WORLD NUCLEAR ASSOCIATION

The Enduring Value of Nuclear Energy Assets

Long-term Operation Task Force

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Cover Photo: Bruce Power
Bruce nuclear power plant, Ontario, Canada.
The plant, first operated in 1977, is undergoing refurbishment
work to secure operation at the site until 2064.

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Executive summary

This World Nuclear Association technical position describes the benefits of long-term operation (LTO) of nuclear power plants, and the main considerations that need to be taken into account to ensure the longevity of nuclear operations in the years ahead.

LTO of nuclear power plants (*i.e.* operation beyond their original licence period or expected period of operation) allows these plants to generate reliable, low-cost, low-emission electricity for many years longer than originally envisioned and thus maximise their value. LTO has been successfully demonstrated and is now standard practice. While not all reactors will achieve longevity, most of the world's currently operating fleet of nuclear power reactors are technically capable of doing so. In fact, the majority of recent nuclear plant closures are attributable to worsening market conditions or else governmental decree, rather than to ageing-related issues.

It is becoming increasingly obvious that LTO of nuclear plants reduces energy costs and helps to protect the environment as part of a clean and resilient energy strategy. In most markets, LTO is the lowest-cost option for generating electricity, and is expected to stay that way for decades to come. With climate change now an urgent global issue, countries cannot afford to retire reliable, low-carbon energy generators that support the entire electricity system.

While LTO increases the value of nuclear reactor assets – both to operators and society at large – a reactor cannot be expected to operate indefinitely. LTO serves as a bridge to new build, helping to preserve core industry competencies in the supply chain and elsewhere. Moreover, refurbishment and modernisation projects as part of LTO preparation develop project experience that can reduce future new build costs.

A successful LTO programme requires action from the industry, government and regulators. Plant operators need to:

- Introduce a plant life management and design change management programme at an early stage.
- Conduct an assessment of political, economic, social, technological, legal and environmental threats and opportunities prior to licensing and modernisation.
- Take steps to amend the work culture to include a focus on modernisation projects and ensure the necessary human capacity, both internal and external, is in place.

Operators and suppliers should also ensure that components remain available over the increasingly long operating life of a nuclear plant. Innovation in an LTO sense should involve harmonising codes and standards internationally and the implementation of 'commercial grade dedication'. New technologies – including digitalisation, additive manufacturing, robotics, artificial intelligence, automation and advanced nuclear fuels – will also play a key role.

Governments should not only allow LTO of nuclear plants, but also remain actively and vocally supportive of nuclear and ensure policy continuity. They should provide investment in the necessary infrastructure with resources for education and training as part of an industrial strategy and redesign energy markets to recognise the benefits of nuclear plants.

For regulators, LTO requires ensuring the compatibility of existing regulatory frameworks with clearly-defined LTO requirements.

1 The remarkable longevity of today's nuclear power plants

While most of today's operating nuclear power reactors were originally designed for between 30 and 40 years of operation, there is in fact no fixed technical limit to the lifespan of a reactor. Operation of nuclear plants beyond their design lifetime is now commonplace, with regulatory compliance, safety and economic performance being assessed on a case-by-case basis.

A significant milestone was reached in 2019 when the world's oldest operating nuclear power plants achieved 50 years of operation. The first reactor ever to accomplish this was Tarapur unit 1 in India; this was joined soon after by unit 2, and later by Beznau 1 (Switzerland), Nine Mile Point 1 (USA) and Ginna (USA). These are the first of many reactors which will cross this threshold in the coming years, and which will continue to generate clean reliable electricity for decades longer than originally anticipated.

Long-term operation (LTO) of nuclear power plants has been successfully demonstrated and is increasingly recognised internationally as standard practice. The USA has one of the oldest fleets of nuclear power plants, with most reactors already having had their operating licences renewed, allowing them to operate for a further 20 years beyond their initial 40-year operating licence period. Despite their age, these plants continue to achieve outstanding performance with capacity factors in excess of 90%. Many plant operators in the USA are now pursuing a subsequent licence renewal which would permit them to operate their plants for a total of 80 years. In December 2019, Turkey Point in Florida became the first plant in the world to be approved for a subsequent renewal.

