Nuclear Energy in the Circular Carbon Economy (CCE)

A Report to the G20

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;

– to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

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.

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Executive summary

Over the last 70 years nuclear power has played an essential role as a competitive source of reliable and sustainable energy in many countries. Today, with 400 GW of installed capacity and about 10% of the world's electricity mix, nuclear is the first source of low-carbon electricity in advanced countries and the second in the world after hydropower.

A growing role for nuclear power as part of the circular carbon economy

In line with the decarbonisation objectives of the Paris Agreement, nuclear power is expected to play a growing role over the coming decades. According to the International Energy Agency (IEA) Sustainable Development Scenario (SDS), installed nuclear capacity needs to increase by about 35% between 2020 and 2040 in order to meet Paris goals. Scenarios from the latest Intergovernmental Panel on Climate Change (IPCC) report also offers a broad range of trajectories to meet the 1.5°C target by 2100. Most of these scenarios foresee an important role for nuclear power with a median increase of the world nuclear reactor fleet by about 115% by 2050.

Meeting this expected growth will require mobilising both the existing nuclear reactor fleet through long-term operation, and deploying new nuclear reactors. In that respect, the nuclear sector has a comprehensive technological offer to meet different market needs. This includes Small Modular Reactors (SMRs) that can be especially well suited in terms of capacity range for the replacement of ageing coal power plants, large Gen-III reactors to meet electricity demand growth in emerging countries and the fleet renewal needs expected in more advanced economies, and Gen-IV reactors with a range of applications thanks to alternative coolants and higher thermal power.

Electricity market reforms and government leadership are essential to foster the development of nuclear energy

However, to meet the target of the SDS scenario, at least doubling the annual installed new nuclear capacity is needed compared to current trends. This increase would be even more significant when looking at IPCC scenarios. A number of specific enabling policies can support these efforts, in particular to attract low cost financing for new build and to support a level playing field across low-carbon electricity technologies. In that respect, a number of electricity market reforms are not nuclear specific but applicable to all low-carbon and capital intensive electricity technologies. In addition, support for innovation, nuclear R&D and efforts to establish international licensing frameworks are also important policy measures that governments wishing to foster the development of nuclear energy should pursue.

More generally, a more forthright recognition by governments and international organisations of the value of nuclear energy's attributes and its contribution to decarbonising the world's energy systems would encourage policy makers to explicitly include nuclear energy in their long-term energy plans and Nationally Determined Contributions under the Paris Agreement.

Similarly, given the long-lasting and deep structural impacts of a nuclear programme on a country's economy and its electricity system, governments must consider nuclear projects as national infrastructure projects of strategic importance. This translates into a clear government responsibility in terms of leadership as well as in uniting various stakeholders – including the public at large.

Non-electric nuclear applications offer significant potential to decarbonise hard-to-abate sectors

As part of the circular carbon economy, the role of nuclear power in future low-carbon energy systems does not stop with baseload electricity. First, most existing and new nuclear power plants can operate in load-following modes that support the integration of variable renewables and maintain electricity security. Second, and just as important, nuclear energy offers unique opportunities to deliver valuable non-electric applications, ranging from district and industrial heat applications, desalination, and large scale hydrogen production.

These non-electric nuclear applications are often neglected in policy debates. This is partly due to the fact that reference decarbonisation scenarios, such as those referenced by the IPCC or developed by the IEA, simply do not include these proven and scalable technological solutions as part of their modelling hypotheses. This is unfortunate, as nuclear energy is one of the few low-carbon energy sources that can generate both heat and electricity. Nuclear heat could in fact play a significant role in decarbonising hard-to-abate sectors, such as high temperature industrial heat applications. These applications also offer competitive value propositions: for instance, coupling nuclear power plants with hydrogen electrolysers allows to operate them with a high load factor, which is critical for the cost competiveness of low-carbon hydrogen.

Nuclear power has a role to play in a post-COVID-19 recovery

As G20 countries recover from the COVID-19 crisis, governments should take advantage of the economic recovery stimulus to accelerate the energy transition towards meeting their climate objectives. Countries should invest in the creation of a modern resilient infrastructure that provides stable, high value jobs for equitable and sustainable economic development.

Nuclear power is one of the low-carbon energy sources best prepared to help many countries achieve these goals. Nuclear power projects are a cornerstone of a resilient energy infrastructure, capable of supplying large amounts of low-carbon electricity and heat cost effectively while creating a large number of high-value jobs in the local and national economies. Each project also builds a well of valuable infrastructure for research and innovation.

Recommendations to the G20

This report highlights the potential role of nuclear in contributing to the circular carbon economy as a low-carbon source of electricity, but also as a source of heat and system integration services. It further highlights the essential role played by the existing nuclear reactor fleet in supporting the resilience of the electricity system through the COVID-19 crisis, and the significant role that the nuclear sector can play in post-COVID-19 recovery efforts.

As with all low-carbon technologies, a number of enabling policies are needed for nuclear power to play its full role in the circular carbon economy. They are outlined in the last section of this report. Building on these conclusions, G20 countries could take specific action in a number of areas, both individually and collectively:

G20 actions for nuclear new build and existing reactor fleets

- **Include nuclear in post-COVID-19 economic recovery plans**. Governments should take advantage of the post-COVID-19 economic recovery to accelerate the energy transition towards meeting climate objectives. Countries should invest in the creation of a modern, resilient infrastructure that promotes stable high value jobs for equitable and sustainable economic development. Nuclear power is one of the low-carbon energy sources best prepared to help many countries achieve these goals.
- **Capitalise on lessons learnt from recent Gen-III construction projects**. With the construction of several FOAK Gen-III nuclear reactors completed, the nuclear industry and its supply chain have in large part redeveloped their capabilities in several OECD countries. By building on these reactor designs, governments have a window of opportunity to realise cost reductions in the early 2020s through timely new-build decisions. Delaying these decisions will prevent the sustainment of capabilities and therefore raise near-term project construction costs.
- **Foster electricity market reforms**. All low-carbon technologies are characterised by large fixed costs and low marginal costs. This type of cost structure is not well suited to withstand the volatility of current deregulated electricity markets. Electricity market reforms are needed to create a level playing field for all low-carbon generation technologies, including support for existing nuclear power plants and new build.
- **Support emerging nuclear technologies**. Increase support to emerging nuclear technologies, in particular small modular reactors (SMRs), that are nearing market deployment and could significantly broaden the contribution of nuclear power to the circular carbon economy.
- **Include nuclear in sustainable finance initiatives**. Nuclear energy should be included in future sustainable finance schemes considering its low-carbon content, benign lifecycle environmental footprint, and the feasibility of long-term solutions for the management of nuclear materials and wastes. In particular, a recent NEA report highlights the international scientific consensus on the safety and effectiveness of deep geological repositories (DGRs) (NEA, 2020a).

G20 actions for non-electric nuclear applications

- **Support nuclear cogeneration demonstration plans**. There is significant focus in the decarbonising all energy sectors, particularly those that cannot be easily electrified. Since nuclear energy is one of the few low-carbon energy sources capable of producing heat at the same time as electricity, optimising the use of this heat, particularly for hard-to-abate energy sectors, can significantly foster the contribution of nuclear energy to the circular carbon economy.
- **Prioritise low-carbon hydrogen production**. Nuclear hydrogen production should be considered on equal footing as hydrogen produced with other low-carbon technologies. Categorisations that may not explicitly make reference to life-cycle CO_2 emissions may hamper the long-term contribution of the hydrogen vector to the circular carbon economy.
- **Include non-electric nuclear applications in decarbonisation pathways**. Non-electric nuclear applications should be systematically considered as a low-carbon solution in decarbonisation scenarios, alongside nuclear electricity.

1. Introduction

Many countries have committed to dramatically reduce their carbon emissions, yet the world is increasingly falling behind its environmental goals. Five years after COP21 delivered a global agreement to limit the increase of global temperatures to 2°C between now and 2100; the 2018 IPCC report anticipates that this limit may already be breached by 2030-2050.

Within the framework of the circular carbon economy, the reduction of CO_2 emissions is expected to be the key pillar of future carbon mitigation policies. This will be especially the case in the energy sector, and even more so for the electricity sector that – according to the latest International Energy Agency (IEA) Sustainable Development Scenario (SDS) – would have to be fully decarbonised by mid-century.

In 2019 nuclear was the second source of low-carbon electricity in the world, after hydropower (the first in advanced economies). It is expected to continue to play a leading role on the decarbonisation efforts of the electricity sectors of many countries. However, this role for nuclear power is not limited to electricity generation. In fact, as emphasised throughout this report, nuclear heat for non-electric nuclear applications offers promising opportunities to foster cost-effective decarbonisation for a range of usages, most notably residential and industrial process heat applications, desalination, and hydrogen production.

This report addresses the role of nuclear power as part of the circular carbon economy. It starts with a review of the current status of nuclear power, followed by an outlook assessment based on the latest SDS scenario from the IEA, looking both at existing nuclear reactors, near term new build potential, and innovative nuclear technologies (both on the reactor side, and in terms of potential applications). The carbon management potential in a range of international scenarios is then analysed, together with a more qualitative assessment of the decarbonisation potential of non-electric applications that are typically not considered in these scenarios. The report concludes with a discussion of potential barriers and enabling policies for nuclear energy to play its full role as part of the circular carbon economy.

1.1. Nuclear power has a very low CO_2 footprint on a lifecycle basis

While nuclear power is recognised as a very stable, secure, and reliable generation technology, it is also a very low-carbon source of electricity. According to the IPCC, the median global emissions from nuclear are 12g/kWh (including indirect emissions from lifecycle analysis). This is similar to the lifecycle emissions of wind energy, and more than three times lower than those of solar PV.

In addition, within the framework of the circular carbon economy, it is noteworthy that these estimates do not include the impact of non-electric applications that would potentially reduce this figure by a factor of three considering that the thermal efficiency of current nuclear reactors is usually in the region of about one third: a typical contemporary reactor needs to generate 3 000 megawatts of thermal power to produce 1 000 megawatts of electrical power.

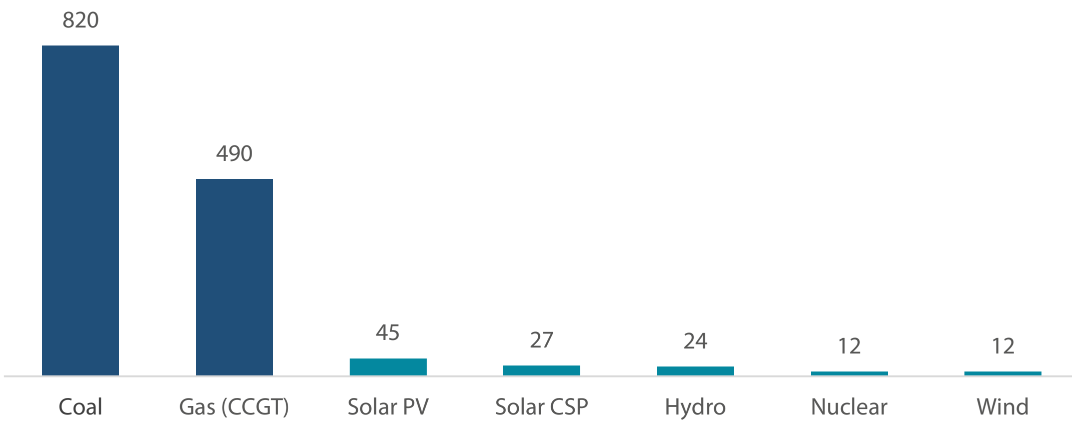

Figure 1: CO_2 emissions in g/kWh over the lifecycle of different sources of electricity

Source: IPPC 5th Assessment Report: Schlömer S. et al. (2014).

1.2. Flexible nuclear operation and non-electric nuclear applications are expected to play an increasingly important role in future low-carbon energy systems

Flexible nuclear operation supports the integration of variables renewables

Traditionally, nuclear reactors have been viewed as a source of electricity and operated as a baseload technology. Considering their high fixed costs and low variable costs, continuously operating a nuclear reactor at the rated power level is usually more efficient, simpler and more economic (NEA, 2011a). In other words, it is in the economic interest of a nuclear operator to maximise the energy produced, i.e. the load factor, to recover these high fixed costs. In addition, nuclear power represents a relatively small share in the electricity mix in most countries, and thus the maneuvering requirements for the plants are typically limited to meeting safety requirements (e.g. safe shutdowns in case of load rejection) and, when required by the system operator, providing frequency regulation.

However, this situation is different in a number of G20 countries (e.g. France, Germany, and Belgium). In these countries, either the share of nuclear power in the national electricity mix is so important that the utilities have to implement or improve the maneuverability of nuclear units, or, flexible operation from nuclear units has been implemented to accommodate the seasonal and inter-annual variability of hydroelectric production, or to ease the integration of variable renewable energy into the system. More recently, some nuclear reactors in Canada and United States have been operated in a flexible mode to manage profitability in deregulated energy markets with priority dispatch for variable renewables.

