTO. At the same time, actual investment patterns tend to be continuous and incremental rather than upfront. As such, it is possible to identify excess investments beyond regular maintenance costs over a given period, which can conservatively be attributable to LTO.
- LTO overnight construction costs can be conservatively estimated at USD 450-950 per kWe, which would lead to an LTO LCOE roughly ranging between USD 25-50 per MWh for most of the world's nuclear fleet. Consequently, LTO remains one of the most cost-competitive, low-carbon technology options in many regions, as confirmed by other recent studies (IEA, 2019; IEA/NEA, 2020).
- LTO project risks are low given their smaller and simpler scope compared to new build, and existing well-developed industrial capabilities. As a result, nuclear operators can carry these projects in their balance sheets with limited financing costs. At the same time, the cost structure of existing reactors is dominated by operational expenditures, which confers an economic advantage to withstand changing market conditions while improving the economic rationale for flexible operations. The share of fixed costs is nevertheless significant, increasing the exposure of existing plants to market risks, especially in those regions with sustained, low electricity prices.
- The result has been early closures for purely market reasons in some regions. These trends also reflect the limits of deregulated energy-only markets to secure low-carbon capacity in the long term. Various regulations and mechanisms are being used to support the development of low-carbon technologies, and these could be extended to LTO. The case of zero emission credits in the United States illustrates the effectiveness of such measures, but more in-depth and structural reforms may be required to reconcile low emissions, affordability and security of supply in current electricity markets. In some specific plants, revenue diversification based on non-electrical applications could be explored.

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7. Conclusions and policy recommendations: Enabling long-term operation

More and more countries are pledging to reach carbon neutrality by 2050, and most of these countries are currently operating nuclear reactors. Achieving the objective of carbon neutrality will be an enormous endeavour, requiring drastic emission reductions and a profound transformation of today's economic models in the coming decades. Against this backdrop, it has become increasingly apparent that phasing out existing nuclear capacity could make the transition towards the clean energy systems of tomorrow unnecessarily more challenging. Affordability and electricity security concerns are also at the core of sustainable energy policies, and the contribution of the existing nuclear fleet worldwide to each of these dimensions should not be neglected. Licence extensions, however, cannot be solely decided based upon policy priorities. They are first and foremost the result of safety considerations, which then must be evaluated under the lens of technical, operational and economic factors. Accordingly, the present report proposes a holistic approach that offers an overview of all of these factors in an attempt to identify the key enablers for long-term operation (LTO) of nuclear power plants. The approach assesses to what extent the internal capabilities (i.e. ageing, operational and human aspects, costs) of existing reactors would allow nuclear technology to remain competitive in the current and near-term external context (i.e. regulations, market and policy trends).

As demonstrated in the report, most of the risks that today prevent nuclear reactors from operating longer are driven largely by policy issues. In fact, early closures of nuclear reactors are primarily motivated by political decisions. In some regions, sustained, low wholesale prices that do not reflect the climate and reliability attributes of existing nuclear reactors are pushing some utilities to cease operations earlier than expected. While ongoing efforts to keep the highest safety standards and reduce operational costs must remain key priorities for the nuclear industry, government and policymakers nonetheless have a key role to play in supporting LTO so as to facilitate decarbonisation strategies.

LTO is a safe and mature solution to foster ambitious decarbonisation strategies

With 444 reactors in operation worldwide, nuclear power remains one of the main sources of low-carbon electricity generation in advanced economies. Long-term operation (LTO) trends continue to increase, with more than 30% of the existing nuclear fleet already operating beyond its initial design lifetime, according to different national regulations. Without widespread licence extensions in the next decade, annual carbon emissions could increase by 1.2 gigatonnes of carbon dioxide ($GtCO_2$) by 2050 (assuming that nuclear capacity is replaced by gas), putting emissions trajectories under stress.

At the same time, LTO is supported by an extensive scientific basis on the main ageing mechanisms and their management, as well as by a considerable amount of operating experience. If utilities continue to implement enhanced ageing management programmes using technical evidence already available, while performing the necessary repairs and replacements, long-term operation should not face any major generic technical barriers. Provisions in safety margins, and continuous monitoring through robust ageing management programmes and research, will nevertheless be necessary in order to properly anticipate and manage potential technical risks that may arise, particularly over very long operating periods.

Key policy recommendations [I]

1. **Maintain existing low-carbon capacity**: Decarbonising the electricity system will be even more difficult if existing low-carbon nuclear capacity is not included in the equation. LTO is a safe and expeditious solution to avoid carbon emissions for decades to come and to manage emission reduction trajectories in a predictable manner under ambitious decarbonisation pathways.