Different countries each face their own set of challenges when it comes to nuclear plant ageing, and not all reactor technologies will be able to

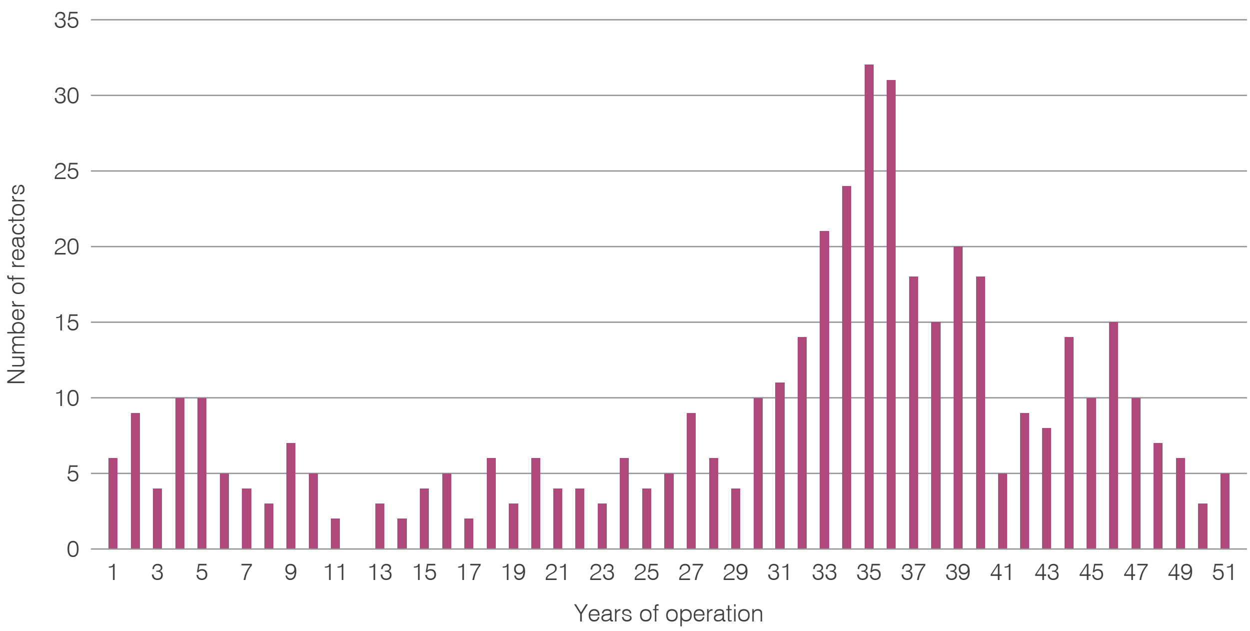

Figure 1. Age profile of operating reactors as of January 2020 (source: International Atomic Energy Agency PRIS database)

Table 1. Nuclear power plants by technology type, as of May 2020

Reactor type	Main countries	Number	Fuel	Coolant	Moderator
Pressurised water reactor	USA, France, Japan, Russia, China	298	enriched UO_2	water	water
Boiling water reactor	USA, Japan, Sweden	65	enriched UO_2	water	water
Pressurised heavy water reactor	Canada, India, China	48	natural UO_2	heavy water	heavy water
Advanced gas-cooled reactor	UK	14	enriched UO_2	CO_2	graphite
Light water graphite reactor	Russia	13	enriched UO_2	water	graphite
Fast neutron reactor	Russia	2	PuO_2 and UO_2	liquid sodium	none
	Total	440			

achieve longevity. For example, the UK fleet of advanced gas-cooled reactors (AGRs) is currently expected to close down during the 2020s at an average age of 40-50 years as irreplaceable life-limiting graphite components start to deteriorate. The Russian fleet of RBMKs also faces graphite challenges, which are reducing the performance of these units and expected to limit their operating lifetimes to about 45 years. However, these designs account for only a small number of the world's nuclear plants. The majority are pressurised water reactor (PWR), boiling water reactor (BWR) and pressurised heavy water reactor (PHWR) designs, which do not face these particular constraints. In addition, the science of ageing management and mitigation keeps evolving. Solutions may even yet be found for graphite-based reactors that permit them to operate longer than currently expected and with higher capacity factors.