New nuclear units are already designed for flexible operations, and existing plants can be retrofitted to improve their maneuvering capabilities. Many of existing light water reactors (LWRs) have been upgraded to improve their operational performances and maneuvering capabilities. The required retrofits involve the instrumentation and control systems, the in-core measurement and monitoring equipment, and the adoption of less absorbing control rods (grey rods).

Table 1 summarises the load-following capabilities of existing nuclear reactors, compared to other dispatchable technologies.

While these flexibility capabilities of nuclear power plants are well known from a technical perspective, they raise a number of economic and policy questions considering the expected transformation of energy markets due to the advance of variable renewables, but also the development of new flexibility solutions with various degrees of technological and industrial maturity.

	Start-up time	Maximal change in 30 sec	Maximum ramp rate (%/min)
Open cycle gas tur-bine (OCGT)	10-20 min	20-30%	20%/min
Combined cycle gas turbine (CCGT)	30-60 min	10-20%	5-10%/min
Coal power plant	1-10 hours	5-10%	1-5%/min
Nuclear power plant	2 hours – 2 days	Up to 5%	1-5%/min

Table 1: Load following capabilities of existing nuclear reactors compared to other dispatchable technologies

Source: NEA (2011a).

Non-electric nuclear applications offer new sources of flexibility and support the decarbonisation of hard-to-abate energy sectors

Since the early 1990s, utilities in Europe and the US have issued requirements for the Gen-III light water reactors (EPRI, 2014; EUR, 2012) to ensure that the new reactors are capable of providing flexibility services to the system. These utility requirements are mainly focused on operational flexibility of the nuclear reactors for the production of electricity.

It is increasingly recognised that advanced reactors (i.e. Gen-III, SMR, and Gen-IV) can also be suitable for applications beyond electricity production. For instance, different fuels and coolants and operation at higher temperatures broaden the scope of non-electric applications that could be met by nuclear power. Building on flexibility criteria first put forward by EPRI (2017), it is possible to expand the traditional approach to flexible nuclear production around three attributes: operational flexibility, deployment flexibility, and product flexibility.

These flexibility attributes are summarised in Table 2 below. A key finding from this analysis is that advanced reactors should be well suited to extended flexible nuclear production beyond operational aspects and to offer deployment and product flexibility attributes.

Main attribute	Sub-attribute	Benefits
Operational flexibility	Maneuverability	Load following
	Compatibility with hybrid energy systems	Economic operation with increasing penetration of intermittent generation, alternative missions
	Diversified fuel use	Economics and security of fuel supply
	Island operation	System resiliency, remote power, micro-grid, emergency power applications
Deployment flexibility	Scalability	Ability to deploy at scale needed
	Siting	Ability to deploy where needed
	Constructability	Ability to deploy on schedule and on budget
Product flexibility	Electricity	Reliable, dispatchable power supply
	Industrial heat	Reliable, dispatchable process heat supply
	District heating	Reliable, dispatchable district heating supply
	Desalination	Reliable, dispatchable fresh water supply
	Hydrogen	Reliable, dispatchable hydrogen supply
	Radioisotopes	Unique or high demand isotopes supply

Table 2: Beyond baseload power: New flexibility attributes for tomorrow's nuclear energy systems

Source: Based on EPRI (2017) framework.

Regarding product flexibility, a renewed interest for nuclear cogeneration can be observed in a number of NEA and non-NEA member countries. This includes active R&D programmes, but also the construction of demonstration unit such as the HTR-PM in China and the restart of the HTTR facility in Japan[1] that aims to demonstrate the coupling of a nuclear reactor with a hydrogen production facility. This interest is driven in part by the suitability of nuclear energy to decarbonise hard-to-abate energy sectors, such as industrial heat applications. At the same time, from a system perspective, non-electric applications could also be viewed as a source of flexibility for the integration of nuclear energy with an increasing share of variable renewable energy (VRE) resources on the grid while improving the overall business case of nuclear operations.

The type of potential applications depends on the temperature of the thermal energy delivered by the nuclear reactor. 74 nuclear reactors around the world (about 17% of the world's fleet) have provided either district heating, desalination or some other form of process heat for industrial applications. Nuclear cogeneration is therefore a proven low-carbon solution from a technical and industrial perspective. The higher temperature advanced reactors will enable additional industrial applications, including heat for the chemical industry, hydrogen production and petroleum refineries.

1.3. Nuclear power is a key pillar of security of electricity supply

As a domestically produced, dispatchable and low-carbon source of electricity nuclear energy is a key contributor to the security of electricity supply and, more broadly speaking, the resilience of the electricity system. In fact, security of supply can be defined as "…the resilience of the energy system to unique and unforeseeable events that threaten the physical integrity of energy flows or that lead to discontinuous energy price rises, independent of economic fundamentals" (NEA, 2011b).

Throughout the COVID-19 crisis, nuclear power plants have been a clear example of resilient facilities. The resilience of nuclear energy is the result of the combination of high levels of safety, operational flexibility and continuous learning from previous major events. By design, and beyond design, nuclear power plants are conceived following the principles of defence-in-depth: prevention, protection and mitigation. This results in the implementation of redundant, independent and diversified safeguards designed to withstand external hazards. From an organisational perspective, nuclear facilities also incorporate emergency and contingency plans to rapidly identify critical activities and maintain normal operations with limited personnel.

Confronted with major disruptions in the past, the nuclear sector has been required to adapt profoundly, while always continuing to provide a stable supply of low-carbon electricity. Current nuclear systems and operations have been refined according to an evolving regulatory environment seeking the highest level of safety and reliability in the most diverse situations, including extreme weather events like those caused by climate change. The resulting nuclear governance models incorporate procedures and approaches that allow the continuous assessment of ongoing practices, the application of corrective measures and the integration of the latest knowledge available.

At the system level, a resilient low-carbon infrastructure requires a balanced and diversified power mix. Different technologies have different complementary roles in low-carbon electricity systems. Flexible power provision by plants that are dispatchable upon demand makes nuclear power an indispensable complement to wind and solar production in countries without large amounts of hydropower capacity. Furthermore, it also supports electric grid stability by providing valuable inertia, reactive capacity and frequency control to the system. Additional operational resilience can be obtained with strategic fuel stockpiles. One of the main advantages of nuclear power is the ease of securing energy-dense uranium fuel for several years of operation.

Finally, with the emergence of variable renewables (wind and solar PV) the resilience of the power system is increasingly impacted by its ability to manage their intermittency. For instance, during the COVID-19 crisis, those countries with nuclear power in their energy mix, took advantage of these features to secure operations and either delay or advance outages, keep the plants running at full power, or adjust their power output to adapt to lower power demand. As highlighted recently by the IEA, nuclear power has been an important source of power flexibility in Europe during the current pandemic (IEA, 2020b).

1. Nuclear Engineering International (2018), "Restart of Japan's HTGR approved", www.neimagazine.com/news/newsrestart-of-japans-htgr-approved-7955965.

2. Current status of nuclear power

2.1. The role of nuclear power in electricity supply

Nuclear power provided 10% of global electricity supply in 2018

In 2018 nuclear power provided more than 10% of the global electricity supply, with 440 nuclear reactors in operation in 30 countries around the world and a total installed capacity of 400 GW. The role of nuclear power is more significant in OECD economies where it accounts for 18% of total generation.

In the European Union 25% of electricity supply comes from nuclear reactors. In Korea and the United States, 20% of electricity supply comes from nuclear power. In Japan, nuclear power amounted to about 5% of electricity generation in 2018, with most Japanese reactors still being evaluated by the national regulatory for possible restart. Before the accident at Fukushima Daiichi in 2011, the contribution of nuclear to electricity production had been roughly the same as coal and gas as the largest sources of electricity in Japan at about 30%.

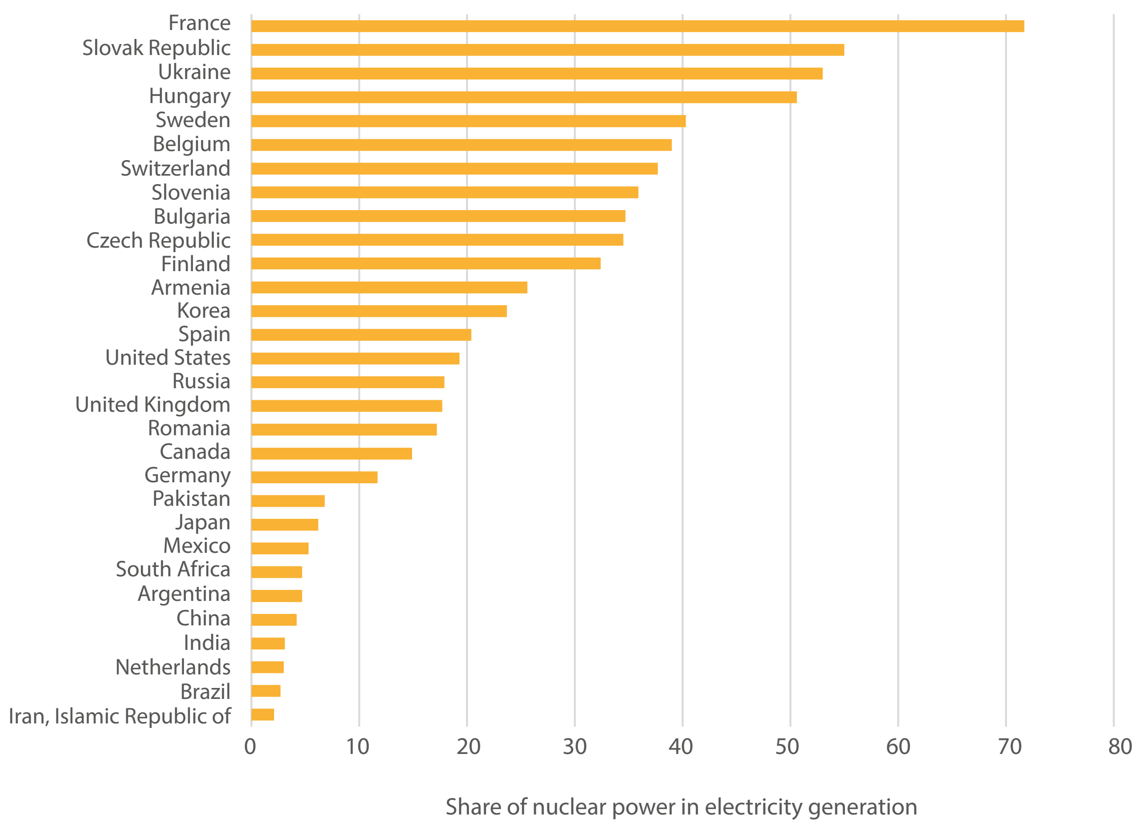

Figure 2: Share of nuclear power in electricity generation, 2018

Source: Based on IAEA/PRIS data (June 2020).

An increasing number of nuclear reactors are taking the required steps to safely extend operations beyond the duration of their initial operating period

Most of the existing nuclear reactors were built during the 1970s and the early 1980s (Figure 3). As demand for electricity levelled off and the cost of natural gas-fired generation capacity dropped significantly, nuclear new build activities were significantly reduced during the 1990s. The advance of Gen-III nuclear reactor since the 2000s partly reversed this trend, in particular in China where 37 nuclear reactors (39.6 GW) have been built over the last decade. However, economic and market factors such as the emergence of shale gas in North America and challenges of completing first-of-a-kind (FOAK) projects in several OECD countries, have contributed over the last few years to a reduction in the rate of nuclear new build. The Fukushima Daiichi nuclear accident (2011) had limited direct impact on nuclear new build decisions apart from a few selected countries such as Japan, Chinese Taipei and some countries in Western Europe (NEA, 2017).