2. **Enlarge the technical basis of information on ageing mechanisms and their management**: Current LTO trends have been possible thanks to extensive research that has been conducted over the years. Longer operational time frames will increase the demands on materials and life-limiting components and will require continued R&D efforts to provide the necessary technical evidence for safe operation. Initiatives fostering international collaboration on lessons learnt in ageing management should continue to be pursued.

Existing nuclear power plants can be enhanced to cope with a changing environment

Existing nuclear reactors have never ceased to evolve from a technical and organisational perspective. Most of the components of a nuclear power plant can be replaced during regular maintenance outages, as well as during more extensive LTO refurbishments. These replacements attenuate the impact of ageing and allow operators to implement the necessary safety upgrades in accordance with the latest available regulations, knowledge and operating experience. These activities are complemented with ageing management programmes involving the entire organisation to continuously monitor the performance of life-limiting components (e.g. vessel, containment building) and take corrective actions when necessary.

Beyond ageing considerations, LTO refurbishments are also an excellent opportunity to implement plant enhancements that will allow for economic improvements in a changing context, including power uprates, information and control (I&C) upgrades (e.g. replacement of analogue equipment with digital one), flexible operations and overall plant modernisation. In some specific cases, non-electrical applications such as district heating, hydrogen production and radioisotope generation could be explored. The accumulation of extensive past and recent experience on these projects, combined with well-established governance and collaborative frameworks, are also unique mechanisms to accelerate potential adaptations and perform LTO based upon best practice.

Key policy recommendations [II]

3. **Support new technologies and plant enhancements**: Nuclear operators have at their disposal robust technical options to enhance and adapt their assets to an evolving context. With stable policies and risk-sharing initiatives, governments can facilitate their adoption and bring additional performance improvements during LTO.

4. **Foster co-operation to capitalise on extensive industrial experience**: An increasing number of utilities around the world are undertaking LTO refurbishments and implementing new technologies. External peer reviews and international operational experience sharing have proven to be effective tools to secure best practices and to enable longer operating periods and plant adaptations. Timely dialogue and co-operation with regulators are in most cases possible and help to accelerate the adoption of the most innovative solutions.

The supply chain is critical in sustaining operational and economic performance

LTO is one of the most cost-competitive, low-carbon technology options in many regions with a levelised cost of electricity (LCOE) ranging between USD 25-50 per megawatt hour (MWh). Cost trends have revealed that LTO refurbishments are well advanced in terms of stages of positive learning, with a constant inflow of projects that sustain industrial capabilities and lower the overall projects risks. At the same time, existing reactors have also observed steady improvements in relation to their safety and reliability levels, despite ageing, which can be explained not only by the replacement of components but also by increasing technical progress and operating experience, combined with governing frameworks that foster continuous improvements.

Obsolescence of structures, systems and components (SSCs) and supply chain issues, however, are an emerging concern, resulting largely from increasing policy risks, degraded market perspectives and high qualification needs. An increased used of commercial grade dedication for safety-related SSCs and the harmonisation of nuclear codes and standards (including the acceptance of alternative codes and standards in national regulations) are effective in mitigating such supply chain risks. Recent national examples have also demonstrated that regulators and operators can work co-operatively to reinforce the network of qualified suppliers. In parallel, problems related to attracting and retaining the best talent have also become pronounced. In light of such trends, and with nuclear power plants operating for longer periods, the ability of utilities to sustain operational excellence and economic performance during LTO could be undermined. Nuclear policies and international co-operation will be key in mitigating such risks.

Key policy recommendations [III]

5. **Sustain supply chain capabilities and nuclear expertise at all levels**: By committing to LTO, countries will directly sustain existing supply chain capabilities and send clear signals to younger generations to renew the nuclear workforce. These actions should be complemented by joint undertakings with regulators, industry and academia to foster nuclear expertise at all levels. Ongoing international collaboration can also play a role in preserving knowledge and developing human capital in the nuclear sector.
6. **Build long-term and predictable industrial plans**: High fixed cost technologies such as nuclear power require policy certainty. Coping with policy risks is sometimes possible, but with a significant cost penalty. Through nuclear industrial strategies, governments can provide the long-term, stable framework necessary to plan and optimise licence extensions.

Recognising the full value of the LTO option in decarbonisation strategies

Sustainable electricity infrastructures require policy frameworks that simultaneously address each pillar of the "energy trilemma": i) environmental protection; ii) economics and affordability; and iii) electricity security and reliability of electricity supply. Nuclear power, and in particular LTO, perform well in each of these three dimensions.