1.1 Why do some reactors close prematurely?

Most recent nuclear plant closures are not attributable to component ageing issues, rather they are the result of worsening market conditions, economics, or governmental decree. In many places it is the government that decides when to close a reactor. Even where the decision sits with operators, governments have the power to introduce new taxes or market changes which can effectively force plants to close. Alternatively, they can push regulators to develop new standards which require investments that existing plants cannot justify. Where governments have taken supportive actions (*e.g.* in several US states), plants have avoided premature shutdown. The choice over whether to build a nuclear power plant and how to sustain and/or regulate it remains fundamentally a sovereign one.

Many of the recent economic closures have taken place in the USA where the emergence of hydraulic fracturing technology has created a very cheap shale gas resource that has caused a reduction of electricity market prices, which in turn has driven the closure of some nuclear plants, primarily older single-unit ones. However, the market structure has also played a substantial role. In Sweden and Spain, recent reactor closures are primarily attributable to government taxes on nuclear plants.

Recent politically driven reactor closures have mostly taken place in Europe, particularly Germany, and in certain Eastern European countries as a condition for joining the European Union. South Korea and Taiwan have also closed units as part of recently-announced phaseout policies.

While some reactor closures can be ascribed to a single cause, most are driven by multiple interrelated reasons – a combination of politics, regulations, maintenance costs and market factors working together. For example, a number of reactors in Japan have retired following the Fukushima Daiichi nuclear accident. The tsunami on 11 March 2011 led to the destruction of four reactors, but utilities across the country have since struggled to obtain permission from local governments to restart reactors and some have decided not to upgrade old units to meet new safety standards, citing costs. The national government now targets returning to a 20-22% share of nuclear by 2030 and is encouraging utilities to pursue efforts to comply with the new regulations for at least half of the pre-accident fleet.

1.2 The value of LTO

The trend of reactors closing due to plant-level economics and political reasons is troubling as it is becoming increasingly obvious that LTO of nuclear plants generally reduces energy costs for consumers and helps to protect the environment as part of a decarbonisation strategy. A growing number of civic groups and international organisations are calling for nuclear energy to be recognised as a climate priority and are putting pressure on governments to stop plants from retiring prematurely.

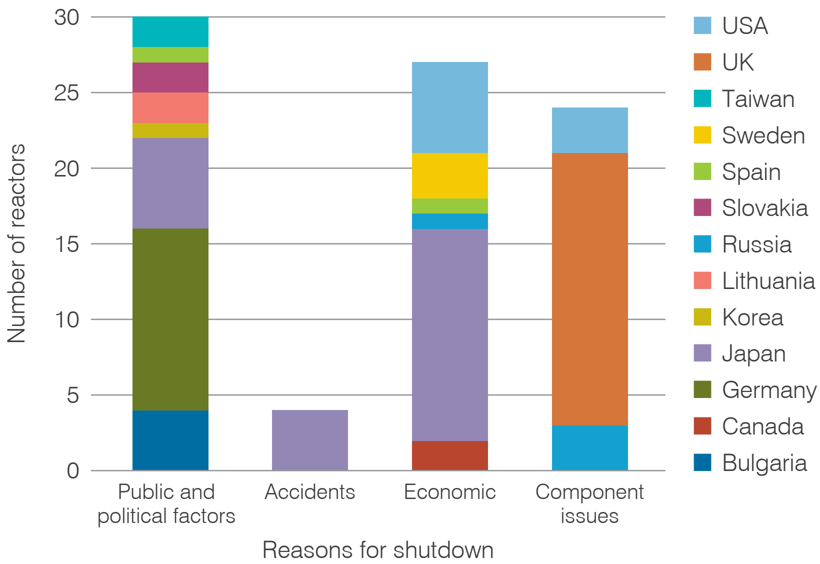

Figure 2. Number of nuclear power reactors retired from 2000 to January 2020, listed according to reason