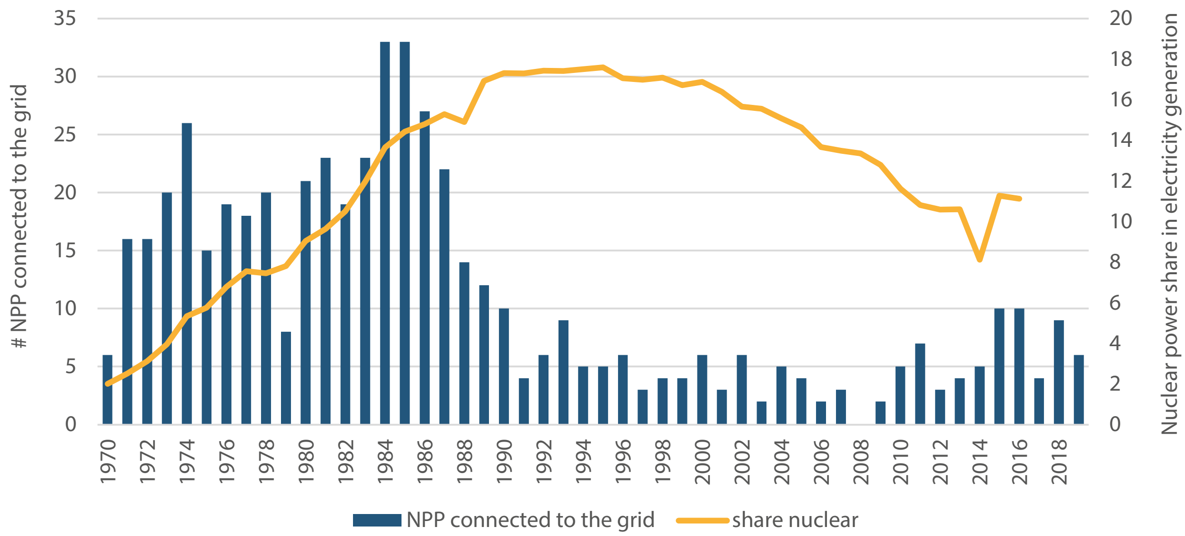

Figure 3: Reactor construction starts and share of nuclear power in total electricity generation

Source: NEA based on IAEA/PRIS (June 2020) and IEA (2019a).

As of 2020, the average age of the world nuclear reactor fleet is 30 years, with 25% having passed over 40 years of operation. An increasing number of nuclear reactors are therefore taking the required steps to safely extend operations beyond the 30 or 40-year of their initial operating period through long-term operation (LTO) investments.

For light water reactors, LTO generally refers to the operation of the facility beyond 30 or 40 years, which is a typical of the initial operating licence granted by regulators or the initial design hypothesis for certain equipment (NEA, 2019a). This time period does not correspond to the technical lifetime of the reactor, which may be periodically revaluated considering actual plant conditions and the latest knowledge available. In this sense, the Western European Nuclear Regulators' Association highlights that, based on technical evidence, "there may be no real cliff edge effect due to ageing when a nuclear power plant is being operated longer than the initial design lifetime of some of its components" (WENRA, 2011). Furthermore, some countries have an indefinite licensing term, which means that nuclear power can be operated with no limitation on time as long as their components perform their expected functions safely. In the United States, for example, some light water reactors (LWRs) have been approved for 80 years of operation.

Figure 4 shows the distribution of LTO by nuclear technology and by country. The current installed capacity is mainly composed of LWRs (82%) in China, Europe, Japan, Korea and the United States. Russian-type LWRs (or VVERs) are also in operation in Russia and other countries.

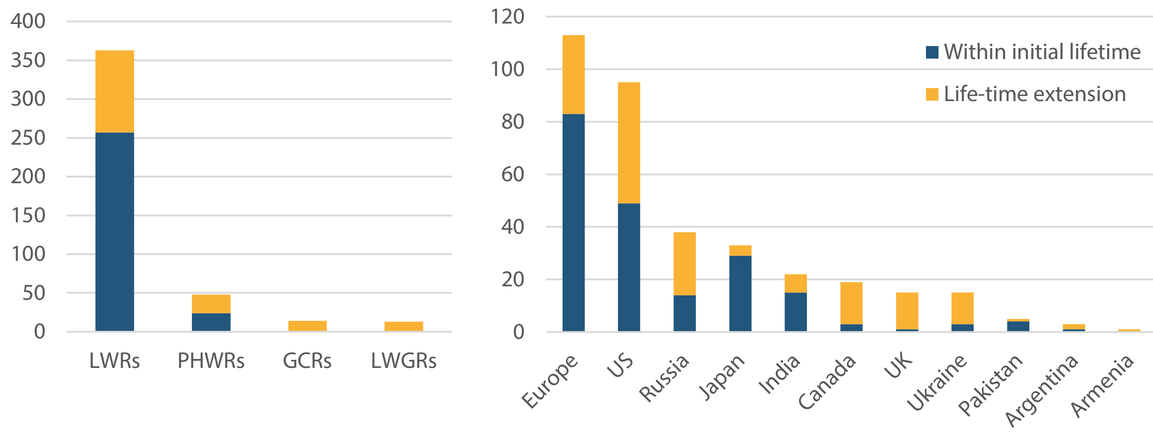

Figure 4: LTO trends by technology and country

Source: Based on IAE/PRIS data (June 2020). Note: For the elaboration of chart the initial operating period by technology have been assumed: 40 years for Western LWRs and 30 years for PHWRs, VVERs, GCRs and LWGRs based on NEA (2019a).

Figure 5 offers a more detailed picture of the age distribution of the existing nuclear reactor fleet. The average reactor is about 30 years old. The United State was the first country to initiate the large-scale deployment of nuclear energy and as a result its reactors have an average age of 40 years followed by Europe with an average age of 35 years.

- In the United States more than 40% of the nuclear reactor fleet is over 40 years old. In the US, from the 95 operating reactors, 88 (>90%) have been granted a first licence renewal allowing lifetime extensions from 40 to 60 years. Furthermore, in 2018, 6 reactors filed for a subsequent licence renewal (SLR) from 60 to 80 years of operation. Of these six, four were approved in 2019 and 2020 and two are expected to be approved later this year. To date, owners of thirteen additional reactors have announced intent to file for SLRs, with formal letters of intent submitted for five (NRC, 2020).
- In Europe, reactors older than 40 years represent less than 20% of the fleet. LTO decisions have already been taken in a number of countries. However, more that 70% of the European fleet is in the range of 31-40 years which means that significant LTO decision will be considered over the next decade. Compared to the US, the situation in Europe is impacted by policy decisions in Belgium and Germany to phase out their use of nuclear power before 2025 and France committed to reducing the share of nuclear electricity generation to 50% by 2035 (though not necessarily reducing the amount of nuclear electricity generated). This context makes projections regarding the generation of nuclear energy in Europe beyond 50 years more uncertain.

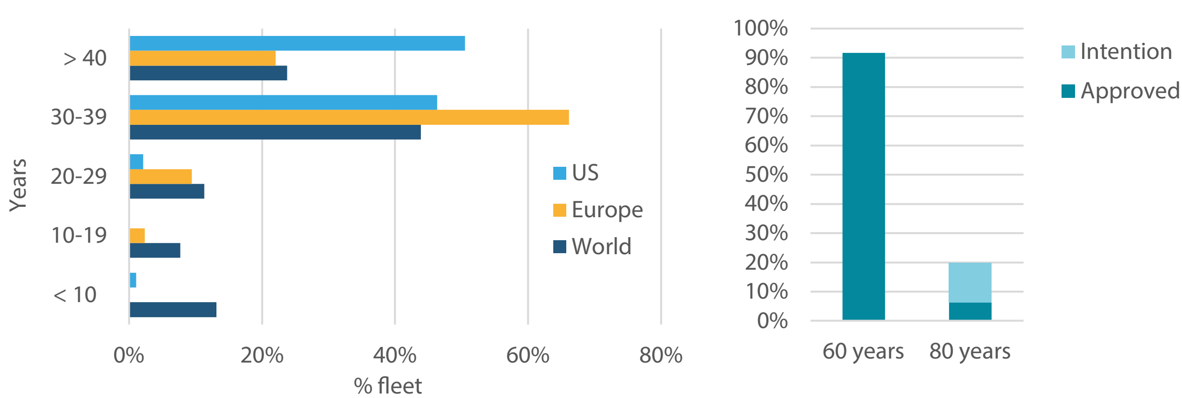

Figure 5: Nuclear reactor fleet age distribution by region (left) and LTO trends in the US (right)

Note: Europe figures include UK and Swiss reactors.
Source: IAEA PRIS data (June 2020).

Source: NRC (2020).

Status of nuclear new build: fifty five reactors under construction in fourteen countries for a total capacity of 60.5 GW

As of May 2020, 55 nuclear reactors are under-construction in 14 countries. This represents 60.5 GW of nuclear capacity under construction, primarily in OECD countries (20 GW), China (10 GW) and Russia (4.9 GW). The OECD countries with the most capacity under construction are Korea (6 GW) the United Kingdom (3.4 GW) and the United States (2.2 GW). Out of the 25 GW of capacity under construction in the rest of the world, the leading countries are India (5.3 GW) and the United Arab Emirates (5.6 GW).

Construction in the United Arab Emirates Barakah project is progressing according to schedule, and fuel loading of the first unit took place in March 2020. In OECD countries, Hinkley Point C is the largest ongoing new build project and the first project for the United Kingdom since 1995. Construction of the two units is on schedule, with the Unit 2 nuclear island base completed in May 2020.

Other new build projects are in the preparation phase in Argentina, Brazil, Bulgaria, the Czech Republic, Egypt, Finland, Hungary, India, Kazakhstan, Poland, Saudi Arabia and Uzbekistan. These are typically large reactor projects (>1 GW), and judging from current policies and ongoing projects this could mean new additions of approximately 35 GW.

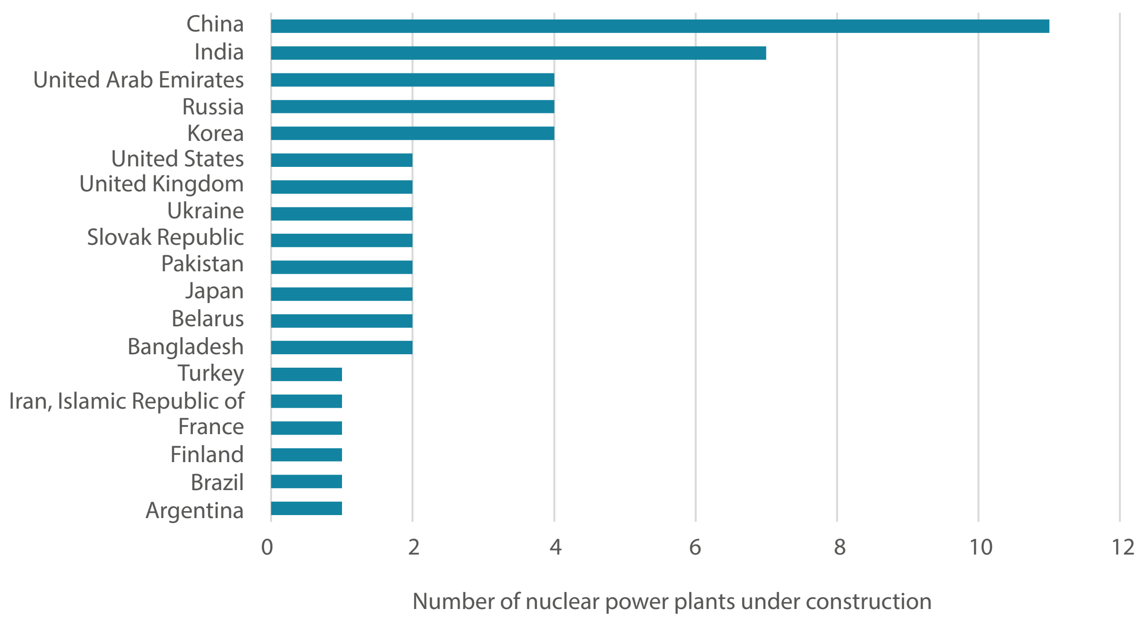

Figure 6: Nuclear power plants under construction as of February 2020

Source: IAEA/PRIS (June 2020).

2.2. Current and historical contributions of nuclear power to climate change mitigation

Today, nuclear power is the leading source of low-carbon electricity in OECD economies

In OECD countries, nuclear power is the largest source of low-carbon electricity, providing 40% of all low-carbon generation. Nuclear production reached 2 000 TWh in 2018, one-third higher than hydropower, and twice the combined output of solar PV and wind.

Nuclear power is the largest low-carbon source of electricity in 13 individual OECD economies: Belgium, Bulgaria, the Czech Republic, Finland, France, Hungary, Korea, the Slovak Republic, Slovenia, Spain, Sweden, the United Kingdom and the United States (IEA, 2019).

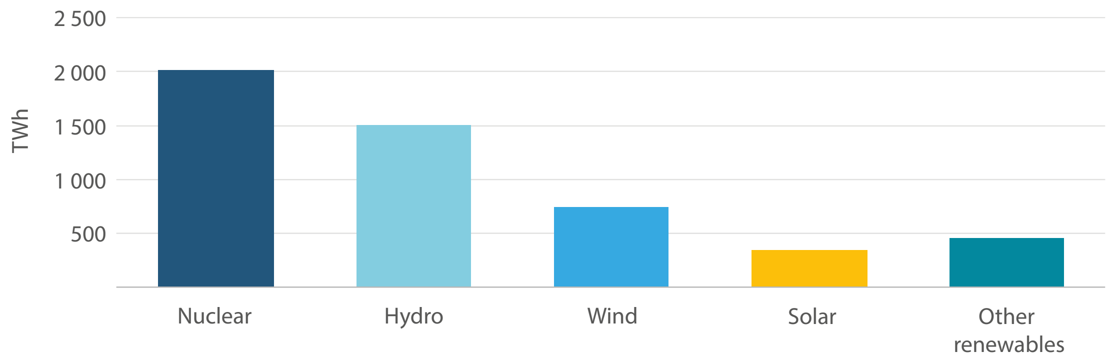

Figure 7: Low-carbon electricity generation in OECD economies by source, 2018

Source: IEA (2019b).