From an environmental perspective, licence extensions allow countries to secure carbon emission reduction trajectories at competitive costs. The affordability of LTO is also confirmed at the system level, where the availability of dispatchable generation, thanks to extended operations, will facilitate the integration of higher shares of variable renewable energy (VRE) at lower system costs. Dispatchability could also reduce the potential security of supply and reliability risks arising from the simultaneous retirement of large amounts of fossil-fired capacity, necessary to be consistent with 2015 Paris Agreement engagements. In interconnected systems, such as those in OECD countries, such positive effects could be noticeable across regions.

Longer operating periods will also bring additional value to policymakers beyond the energy trilemma. The additional time unlocked through LTO can be used to secure additional funding and the infrastructure needs for back-end activities, optimise investment and industrial plans and develop new technologies. The resulting, enlarged technology portfolio, combined with the relatively immediate effects of LTO decisions, adds more flexibility in the energy planning so that unexpected risks can be absorbed without jeopardising decarbonisation strategies.

Lastly, supporting LTO will require market regulations that adequately price all the aforementioned attributes and provide revenue certainty in the long term. The experience gained by governments in developing support mechanisms for low-carbon technologies could be used to develop policy packages for LTO in an effort to serve current decarbonisation pathways. Structural market reforms that will foster low-carbon investment and ensure long-term system adequacy will also benefit licence extensions.

Key policy recommendations [IV]

7. **Reform market regulations to ensure that the system value of long-term operation adequately remunerated:** In many regions, different types of regulations and mechanisms are used to overcome market challenges and support low-carbon technologies. These regulations and mechanisms can be extended to LTO in order to adequately remunerate the value that they provide to the system in terms of emission avoidance, but also in terms of system adequacy and grid reliability. Other options such as the review of nuclear taxation regimes can be envisaged as well.

Appendix 1: List of experts

This study was written by Antonio Vaya Soler from the Nuclear Energy Agency (NEA) Division of Nuclear Technology Development and Economics, based on evidence collected from the different references cited in the report, as well as the insights and specific inputs provided by the NEA Expert Group on Maintaining Low-Carbon Generation Capacity through LTO of Nuclear Power Plants: Economic, Technical and Policy Aspects (EGLTO) and other experts. EGLTO members, along with the NEA Working Party on Nuclear Energy Economics (WPNE), supervised the study at all stages and recognised its results. Additionally, the NEA Secretariat conducted individual interviews with senior nuclear industry professionals to collect insights from the industry on selected topics. A list of the different experts that formally participated in the study is provided below.

Members of the EGLTO expert group:

Country representatives

Mr Ricardo Sainz	Argentina
Mr Arnaud Meert	Belgium
Mr Jeff Lehman	Canada
Mr Paul Smeekes	Finland
Mr Myriam Colacicco	France
Dr Nobuyuki Ueda	Japan
Dr Masao Chaki	Japan
Mr Adrian Gabriel Dumitriu	Romania
Mr Eduardo Serra Sintes	Spain
Mr Jan-Erik Lindback	Sweden
Mr Steffen Asser	Switzerland
Mr Bruce Hallbert	United States

Representatives of international organisations

Ms Sherry Bernhoft	EPRI
Dr Aliki I. Van Heek	IAEA

Observers and other experts

Mr Koji Nagano	CRIEPI
Mr Paul-Etienne Pini	IAEA
Mr Oliver Martin	JRC
Mr Pablo Luna	NASA
Mr Gustavo Diaz	NASA
Mr Matt Crozat	NEI
Mr Alexey Lohkov	Rosatom
Mr Tim Freeman	SNC Lavalin
Mr Jean-Philippe Mathieu	EDF

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Long-Term Operation of Nuclear Power Plants and Decarbonisation Strategies

The existing nuclear fleet remains the largest low-carbon source of electricity generation in OECD countries. In 2021 the average nuclear power plant had already been operating for 31 years and some 30% of reactors worldwide were already operating under long-term operation conditions. The long-term operation of this existing nuclear capacity will be essential over the next decade to keep decarbonisation targets within reach. At the same time, by keeping the long-term-operation option open, countries could also reap a wide-range of socio-economic benefits including more affordable and secure electricity supply. Nevertheless, an increasing number of reactors are being shut down earlier than expected due to policy decisions and increasing market pressures in some regions.

In light of these trends, this study takes a holistic approach to identifying the key enablers for long-term operation of nuclear power plants. The attractiveness of long-term operation lies in its technical maturity, cost-competiveness and ease of implementation: it is a high-value option to support the energy transition while minimising potential risks along the way.

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