In most energy markets, LTO is the cheapest option for generating electricity on a Levelised Cost Of Electricity (LCOE) basis, and is expected to stay that way for decades to come. While in most developing countries, new nuclear remains among the cheapest low-carbon technologies, in developed countries, such as the United States, it costs over twice as much to build a First-of-a-Kind nuclear plant as it does to upgrade and extend the operating lifetime of an existing plant (Figure 3). In both cases, LCOE for nuclear internalises all costs including waste management. By contrast, LCOE does not internalise the costs of carbon associated with fossil fuels, nor the grid enhancements and balancing, frequency control and electricity backup/storage needed for variable renewables. These costs must be met by the consumer.

Even where other options are cheaper and market conditions are challenging, nuclear plants offer many benefits beyond just electricity. Among the key factors influencing its future prospects is whether governments recognise and reward these qualities when determining the market framework.

Benefits of nuclear energy

- Low-carbon, with low life-cycle emissions
- Small land and resource footprint compared to other energy sources
- Avoids pollution such as NOx, SOx, heavy metals and particulate matter
- Provides continuous power, or can load follow if desired supporting peak and low demand
- Increases resilience, by decreasing vulnerability to extreme weather phenomena and external threats
- Provides rotational inertia that helps to stabilise the grid and regulate frequency
- Enables stockpiling of fuel, which boosts security of energy supply
- Major employer in non-urban areas, supporting skilled hi-tech jobs and local economic activity
- Can provide isotopes and support for research, medicine, industry and agriculture
- Can enable decarbonisation of heat, industry and transport sectors

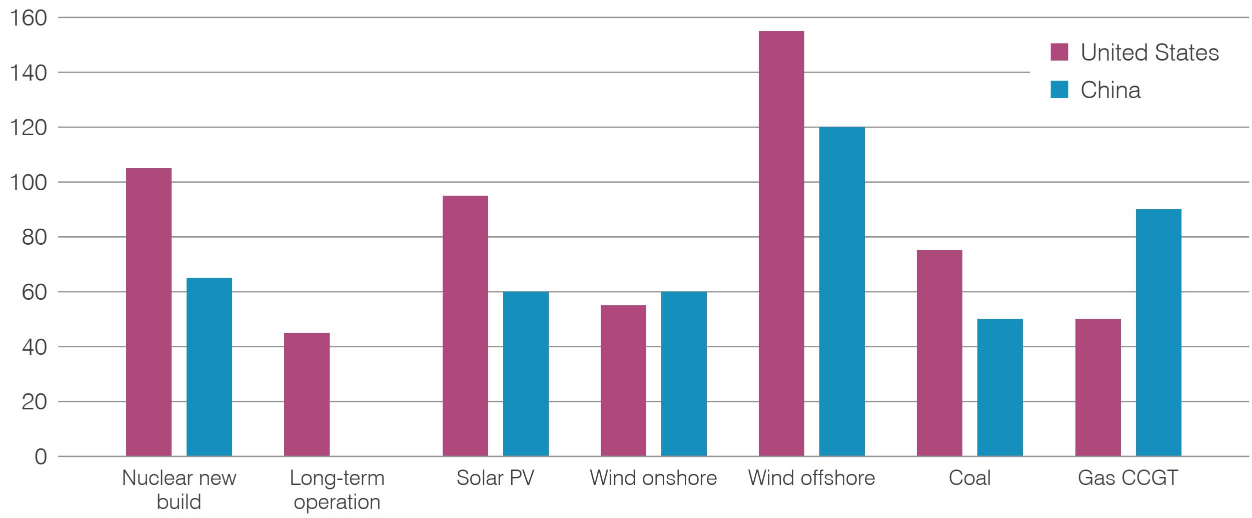

Figure 3. Levelised cost of energy (LCOE) by technology for China and United States (data: WEO 2019, IEA)

Nuclear energy is increasingly being recognised as a crucial technology for combatting climate change which, following the publication of recent scientific reports[1], has grown in terms of public urgency. According to IEA Executive Director Fatih Birol: "Lifetime extensions for nuclear plants are not only a cost-effective solution, but also keep our climate targets alive… They are the most urgent policy challenge today." [2]

Countries cannot afford to delay emissions reductions by retiring reliable low-carbon energy generators instead of fossil plants. For instance Germany, despite being considered by many to be an environmental champion, emits the most carbon dioxide in absolute terms of any European country[3] and appears to have locked itself into a fossil-dependent future as a result of its nuclear phaseout policy. This point was reinforced with its recently announced coal phaseout timetable, which would see the country exit coal by 2038 while still maintaining gas dependence after then.