Over the last 47 years, nuclear power has avoided 62 Gt of CO_2 emissions at a global level

In OECD countries, nuclear power has played a central role in limiting CO_2 emissions over the last 50 years. This is particularly true in the European Union and the US where nuclear power still represents over 50% of the low-carbon sources of electricity. The IEA (2019b) estimates that nuclear power generation has allowed the avoidance of 63 gigatonnes of CO2 from 1971 to 2018 (Figure 8, below). This means that over this period CO_2 emissions from the electricity sector would have been 20% larger in the absence of nuclear power.

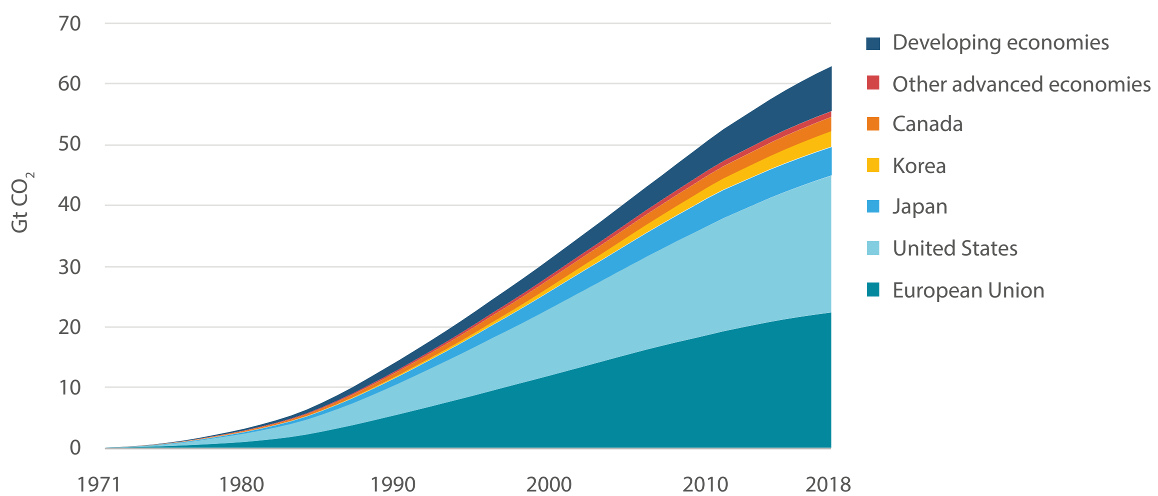

Figure 8: Cumulative CO_2 emissions avoided through the use of global nuclear power to date

Source: IEA (2019b).

2.3. Significant efforts are taking place to support the development of new reactor technologies

The nuclear power industry has been developing and improving reactor technologies for more than five decades and is starting to build a new third generation of nuclear power reactors. Several generations of reactors are usually distinguished:

- generation I reactors – initial demonstration and commercial reactors developed in the 1950s and 1960s;

- generation II reactors – most of the reactors from the existing fleet currently in operation;
- generation III reactors – most of the nuclear reactors developed since the 1990s under construction and recently completed;
- generation IV reactors – new designs offering alternative fuel and coolants but not expected to be commercially viable before 2030-40.

In parallel, a number of vendors are also developing small modular reactors (SMRs) that aim to improve the economics and flexibility of nuclear energy while also broadening the market opportunities for new nuclear power plants, including in regions where large nuclear power plants are not well-suited due to grid constraints and site characteristics.

Finally, important efforts should also be noted for the development of cross-cutting non-electric nuclear applications.

Large Gen-III nuclear reactors

Generation III (Gen-III) reactors are Light Water Reactors (LWRs) that have been developed since the 1990s. Six countries are currently commercialising reactor designs: China, France, Japan, Korea, Russia and the United States. These reactors present a number of additional economic and safety benefits compared to Gen-II reactors, including higher availability and an operating design life of at least 60 years.

Table 3 below summarises the large Gen-III reactors recently completed and under construction. In addition, several additional designs are under development but have not been commercialised yet. This includes the ESBWR from GE-Hitachi (1 600 MW, BWR) and the ATMEA from Framatome and Mitsubishi (1 150 MW, PWR).

Reactor	Developer	Country	Type	Size (MWe)	Status
ABWR	GE Hitachi, Toshiba	Japan, United States	BWR	1 380	**In operation**: Japan (4 units)
AP1000	Westinghouse	United States	PWR	1 250	**In operation**: China (Sanmen 1 & 2, Hai-yang 1 & 2) **Under construction**: United States (Vogtle 3 & 4)
APR1400	KHNP	Korea	PWR	1 450	**In operation**: Korea (Shin Kori 3 & 4) **Under construction**: Korea (Shin Hanul 1 & 2), UAE (4 units at Barakah).
EPR	Framatome	France	PWR	1 650	**In operation**: China (Taishan 1 & 2) **Under construction**: Finland (Olkiluoto 3), France (Flamanville 3) and the UK (2 units at Hinkley Point C)
Hualong One (HPR1000)	China	CNNC and CGN	PWR	1 170	**Under construction**: China (2 units at Fangchenggang, 2 units at Fuqing), Pakistan (2 units)
VVER-1200 (AES-2006)	Rosatom	Russia	PWR	1 200	**In operation**: Russia (Novovoronezh II and Leningrad II) **Under construction**: Turkey (4 units at Akkuyu), Bangladesh (2 units at Rooppur).
VVER-TOI	Rosatom	Russia	PWR	1 300	**Under construction**: Russia (Kursk II)

Table 3: Summary of large Gen-III nuclear power plants recently completed and under construction

Small modular reactors

Small modular reactors (SMRs) are defined as nuclear reactors with a power output between 10 MWe and 300 MWe. Designs with power outputs smaller than 10 MWe, often designed for semi-autonomous operation, have been referred to as micro modular reactors (MMRs).

SMRs are often designed for factory fabrication, taking advantage of the benefits of economies of series production, to be transported and assembled on-site, resulting in shorter construction times. This is one of the key elements that might prove to make SMRs cost competitive with other energy options.

The most mature SMR concepts are based on LWR technology. Other concepts are Generation IV reactors that incorporate alternative coolants (i.e. liquid metal, gas or molten salts) and advanced fuels. SMR deployment configurations can vary between single unit installations, multi-module plants, or mobile installations such as floating (i.e. barge-mounted) units. In 2018, the International Atomic Energy Agency (IAEA) identified more than 50 concepts under development with different technology and licensing readiness levels, including four concepts that were under construction at the time.

Due to smaller reactor cores and very large water inventories, LWR SMRs may benefit from reduced shielding requirements and reduced or eliminated offsite Emergency Planning Zones (EPZ) which, in turn, will result in added flexibility for the siting of these reactors. SMR designs often include an integral nuclear steam supply system and take advantage of overall system simplification. Inherent passive safety systems provide SMRs with greater and, in some cases indefinite, coping times in case of a loss of offsite power. Many SMRs are designed to be installed below grade resulting in higher physical protection and protection from external hazards.

From an economic perspective, SMRs are presented by vendors with several distinctive features:

- **Affordability**: The lower overall capital outlay implies that private investors will face lower capital at risk, which could make SMRs a more affordable option. In turn, this could attract new sources of financing and lower the cost of capital.
- **Scalability**: For multi-units SMRs, the ability to add modules and start generating electricity incrementally reduces both the upfront investment and the capital at risk, which translates into lower financial costs.
- **Portfolio strategy**: For multi-units SMRs, the ability to add modules incrementally could also allow investors to adjust to changes in electricity demand, cash flow/financing availability, improving the management of financial risks.
- **Shorter payback**: shorter construction duration promoted by SMR developers would further reduce the cost of financing.

Table 4 below summarises the status of a representative sample of SMR design under development.

Design	Size per module (MWe)	Number of modules (if applicable)	Type	Designer	Country	Status
			Single Unit LWR SMRs			
CAREM	30	1	PWR	CNEA	Argentina	Under construction
SMR-160	160	1	PWR	Holtec International	United States	Conceptual design
BWRX-300	300	1	BWR	GE Hitachi	United States-Japan	Under NRC review
UK SMR	450	1	PWR	Rolls Royce	United Kingdom	Conceptual design
			Multi-module LWR SMRs			
NuScale	50	12	PWR	NuScale Power	United States	Detailed design ongoing licensing, FOAK planned mid-2020s
RITM-200	50	2	PWR	OKBM Afrikantov	Russia	Conceptual design
NUWARD	170	2 to 4	PWR	CEA/EDF/ Naval Group/ TechnicA-tome	France	Conceptual Design

Design	Size per module (MWe)	Number of modules (if applicable)	Type	Designer	Country	Status
Mobile SMRs						
ACPR50S	60	1	Floating PWR	CGN	China	Under construction
KLT-40S	70	2	Floating PWR	OKBM Afrikantov	Russia	In operation
MMRs						
eVinci	0.2-5	1	Heat pipe reactor	Westinghouse	United States	Basic design
Aurora	2	1	LMFR	Oklo	United States	Under NRC review
UBattery	4	1	HTGR	Urenco and part-ners	United Kingdom	Basic design
Generation IV SMRs						
Xe-100	35	1	HTGR	X-energy LLC	United States	Conceptual design
ARC-100	100	1	SFR	Advanced Reac-tor Concepts	Canada	Conceptual design
IMSR	190	1	MSR	Terrestrial Energy	Canada	Basic design
HTR-PM	210	2	HTGR	China Huaneng/ CNEC/Tsinghua University	China	Under construction

Table 4: Representative samples of SMR design under development

Large Gen-IV reactors

In addition to the Gen-IV SMRs highlighted in the previous section, a number of public and private institutions are also investing in the development of large Gen-IV reactors.

At the international level, the Generation IV International Forum (GIF) has identified since the early 2000 six nuclear energy systems as being the most promising to meet its objectives, assuming a deployment horizon beyond 2030:

- gas-cooled fast reactor (GFR);
- lead-cooled fast reactor (LFR);
- molten salt reactor (MSR);
- sodium-cooled fast reactor (SFR);
- supercritical water-cooled reactor (SCWR);
- very high temperature reactor (VHTR).

A number of demonstration power plants have been built over the years. For instance, SFR are in operation in Russia (BN-600, BN-800), and were operated in France (Phenix, Superphenix), Japan (Monju) and the United Kingdom (Dounreay PFR). Similarly, China is pursing efforts in several systems, including the HTR-PM under-construction.

These future nuclear systems aim to meet stringent criteria of GIF goals in sustainability, economics, safety and reliability, proliferation resistance and physical protection. In addition, while all six systems are certainly capable of producing electricity, they have been developed from the onset considering potential applications for their nuclear heat, particularly those systems capable of outlet temperatures ranging 700-950°C (i.e. VHTR, GFR, LFR and MSR), and ~550°C (SFR). Nuclear heat can be used in the production of hydrogen or industrial process heat for such chemical processing facilities as petroleum refineries.

Cross-cutting efforts in non-electric nuclear applications

The potential of nuclear energy as a source of low-carbon heat is often neglected in policy debates, even though there is proven industrial experience. Historically, 74 nuclear reactors around the world (about 17% of the world's fleet) have provided either district heating, desalination or some other form of process heat for industrial applications.

Hence, coupling advanced nuclear reactors with non-electric applications could provide policy makers with alternatives to decarbonise commercial transport (i.e. carbon-free hydrogen and synthetic fuels production using nuclear heat and electricity), and process heat applications could be used in energy-intensive industrial sectors.

In particular, while several alternatives are available to decarbonise the power sector, there are fewer options to decarbonise applications for which fuel switching (electrification) is not possible or is limited. In particular, industrial heat demand represents almost half of global heat demand and there are significant opportunities for further CO_2 reduction using non-electricity application of nuclear energy in industrial heat supply. As summarised in Figure 9 below, the temperature required for different industrial heat applications covers an exceptionally large spectrum, from a few dozens of degrees up to more than 1 600˚C that would match the capabilities of different nuclear reactor designs.

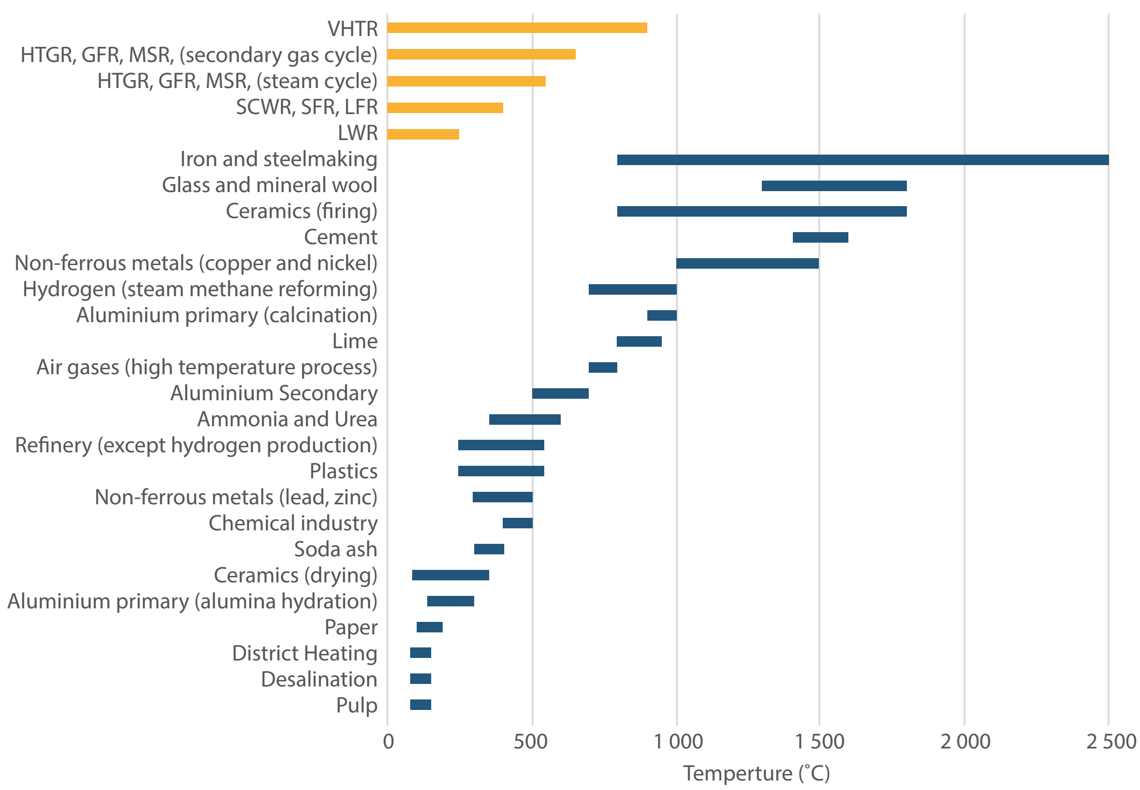

Figure 9: Process temperature ranges by industrial application and reactor capabilities

Source: NEA (Forthcoming).

Using nuclear reactors for non-electric applications could also provide energy system storage – i.e. energy could be stored in the form of heat, with excess energy used for water desalination or as another energy vector such as hydrogen. This is the basic concept behind integrated energy systems. Furthermore, the possibility of generating multiple revenue streams (by selling electricity as well as heat or hydrogen) can improve the business case for investing in nuclear technology, which will remain a capital-intensive technology.

3. Nuclear power outlook

3.1. More efforts needed for nuclear power to meet its expected contribution to climate and sustainable development goals

As a mature source of low-carbon and dispatchable electricity, nuclear power is expected to play an important role in the future. Figure 10 illustrates that, in order to keep up with the capacity assumptions of the IEA SDS scenario, nuclear power capacity should increase by 35% by 2040 compared to today's levels. Under current development trends,[1] 2030 targets could be achieved but more efforts would be needed to meet SDS capacity trends by 2040. At least a doubling of the annual rate of capacity additions (from approximately 6 GW to 13 GW) would be required to cover a capacity gap of 145 GW by 2040.[2]

Consequently, effectively reaching SDS nuclear power capacity targets would require the mobilisation of three main nuclear development levers at different time scales: long-term operation (LTO) of existing nuclear power plants, new build large Gen-III reactor projects and – potentially – emerging technologies such as SMRs. While LTO and new builds will continue to play an essential role by 2040, ongoing SMR demonstration projects may permit the beyond 2030 horizon. The opportunities and challenges associated with each of these development levers are covered in detail in the next sections.

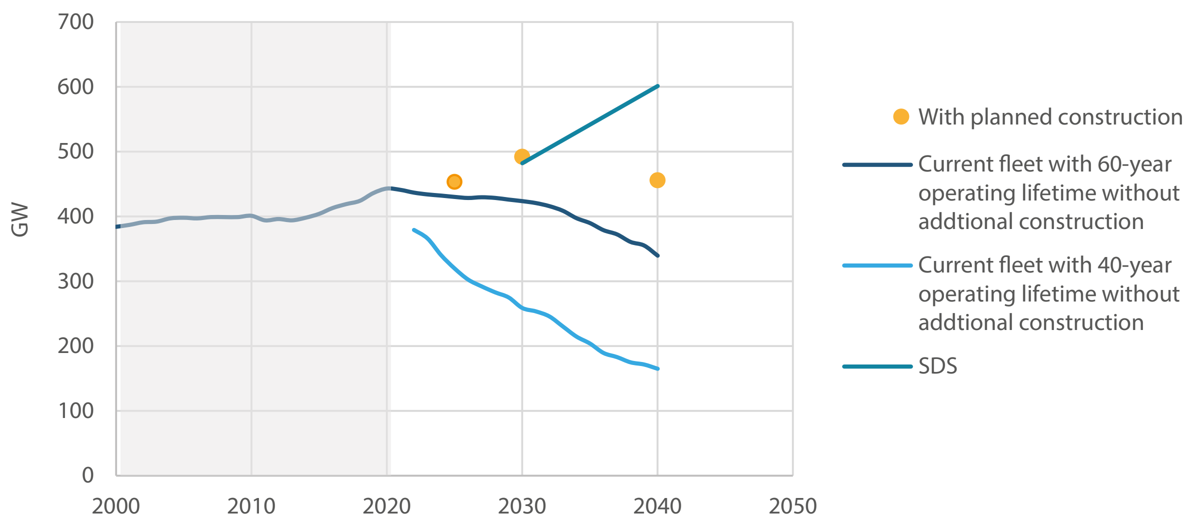

Figure 10: Global nuclear capacity by scenario, 2000-2040

Source: IEA (2020b).

1. It is assumed that most of the reactor fleet will have a 60-year operating lifetime and that planned construction projects do not experience major delays.

2. IEA (2020b), *Tracking Power 2020*, IEA, Paris, www.iea.org/reports/tracking-power-2020.

3.2. The role of long term operation for the existing nuclear reactor fleet

The 441 nuclear reactors in operation worldwide a represents a backbone of low-carbon capacity that avoids yearly around 1.6 $GtCO_2$ of emissions and could safely support the transition towards a decarbonised economy along with other low-carbon technologies.

This key role of the existing nuclear reactor fleet, and more specifically its LTO, becomes more evident if it is assumed that installed capacity is decommissioned after 40 years of operation. As illustrated in Figure 10, this hypothesis would lead to a sharp decline of more than 50% for nuclear capacity by 2040 compared to current levels.

From an economic perspective, and despite the falling cost of wind and solar power equipment, adding new renewable capacity requires considerably more capital investment than an LTO project for the existing nuclear reactor fleet, with a similar lifetime period for both options. With other dispatchable generation also fading away, the system costs associated to grid upgrades, extension of transmission lines and addition of storage capacities to integrate variable renewables have to be taken into account. According to the IEA, without widespread lifetime extensions or new nuclear projects, electricity supply costs could be on average USD 80 billion higher per year in OECD economies (IEA, 2019).

Over the last few years, and motivated by an ageing reactor fleet and the potential environmental and cost impacts mentioned above, LTO investments have been gaining momentum.[3] LTO investments are also attractive in the context of the post-COVID-19 economic recovery, as they can help maintain resilient electricity systems and create many long-term highly-skilled domestic jobs.

Performance and technical considerations

The performance of a nuclear power plant over time is the combination of systems, structures and components (SSCs) ageing and governance systems continuously improving the operation of the plant from a technical and organisational point of view. From a technical perspective, most of SSCs of a nuclear power plant are replaced as part of normal maintenance procedures and more extensive LTO refurbishments. On the other hand, there are SSCs whose replacement can be considered unfeasible for technical or economical reasons, or both. Consequently, the ageing of these components will ultimately limit the lifetime of the plant

The evolution of the unplanned capability loss factor[4] (UCL) illustrated in Figure 11 highlights the interplay between ageing and operational experience during the lifetime of a nuclear power plant. This chart traces back the evolution of UCL for the global nuclear reactor fleet as a function of reactor age between 2014 and 2018. The first years of operation correspond to the natural running-in period of any complex 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 prevail over operating experience driving UCL levels up. Major replacements and plant enhancements executed during LTO project allow to return performance to previous levels. The evolution of the unplanned scrams factor[5] presented in Figure 11 also leads to similar conclusions.

Economic competiveness of LTO

According to the results of a forthcoming NEA study on the role of LTO of nuclear power plants, the average overnight investments of LTO projects ranges between 450-950 USD/kWe. These costs typically

3. In 2017 LTO investments almost equated those in new build: USD 9 billion for new builds vs. USD 8 billion for LTO. Similar trends were observed in 2018.

4. 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 due to 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).

5. This indicator is defined as the number of unplanned automatic/manual scrams (reactor shutdown protection system) normalised to 7 000 hours of critical operation. Its purpose is to monitor performance efforts in reducing the number of unplanned automatic/manual reactors shutdowns. Indirectly, it also provides an indication of how well a plant is maintained and operated.

include the replacement of heavy mechanical, electrical and instrumentation and control equipment as well as post-Fukushima safety upgrades. The variability can be explained by the fact that the scope of LTO refurbishments is not fixed and varies between plants and countries depending on historical operating experience, previous investments and regulatory frameworks, among other aspects. Labour and indirect costs are also part of the scope of the LTO investment. Main indirect cost items involve project management, regulatory and licensing interfaces and initial engineering efforts necessary to evaluate to extent of the LTO refurbishment.

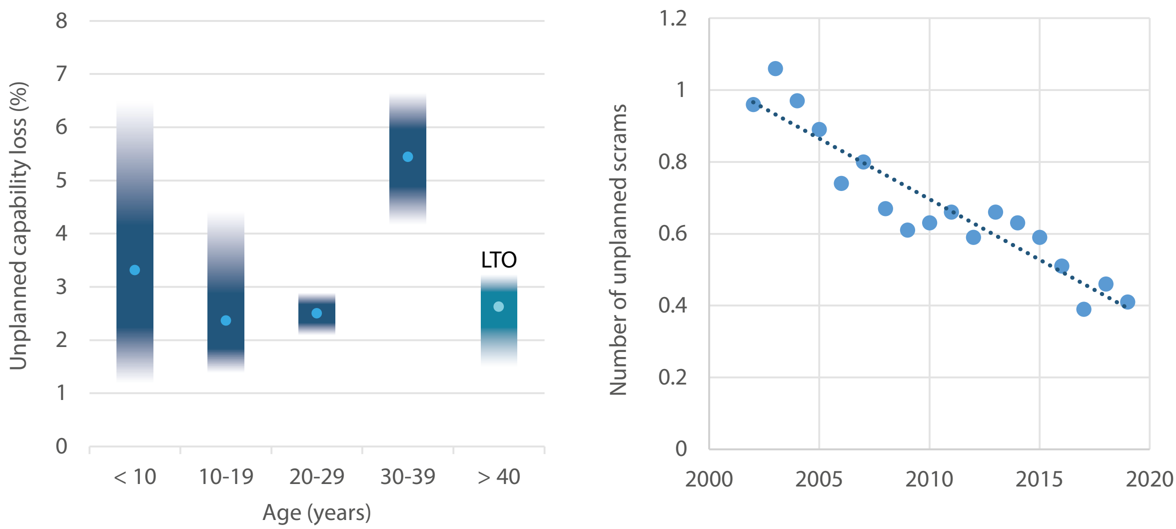

Figure 11: Evolution of selected plant performance indicators during the lifetime of a nuclear plant

Source: Based on IAEA PRIS data (June 2020).

Note: Each column captures the variability of UCL between 2014 and 2018 for a given age range. The point corresponds to the average value observed in during this period.

Source: IAEA PRIS.

The projected LTO LCOE values along with those of other technologies in Europe by 2040 are present in Figure 12. The capacity factor of the existing reactors is typically around 85% however, for these computations, a capacity factor of 75% has been considered in order to account for the short-term economic penalty associated with higher shares of variable renewables in the electricity system. These results illustrates that LTO remains one of the most competitive options for low-carbon electricity generation in many regions by 2040, in line with recent IEA analysis (IEA, 2019).