From the perspective of a nuclear plant operator, LTO of existing nuclear plants makes a lot of sense. Operators have experience with the technology as well as the necessary staff and supporting infrastructure. The licensing process will be cheaper and easier than the one associated with building a new nuclear facility and it also allows for more time to build up waste disposal and decommissioning funds. The local community is also likely to be supportive of the facility and partially dependant on the revenues the plant generates. Closing a nuclear power plant causes a significant degree of social upheaval; for example, when Vermont Yankee in the USA retired in 2014, over $60 million was lost to the local economy and at least $12 million in taxes. The loss of jobs has affected businesses and the nearby town of Vernon decided to disband its police department[4].

Part of the reason that LTO of existing nuclear plants is so attractive is that recent experience with new build in the USA and Europe has seen projects run dramatically over time and budget. However, as existing plants eventually have to close, LTO cannot be considered to be a replacement for new nuclear build. LTO is fundamentally a stop-gap measure and requires less investment. Nevertheless, building new nuclear plants is essential both to the long-term prospects of the nuclear industry and for meeting climate goals. LTO should serve as a bridge to new build, helping to preserve core industry competencies and developing project experience, which in turn can help bring future new nuclear costs down.

[1] See for example: Intergovernmental Panel on Climate Change, *Global Warming of 1.5 °C* (2018)

[2] Financial Times, *Western countries urged to maintain nuclear power plants* (28 May 2019)

[3] Energy For Humanity, *European Climate Leadership Report 2017: Measuring the Metrics that Matter* (November 2017)

[4] Meredith Angwin, Nuclear Engineering International, *Circles Of Pain Around Vermont Yankee Closing* (28 January 2015)

2 Ensuring a successful LTO programme

Several factors must be addressed in order to ensure that LTO projects are cost-effective and keep plants running beyond their original design operating lifetimes and licence periods at high performance levels. This involves preparation and planning from the industry (including both operators and the supply chain) as well as regulators and policy-makers.

2.1 Operators

For nuclear plant operators, LTO should be considered as early as possible, and preferably at the design phase of the project. A range of factors will affect the required preparation for LTO, such as regulatory readiness, the size of the fleet and any previous experience with LTO. Delaying this preparation may increase the costs and risks of an LTO project.

Establishing a plant life management programme (PLiM) is essential. The purpose of a PLiM is to identify all the factors and requirements for the overall life-cycle of the plant in order to maintain a high level of safety and optimise plant performance. It integrates ageing monitoring with economic planning, and addresses extended lifetime ageing issues, maintenance prioritisation, periodic safety reviews, and education and training.

As part of PLiM, operators should adopt outage and maintenance optimisation techniques, utilising modified condition-based maintenance where possible, working to support an optimised long-term asset management plan. Experience gained over years of operation can be used for the next phase of procedures and tooling.

Successful LTO is also dependent on effective design change and knowledge management programmes being in place. This is especially important for maintaining fleets of standardised reactors. Over time, many plants have undergone alterations that have not been sufficiently documented, making the process of upgrading and replacing components and systems more challenging.

Prior to commencing any LTO upgrades and licensing activities, plant operators should also analyse the opportunities and threats likely to emerge in the coming decades. This means taking into account the growth of new technologies – such as renewables, smart meters and electric vehicles – and considering whether they need to adapt nuclear operations by introducing load following or potentially exploiting cogeneration opportunities such as hydrogen production, district heating or other industrial applications in order to maintain economic viability.