Additionally, a comparison with 2012 data (NEA, 2012) highlights that LTO costs are well contained in contrast with the cost escalations observed in new nuclear builds over the same period. In fact, from the 441 currently in operation, more than 150 reactors are operating in LTO conditions. Assuming that all of them have experienced major refurbishments, such a volume of projects is enough to ensure learning effects and sustain supply chain capabilities over time.

Despite these favourable economic features, nuclear power plants continue to be closed prematurely in some countries. The main reasons are policy decisions in Europe and degraded market conditions, especially in the US with the presence, among other reasons, of cheap and abundant shale gas. In recent times the nuclear industry has made significant efforts in reducing its operating costs and increasing the availability of the plants with the implementation of major modernisation works. Nevertheless, additional policy efforts will be required to revisit current market designs and maintain low-carbon generation through LTO in the long term.

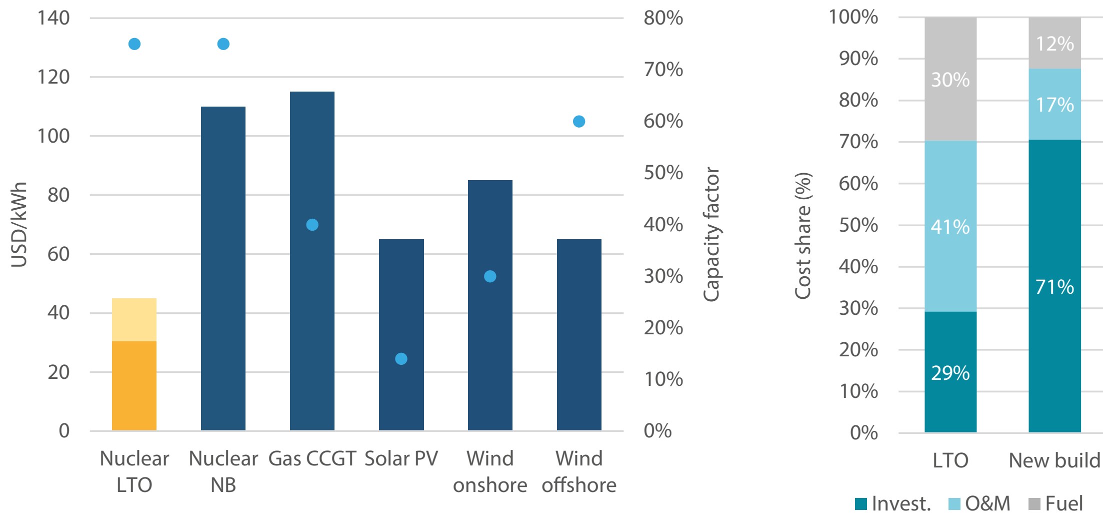

Figure 12: Projected LCOE values for selected technologies in Europe by 2040 (left) and cost structure of lifetime extensions versus new nuclear construction (right)

Note: These values have been computed for a discount rate of 7%. The shaded area for the LTO values represents the variability associated with an overnight costs range of USD 450-900 per kWe and lifetime extensions periods of 10 and 20 years.

Source: IEA/NEA (forthcoming) and IEA (2019b).

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%.

Source: IEA/NEA (forthcoming).

3.3. Nuclear new build: Unlocking reductions in construction costs

Nuclear new build in OECD countries is at a critical juncture with the completion of several FOAK projects. These projects were initiated after a long hiatus for nuclear construction that significantly eroded the nuclear supply chain and the industry's capabilities. This is reinforced by a de-industrialisation trend in some OECD regions. In addition, initial budget estimates were heavily influenced by the lack of design maturity and execution planning at the time construction began, as well as the increasingly uncertain political context. The sums invested in these FOAK projects have served to finance not only the construction of the reactors themselves, but also to rebuild these capabilities.

Recent trends in nuclear new build

The trend in projected overnight construction costs is presented in Figure 13 below for OECD countries and shows a significant increases in costs between 2010 and 2015. The same applies to the construction delays. The announced schedules for these projects were typically between 5 and 6 years. Those already in operation were built in around 10 years. Some of these are still under development and could be tentatively delivered more than 15 years after construction began.

As identified in a recent NEA study, if the nuclear industry in western OECD countries takes advantage of the accumulated experience and the lessons learnt from recent projects, nuclear plant construction can enter in a more rapid learning phase allowing it to deliver future projects at a lower cost (NEA, 2020b).

In several countries, nuclear power is delivered today essentially on time and on budget. In China and Korea, a significant number of projects have been executed in less than 6 years over the last decade. These differences could be explained by alternative design features (in terms of constructability, for example). However, even for a same design, there are notable differences depending on the country in which the reactor is being built. This gap cannot be explained solely by site-specific conditions inducing slight design modifications. Thus, the challenges experienced in Western OECD countries in delivering new nuclear energy projects are not inherent to the technology itself but rather depend on the conditions in which these projects are developed and executed, and on the interactions between the different stakeholders.

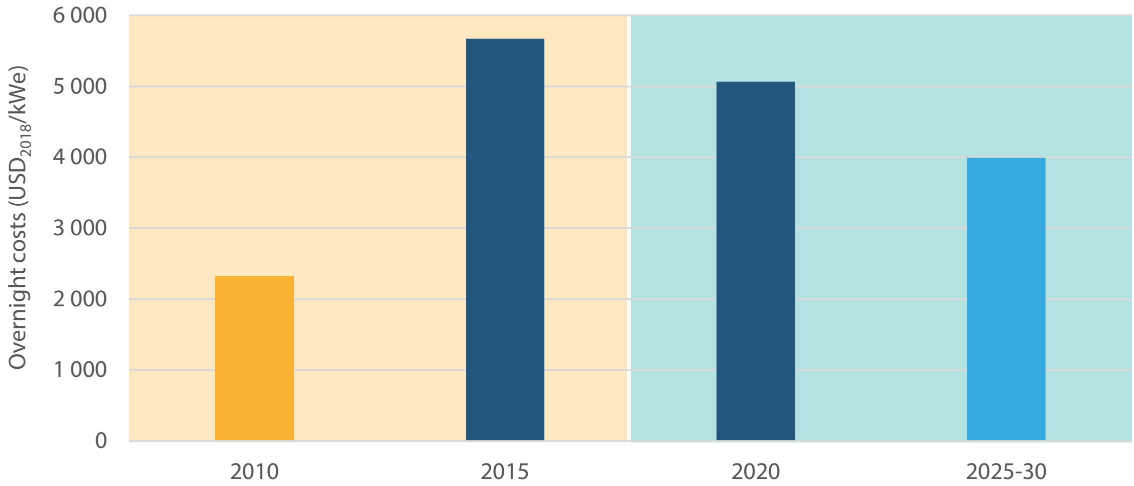

Figure 13: Trends in the projected costs of nuclear new build in OECD countries

Note: 2010, 2015 and 2020 overnight construction costs data based on 2005, 2010 and 2015 NEA/IEA projected costs reports, adjusted for USD inflation using OECD statistics.

Source: NEA (2020b).

Key drivers for reducing the construction costs of nuclear new build

For nuclear construction cost reduction, the NEA has identified eight drivers to unlock positive learning as well as continuous improvement on large Gen-III reactor projects. These drivers are summarised in Figure 14 below.

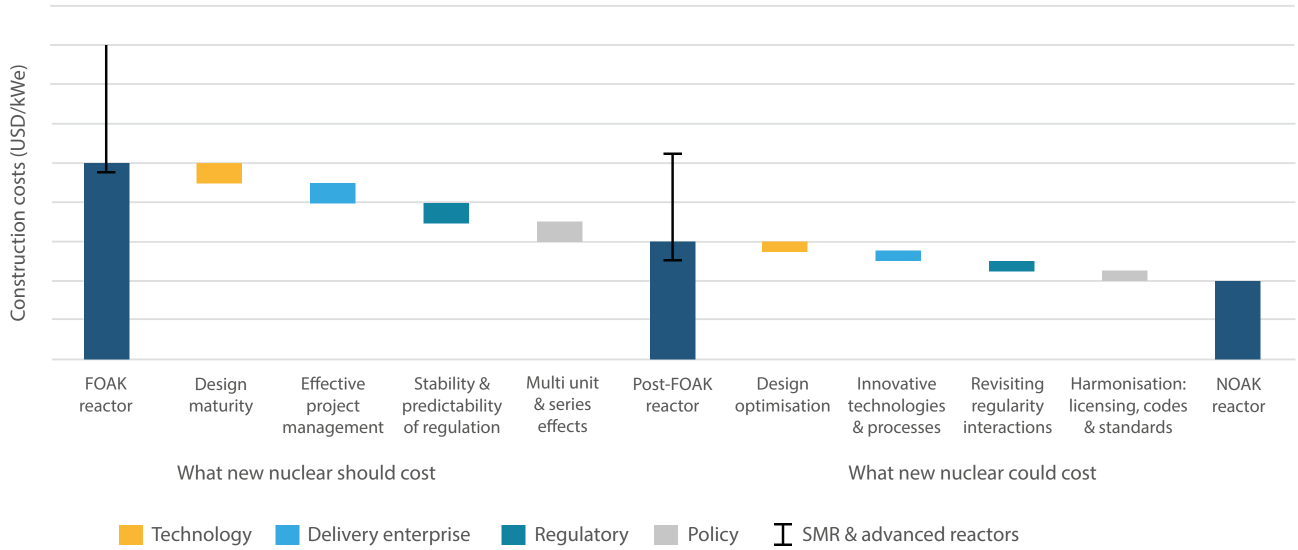

Figure 14: Nuclear cost and risk reduction drivers

Source: NEA (2020b).

Lessons learnt

Historical and recent evidence suggest that the lessons learnt are well understood and can be easily implemented in future projects. Several non-OECD countries delivering competitive nuclear projects today, are already taking advantage of them. As a result, the next nuclear project should be delivered at lower costs after entering in a phase of more rapid learning. Key lessons learnt include:

- **Design maturity**: The detailed design has to be completed and ready for construction. This implies early involvement with the supply chain during the design process in order to integrate the necessary requirements to improve constructability.
- **Effective project management**: The design also requires a robust implementation strategy with a clear definition of responsibilities and identification of competences at all levels and stages of the project. A strong and experienced project management team is essential to ensure its proper execution and to deal effectively with all interfaces and unexpected risks.
- **Stability and predictability of regulation**: A precondition for the implementation of these measures.
- **Multi-unit and series effects**: Once a sufficient level of design maturity has been achieved, freezing the design configuration and systematically replicating it as many times as possible (multi-unit and series effect) offers a strong opportunity to build up supply chain capabilities.

In the near term (early 2020s), considering these lessons learnt, the most effective way to achieve construction costs reduction is to develop a nuclear programme that takes advantage of serial construction with multi-unit projects on the same site, and/or construction of the same reactor design on several sites.

Cost reduction opportunities in the short term (up to 2030)

In the short term (up to 2030), with the previous drivers and conditions already in place, the cost of nuclear projects could be further reduced. A range of cost reduction opportunities can be exploited through the interplay between the reactor design and the associated delivery processes. These drivers are not necessarily sequential and can be mobilised even during early planning stages in order to accelerate learning. There is evidence that countries in more advanced stages of learning are already benefiting from these opportunities and working on a continuous improvement basis similar to other industries. In addition, in order to maximise the potential of cost reduction, the right balance between improvement and replication needs to be found in order not to alter the positive learning dynamics. Timely decision making has also to be acknowledged with the objective to ensure the right pace of new construction and diminish the risk of over engineering.

At the reactor design level, the experience gathered during the first construction projects can be used to reach higher levels of simplification, standardisation and modularisation as well as to integrate the latest technical advances in later projects. Organisational efficiencies can also be unlocked through a new set of innovative processes.

Additional opportunities in the longer run (beyond 2030)

Longer term (beyond 2030) cost reductions are also possible. There are indications that countries in more advanced learning stages are moving in this direction.

Further cost reductions can be unlocked by means of higher levels of harmonisation in codes and standards, and licensing regimes. Other highly regulated activities, such as the aviation sector, have already undertaken significant efforts in this field with positive results. Without neglecting the strong political dimension and the need to protect the sovereignty of national regulators, international collaboration for regulatory harmonisation has demonstrated that it is possible to reach common positions in some areas.

3.4. The economics of small modular reactors

Key economics drivers of SMRs

While smaller cores bring the benefits described above, they also have a negative effect on the economic competitiveness of the unit. Reactor designers have traditionally scaled reactors up to larger sizes to take advantage of the economies of scale. In other words, because the fixed costs associated with a nuclear reactor grow very slowly as the size of the reactor increases, it makes sense to increase the output of the reactor to reduce as much as possible the cost per unit of electricity produced. To counterbalance the impact of diseconomies of scale, the business case of SMRs is supported by economies of series production, which in turn relies on design simplification, standardisation and modularisation.

The benefits of serial construction have been well documented in other industries, such as the shipbuilding and aircraft industries, in which serial manufacturing have resulted in learning rates between 10 and 20% (NNL, 2014). For the first SMRs units, serial production may also allow to amortise non-recurrent costs, such as research, development and design certification costs.

To support serial construction and achieve learning rates of the same order of magnitude as these other industries, several specific drivers have been identified as summarised in Figure 15 below.

- **simplification** of the reactor design;
- **standardisation** of the technology;
- **modularisation** and factory build construction;
- **harmonisation** of the licensing framework.

Attaining these economic benefits will require a coordinated effort between the different stakeholders, as well as a dedicated policy and regulatory framework. It is also imperative to appropriately estimate the size of the global market required to establish a robust supply chain and sustainable construction know-how that result in cost competitive capital costs.

If SMRs can be serially manufactured in a manner similar to commercial aircraft, the economic benefits are significant. This requires, however, the market for a single design to be relatively large, which denotes the need for a global market. For this to be realised, regulators will need to consider how they might co-operate to enable a true global market for nuclear technologies.

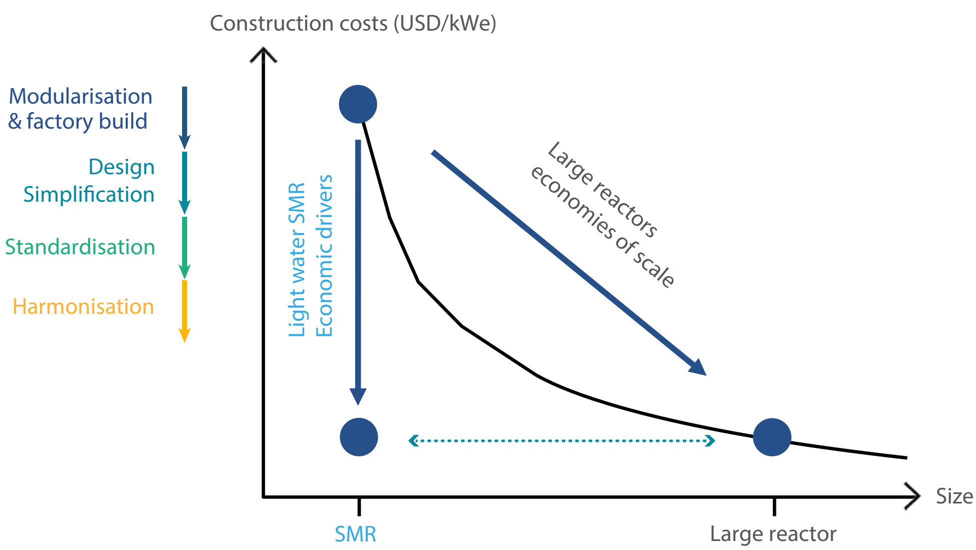

Figure 15: SMR economic drivers that help compensate diseconomies of scale

Source: NEA (2020b).

Market potential for SMRs

The smaller size and the shorter delivery times predicted make the upfront investments needed for SMRs smaller. As a result, customers and investors may face lower financial risk, which could make SMRs a more affordable and attractive option. Given their smaller size, SMRs also offer more flexibility to meet demand growth in smaller increments, which would also improve their overall business case.

However, the anticipated advantages of series deployment will only be realised if SMRs can take advantage of a global supply chain and a global customer basis, which require a streamlined multinational licensing framework and co-ordinated international codes and standards for the manufacture of systems and components.

Although most SMR technologies are in the relatively early stages of development and significant uncertainties remain for their market outlook, at least three potential applications have been identified for SMRs, in addition to the traditional role of providing baseload electricity:

- **Decarbonising energy systems** by replacing coal plants and providing power for district heating and desalination applications. Most advanced designs such as non-LWR SMRs, that are designed to have higher operational temperatures, could supply process heat for industrial sectors where substituting carbon-intensive sources of energy would otherwise not be possible.
- **Complementing the penetration of Variable Renewable Energy (VRE)** by providing system benefits based on the flexible operation of SMRs and the possibility to be part of an integrated portfolio of solutions in "hybrid" energy systems.
- **Facilitating the expansion of the nuclear sector** in regions where economic, geographical and/or grid-related constraints do not allow the use of large nuclear power plants. For such markets, SMRs may already be a cost-competitive way to replace diesel generators to produce electricity, heat and fresh water.

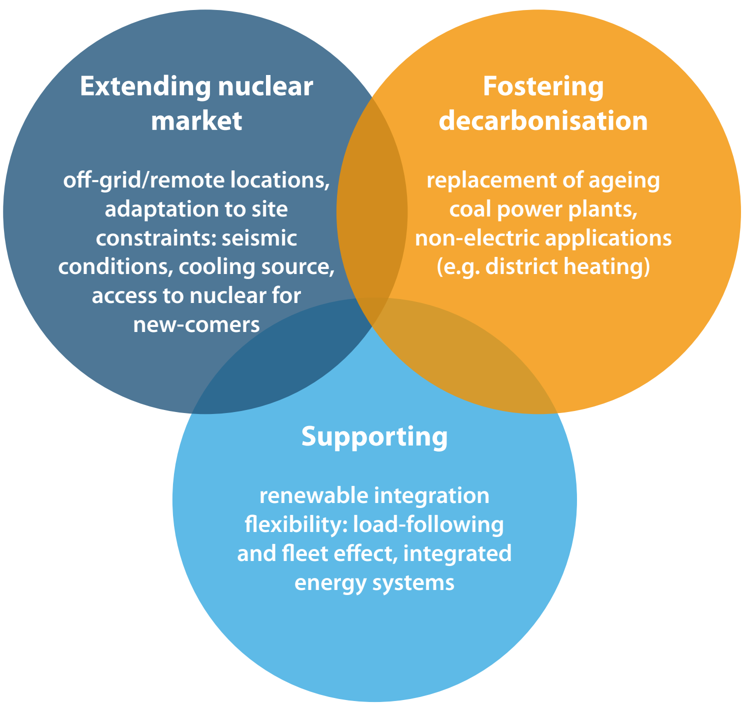

Figure 16: The market opportunities for SMRs

4. Carbon management potential of nuclear power

Nuclear power is the electricity technology that avoids the highest quantity of CO_2 emission per GW of installed capacity. Depending on country electricity mixes characteristics, nuclear is especially well suited to replace baseload power plants such as coal power plants and combined cycle gas turbines (CCGT).

As highlighted in Figure 17 below, nuclear power is expected to displace twice as much CO_2 emissions as offshore wind power per GW of capacity installed, and three times more than solar PV. This result reflects the higher load factor of nuclear power. Furthermore, it does not take into account the need for back-up capacity to support the integration of variable renewables, in particular natural gas in countries with limited hydropower capacity and that do not include nuclear in their mix of low-carbon energy solutions.

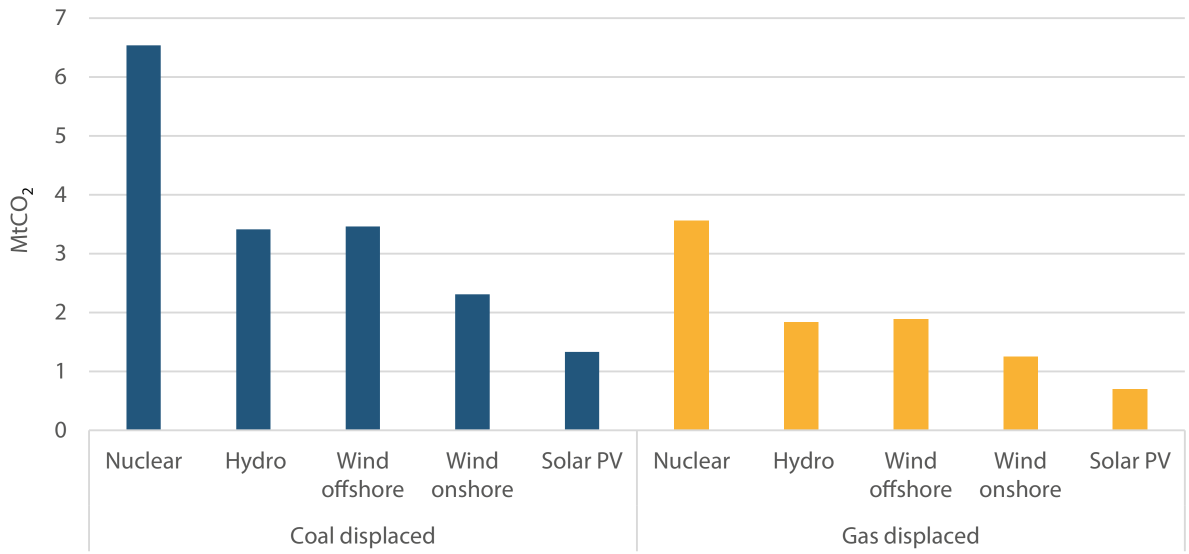

Figure 17: Annual CO_2 emissions avoided per 1 GW of installed capacity by technology and displaced fuel

4.1. Nuclear power in the IPCC scenarios

In 2014, the IPCC set a target of 80% low-carbon electricity in 2050 to limit the rise in world temperatures to 2°C before 2100. With the upward revision of the target to 1.5°C in 2018, the main IPCC scenarios now require a complete decarbonisation of the electricity system by 2050, with negative emissions afterward.

In that respect, the latest IPCC report includes four scenarios (P1-P4) in its Summary for Policymakers based on different societal approaches. The P3 scenario is based on the continuation of technological and societal developments, in particular. The share of nuclear energy increases in all four scenarios compared to 2010: + 59-106% by 2030, + 98-501% by 2050. The P3 scenario includes the most notable increase (+ 501%) in nuclear production by 2050 (IPCC, 2018).

A detailed review of the 78 scenarios included in the 2018 IPCC report shows that the median output of nuclear energy needs to more than double between 2020 and 2050, from 3 000 TWh to about 6 600 TWh to meet the required decarbonisation goals. This would mean that the share of nuclear in the overall electricity mix remains relatively constant at about 9% through 2050. Assuming that nuclear power primarily displaces gas power plants, this further translates into the avoidance of 1.5 $GtCO_2$/year in 2020, rising to 3.25 $GtCO_2$/year by 2050. These CO_2 emissions avoided by 2050 represent about 10% of the CO_2 emissions of the energy sector in 2018. Should nuclear energy displace coal power plants these figures would be twice as high.

Based on this analysis, the IPCC indicates that "There are large differences in nuclear power between models and across pathways. One of the reasons for this variation is that the future deployment of nuclear can be constrained by societal preferences assumed in narratives underlying the pathways." In other words, it is important to bear in mind that the constraint regarding nuclear development in these scenarios have more to do with specific assumptions from modelling teams in terms of societal preference toward nuclear power, rather than reflecting the output from a cost optimisation exercise.

However, in the spirit of the circular carbon economy, a more detailed review of these scenarios reveals that most of them rely primarily on existing nuclear technologies for electricity production. For instance, less than one third of the 21 models used include SMRs, or the possibility of non-electric nuclear applications such as nuclear heat.

Figure 18 below summarises the expected contribution of nuclear power to decarbonisation efforts in the 78 scenarios available in the IPCC database. On the left-hand side, nuclear power production in all scenarios in 2020, 2030 and 2050 is presented in box-and-whisker summary charts that report the medium, first and third quartiles, as well as minimum and maximum values. On the right-hand side, the CO_2 emissions avoided are reported based on the median IPCC scenario and assuming that nuclear would be displacing gas.

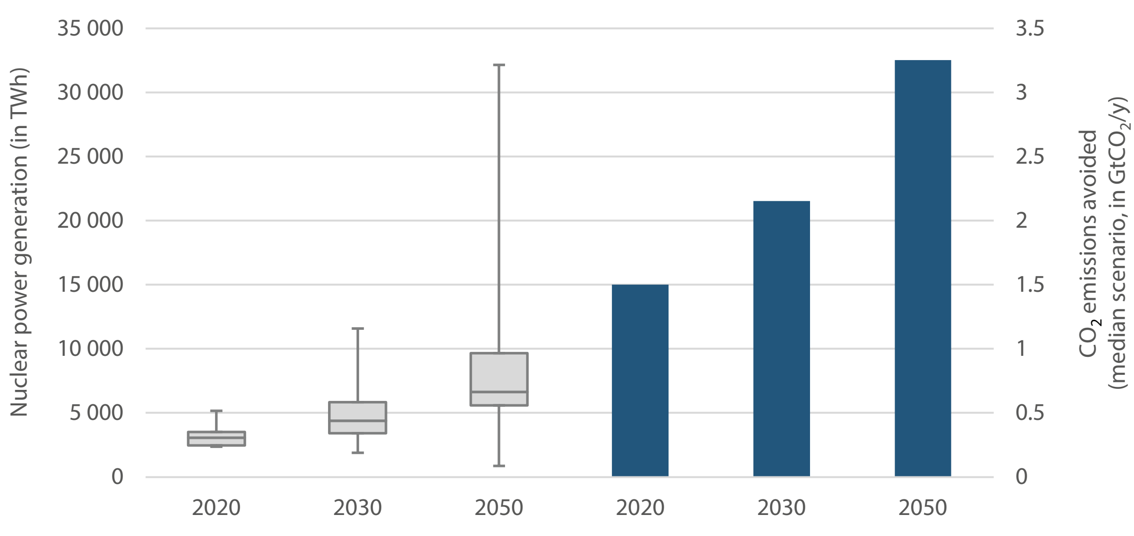

Figure 18: Contribution of nuclear power in the 1.5°C IPCC scenarios

Source: Based on IPCC data, Huppmann et al. (2019) and Rogelj et al. (2018).