Certain plant economic and legal factors must also be addressed prior to licensing. For example:

- Ownership. Some currently operating plants have complex ownership structures and multiple owners who may not all agree on whether to pursue LTO. If the plant is to keep operating, it may be necessary to change the ownership structure or at least to create a clear pathway by which decisions can be reached.
- Site lease. It may be necessary to renegotiate use of the site.
- Market conditions. Factors to be considered include whether it will prove possible to secure a return on LTO investments in the new period of operation. For example, will a long-term power purchase agreement be available?
- Decommissioning and waste management funds. Ongoing payments to these may need to be adjusted to reflect the extended period of operation and future waste volumes.

A final consideration for nuclear plant operators contemplating LTO is the human one. A plant operating lifetime of 60 years is longer than the working life of an average person. This means that new staff will have to be trained to replace experienced veterans – probably several times over – during the plant's eventual operating lifetime. However, workforce expectations are evolving, with, among other things, a greater emphasis on flexible working conditions, a desire to always be digitally connected and a preference for 'bottom-up' management styles. Plant operators should therefore take steps towards adjusting workplace culture and employment benefits to ensure that a suitably qualified workforce can continue to be attracted in the coming years.

2.2 Supply chain and innovation

Some of the more intractable LTO challenges relate to the supply chain. Nuclear infrastructure is long-lived, and components are replaced infrequently. The relatively small number of high value orders for some components makes it hard for suppliers to justify maintaining expensive nuclear certifications, resulting in a smaller pool of suppliers and higher costs. Operators and suppliers need to cooperate to find ways of ensuring a ready supply of consumables stays available over the entire operating lifetime of a nuclear plant.

There is a strong drive for innovation in the nuclear sector, which is rooted in the recognition of nuclear's essential role in a low-carbon energy mix and the need to accelerate the development of complementary technologies. When it comes to LTO, innovation is often linked to obsolescence. Nuclear plants face challenges with the availability of components that may no longer be offered or supported. In addition, nuclear industry standards often preclude the use of 'off-the-shelf' items which can be used in other sectors and licensing requirements require diverse and redundant systems be maintained as part of defence-in-depth – meaning that older systems must be kept in service either as a back-up or alternatives to newer systems. The classic example is rotary phones, which many facilities still use. Innovation from the perspective of LTO involves greater efforts to harmonise codes and standards internationally and the implementation of 'commercial grade dedication' – whereby more commonly available commercial grade items are qualified for use in the nuclear sector.

New technologies also have an important role to play. Key LTO enabling technologies include:

- Digitalisation/digital twinning. This can assist with design change/knowledge management activities.
- Additive manufacturing. This can ensure the availability of some bespoke components that suppliers may stop providing.
- Automation and sensor technologies. Plant telemetry will facilitate better system health monitoring and maintenance regimes, prolonging the life of critical components.
- Artificial intelligence. This can help to improve project scheduling thereby reducing the cost, time and risks of outages and upgrades.
- Robotics. New robots are increasingly finding applications in difficult to access and high radiation environments, allowing tricky maintenance tasks to be carried out remotely.
- New fuel designs. These can improve safety and decrease the risks and impacts of accidents while facilitating flexible operations and power uprates.

2.3 Government, regulators and stakeholders

The role of government is to remain actively and vocally supportive of nuclear and ensure policy continuity. It is not enough for governments to simply allow LTO, they need to actively invest in it. This means:

- Investing in basic education and higher-level academic institutions and training programmes to ensure that there is a skilled pool of workers.
- Developing an industrial strategy so that the supply chain is in place.
- Reforming markets so that they value the non-power benefits of nuclear alongside other clean energy technologies.
- Public participation for LTO is a requirement in some countries but not others. For countries that do require it, the government should ensure that the process is transparent and that stakeholders are provided with fact-based information not only on safety and environment risks but also on socio-economic benefits.

Phaseout policies, even if temporary, will disrupt LTO activities and are likely to increase the costs in the future as companies and financial institutions factor in policy risk of doing business in the country. They will make national climate targets harder to reach.

Throughout the plant operating lifetime, regulatory body organisational and personnel changes will affect the LTO programme implementation, hence regulatory bodies will also need to have a long-term programme with respect to LTO. The existing regulatory framework should be compatible with LTO requirements, which should be clearly defined. This can be ensured by having an adequate legal authority, technical and managerial competencies, and human and financial resources. International cooperation between regulators can also facilitate LTO by sharing operational history from similar plant and lessons learned from other LTO programmes.

The relationships between the operator, the government and the regulatory body are important components, as are the identification and relevant engagement with other stakeholder groups (*e.g.* local communities). It will be important to re-evaluate existing engagement and communication efforts to determine their effectiveness with regard to the objectives and particular challenges of LTO – just because certain engagement and communication approaches have worked in the past, it does not mean they will continue to work.

3 Conclusions

Long-term operation (LTO) of nuclear power plants has been successfully demonstrated and is now standard industry practice. The vast majority of nuclear power plants operating around the world today are technically capable of operating for 60 years and even longer, with 80 years being the new benchmark. LTO means that existing nuclear plants can continue to produce large amounts of reliable, low-carbon electricity for much longer than originally envisioned, thereby dramatically increasing the value of these extraordinary generating assets.

The main factor behind most recent reactor closures has been politics rather than technical capability. Most of the closures which are commonly attributed to economic reasons also have a strong political element; *e.g.* the Japanese plants where utilities have decided against implementing expensive upgrades required by regulators as a condition of restart following the March 2011 accident at the Fukushima Daiichi plant. Most of the remaining economic closures reflect market failure rather than a genuine lack of competitiveness from the plants affected. The trend of reactors closing for political and market reasons urgently needs to stop if countries are serious about decarbonising their energy supplies and preserving the many other benefits these plants provide.

While LTO is an urgent global priority, it should not stop existing nuclear countries from also pursuing the construction of new reactors. Operating nuclear plants will eventually need to be replaced and LTO can serve as a bridge to nuclear new build by ensuring that key competencies are retained. LTO and new nuclear build programmes should be pursued in parallel to help meet carbon dioxide reduction targets.

Action from the industry, government and regulators is urgently needed to maximise the output of existing nuclear plants. Plant operators should:

- Introduce a plant life management and design change management programme at an early stage.
- Conduct an assessment of political, economic, social, technological, legal and environmental threats and opportunities prior to licensing and modernisation.
- Take steps to amend the work culture to include a focus on modernisation projects and ensure the necessary human capacity, both internal and external, is in place.

Operators and suppliers should also ensure that components remain available over the entire operating lifetime of a nuclear plant. In addition, codes and standards should be harmonised internationally to broaden the supply chain, and efforts should be made to increase 'commercial grade dedication' (whereby commercial grade items are qualified for use in the nuclear sector). Innovative new technologies – such as digitalisation, additive manufacturing, robotics, artificial intelligence, automation and advanced nuclear fuels – will also play a key role.

It is not enough for policy-makers to simply legally allow LTO; they need to remain actively supportive of their country's nuclear sectors and ensure policy continuity for LTO to occur. They should invest in the necessary infrastructure – providing resources for education and training, implementing an industrial strategy and redesigning energy markets to recognise the benefits nuclear energy brings. With the help of governments, existing nuclear plants will play a larger role in helping to reduce emissions, lower energy bills and keep the lights on than previously envisioned.

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With the average age of the global nuclear fleet exceeding 30 years, the global nuclear industry is focusing more of its attention on ensuring plants continue to perform reliably and meet regulatory requirements in some cases for longer timeframes than were envisaged when the facilities were commissioned. A number of plants have already operated for 50 years, and several utilities are committed to operating their facilities to 60 years, with a few preparing for 80 years. This World Nuclear Association technical position describes the benefits of long-term operation of nuclear power plants, and the main considerations that need to be taken into account to ensure the longevity of nuclear operations in the years ahead.

The Long-term Operation Task Force provides a forum for experts from throughout the industry to exchange leading practice and new developments in relation to long-term operation. It further seeks to: demonstrate through research, analysis and development of positions that long-term operation of nuclear facilities is proven and viable; identify and advocate policies that can help facilitate the long-term operation of nuclear facilities; promote improved safety, efficiency and innovation in long-term operation.