4.2. Nuclear power in the IEA Sustainable Development Scenario

The IEA SDS scenario is designed to meet the objectives of the Paris agreement in terms of CO_2 emissions reductions by 2050. It also tackles several objectives of the Sustainable Development Goals (SDGs) in terms of universal access to energy (SDG 7), reduction of the severe health impacts of air pollution (part of SDG 3), together with climate change (SDG 13).

As stated in the outlook chapter, installed nuclear capacity increases from about 400 GW today to 601 GW by 2040. Assuming again that nuclear power would primarily displace gas, the CO_2 mitigation potential of nuclear power in 2040 in the SDS can be broken down in four categories:

- The contribution of the existing reactor fleet that would have less than 40 years of operation by 2040: this represents 141 GW or 0.51 $GtCO_2$ avoided/year.
- The additional contribution of the existing reactor fleet taking into account announced policy decisions regarding closures and LTO programmes: this represents an additional 53 GW or 0.19 $GtCO_2$ avoided/year.
- The additional contribution of the existing reactor fleet assuming that policy decisions enable long term operation to 60 year: this represents an additional 154 GW or 0.56 $GtCO_2$ avoided/year;
- The contribution of planned nuclear new build: this represents an additional 119 GW or 0.43 $GtCO_2$ avoided/year.
- The additional nuclear new build capacity needed to meet the SDS scenario, assuming that the entire nuclear reactor fleet can operate for up to 60 years: this represents an additional 134 GW or 0.48 $GtCO_2$ avoided/year.

Overall nuclear power can therefore be expected to contribute to about 2.2 $GtCO_2$ avoided per year by 2040 on the assumption that it is displacing natural gas. This figure would be about twice as high if nuclear power displaces coal.

The above analysis provides an order of magnitude for the respective contribution of the existing nuclear reactor fleet and nuclear new build to decarbonisation efforts for the electricity sector. In that respect, it is worth pointing out that 60 years is not the expected end of life of nuclear power plants as several units in the US are moving toward extending their operation to 80 years. Conversely, even in such a scenario where the world is on track to meet its climate objectives some reactors may not be able to reach 60 years, for specific technical reasons and, in most cases, due to political decisions. These two factors would affect the additional nuclear capacity required to meet the SDS scenario.

In addition, like with IPCC scenarios, the IEA SDS scenario only relies on existing nuclear technologies and does not consider innovative nuclear technologies, nor the potential of non-electric nuclear applications.

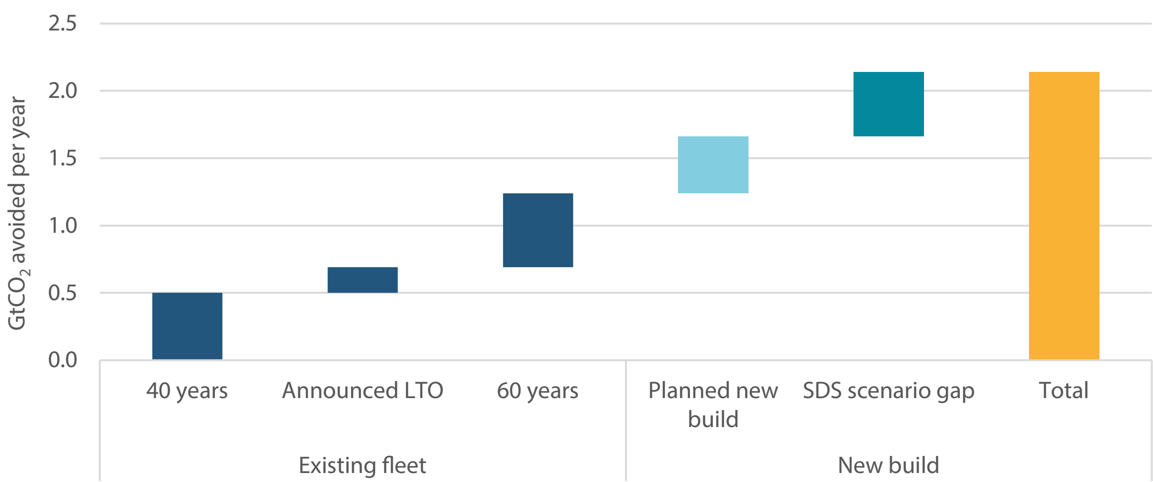

Figure 19: CO_2 emissions avoided by nuclear power in the IEA SDS scenario in 2040

4.3. The role of nuclear non-electric applications to support the decarbonisation of other energy sectors

As stated above, non-electric applications are usually neglected in decarbonisation scenarios that either lack the level of technological granularity to take into account their potential, or simply because these hypotheses are not considered by modellers.

As of 2018, heat is the largest energy end-use and accounts for about 50% of the world final energy consumption. Fossil fuels dominate supplies and, consequently, the heat sector is responsible for 40% of the energy sector CO_2 emissions. The heat market is evenly divided between industrial processes (50% of the market) and buildings (46%). The remaining 4% is largely attributable to agriculture.

Heat is a hard-to-abate sector given the limited renewable options available beyond biomass, whose potential depends on countries specific conditions in terms of resources. In this context, nuclear cogeneration has a significant potential but remains an option largely overlooked by policy makers.

In addition, nuclear cogeneration could play a role in adapting nuclear plants to the flexibility needs of the electricity system through two key features:

- Fast switching, from electricity production to the co-generated product: this provides flexible adjustment of power whilst maintaining a continuous operating point for the nuclear power plant.
- Storage of cogenerated product (hydrogen, water): this relieves time constraints and provides easy back and forth operation.

The type of potential applications depends on the temperature of the thermal energy delivered by the nuclear reactor. Past and current experience with nuclear co-generation relates to lower-temperature applications such as district heating, sea-water desalination and process steam for industrial applications. The higher temperature advanced reactors would enable nuclear energy to also support industrial applications that have heat temperature requirements above 300°C, including hydrogen production and petroleum refineries.

Low-temperature non-electric applications

Low-temperature non-electric limitations are typically those requiring thermal energy at less than 300°C; which can be supplied by most of the existing reactors and Gen-III+ reactors.

Desalination

Sea-water desalination capacity around the world is increasing rapidly to meet the increasing demand of fresh water in both developed and developing countries. According to the research by the Global Clean Water Desalination Alliance[1], most seawater desalination plants currently run by fossil fuel and their CO_2 emissions account up to 76 $MtCO_2$ per year, and it is expected to reach 500 $MtCO_2$ in 2040 under the current trend.

Nuclear desalination has been demonstrated, can be economically competitive and meets the product water quality through a properly designed coupling system between a nuclear reactor and a desalination plant, while providing the product with low-carbon emissions. Several technological solutions can be considered:

- thermal processes: multi-stage flash (MSF) and multi-effect distillation (MED);
- membrane processes: reverse osmosis (RO) and electro-dialysis (ED).

Thermal processes require saturated steam up to maximum 140°C which can be supplied by the current generation reactors. In Aktau, Kazakhstan, ten units of MED plants were coupled to a 1 000 MWth liquid metal cooled, fast breeder reactor (BN-350) to produce 14 500 m^3/d. It produced very high-quality water for industrial and potable needs using MSF desalination units and ran for 26 years before shutting down in 1999.

1. Global Clean Water Desalination Alliance (2019), *The Global Clean Water Desalination Alliance Calls for increased Global Action to Ensure Security and Sustainability of Water Access*, www.oieau.fr/sites/www.oieau.fr/files/gcwda_communique_on_sustainable_desalination.pdf.

Although the current generation reactors can meet the energy demand and temperature requirements for all seawater desalination technologies, some of the advanced reactors are also being proposed for this service. Some of the new integral SMR concepts, are proposed for water desalination services. High-temperature, gas-cooled reactors have also been proposed for water desalination services as a lower-temperature cogeneration application.

District heating

District heating systems exist in many countries in Europe and North America and most of these systems are fossil-fuelled. District heating systems are usually based on either hot water or low pressure steam and range in size from 600-1 200 MWth for large cities down to 10-50 MWth for smaller communities.

As of 2018, 46 commercial nuclear plants in 12 countries were being used or have been used for district heating purposes with a heat output between 5-240 MW, demonstrating a safe and reliable operation. One example of pressurised water reactor which is run in a co-generation mode for district heating is Beznau nuclear plant in Switzerland. Beznau plant began to supply nuclear district heating in early 1980s and continues to do so today, serving a population of nearly 20 000. Experience in Switzerland shows that nuclear-based district heating is economical, safe, reliable and acceptable.

Other industrial process heat

Some other industrial sectors that required relatively lower temperature heat, such as pulp, paper, food and tobacco industries, may benefit from heat supply by present reactor types, although the overall heat demands of these sectors are currently limited compared with those for buildings and water desalination. Some of these applications require higher temperatures than district heating and desalination and use pressurised steam up to 250°C, which is still compatible with current nuclear reactor technologies.

High-temperature non-electric applications

High-temperature non-electric applications require thermal energy supply at temperatures above 300°C and therefore are not currently available due to the limitation on reactor outlet temperature of existing reactors. Ongoing development of advanced reactors with significantly higher temperatures has created possibilities for using nuclear heat for additional industrial applications.

At the European level, the EUROPAIRS study (Bredimas, 2011) found that the most significant heat market is below 550°C (chemical, plastic, pulp and paper industries) and above 1 000°C (cement, steelmaking), with very few processes requiring energy in the temperature range of 550°C and 1 000°C. In that respect, process heat currently provided by fossil fuel fired cogeneration plants or boilers can be replaced by heat from nuclear plants that would utilise existing heat distribution infrastructure.

Among reactor concepts currently under development, HTR can be a near-term solution for suppling process heat up to 550°C. There are two experimental units in operation (HTTR in Japan, HTR-10 in China) and two FOAK units under construction (HTR-PM, in China). In the past, several other experimental and industrial prototypes operated, although none of them were used for heat supply.

Hydrogen production

Hydrogen has long been considered as an energy carrier but has not made much impact in the total world energy supply because of the practical difficulties of introducing hydrogen in the energy system (IEA, 2019). Hydrogen has to be produced using a primary source of energy and the energy efficiency of the production process must be such that hydrogen can be economically deployed as an energy carrier. Over 90% of the hydrogen currently produced is from fossil fuels and is primarily used in chemical production plants. Only a small fraction of hydrogen is currently used in the energy sector, mainly in fuel cells for electricity production or in vehicles.

To be used as energy carrier, hydrogen must be produced from water, using energy efficient processes and low-carbon electricity such as nuclear energy. Three options for nuclear hydrogen production are considered:

- **low-temperature electrolysis**: the most mature technology that uses electricity and can thus be combined with existing nuclear reactor technologies;

- **high-temperature electrolysis**: that requires a heat intake and can be combined with High Temperature Reactors under-development;
- **thermo-chemical cycles**: also using high temperature reactors.

Nuclear hydrogen production can present significant economic benefits considering that the different hydrogen processes considered are highly capital intensive, and therefore require a low-carbon technology that can operate at a high capacity factor.

Other high-temperature applications

A significant potential can be identified for an "extended" heat market such as for oil refining, iron and steel and cement manufacturing where heat is mostly provided by embedded boilers and burners. In particular, two sub-markets can be highlighted:

- "Polygeneration": production of base raw materials such as industrial gases (hydrogen, nitrogen, oxygen) in addition to cogeneration of heat and power.
- "Pre-heating" for industries steel and glass manufacturing. For instance, the use of High Temperature Reactors for steam supply for the in-situ extraction of bitumen from oil sands has also been investigated in Canada.[2] Various studies of potential cogeneration of high-temperature reactors for petrochemical and steel sectors are also summarised by the IAEA (IAEA, 2012).

Although various cogeneration possibilities for high-temperature reactors have been studied; the challenges of economic competitiveness, licensing ability of co-location and coupling of nuclear plants to a production plant and public acceptance have to be addressed for these solutions to meet their long-term potential.

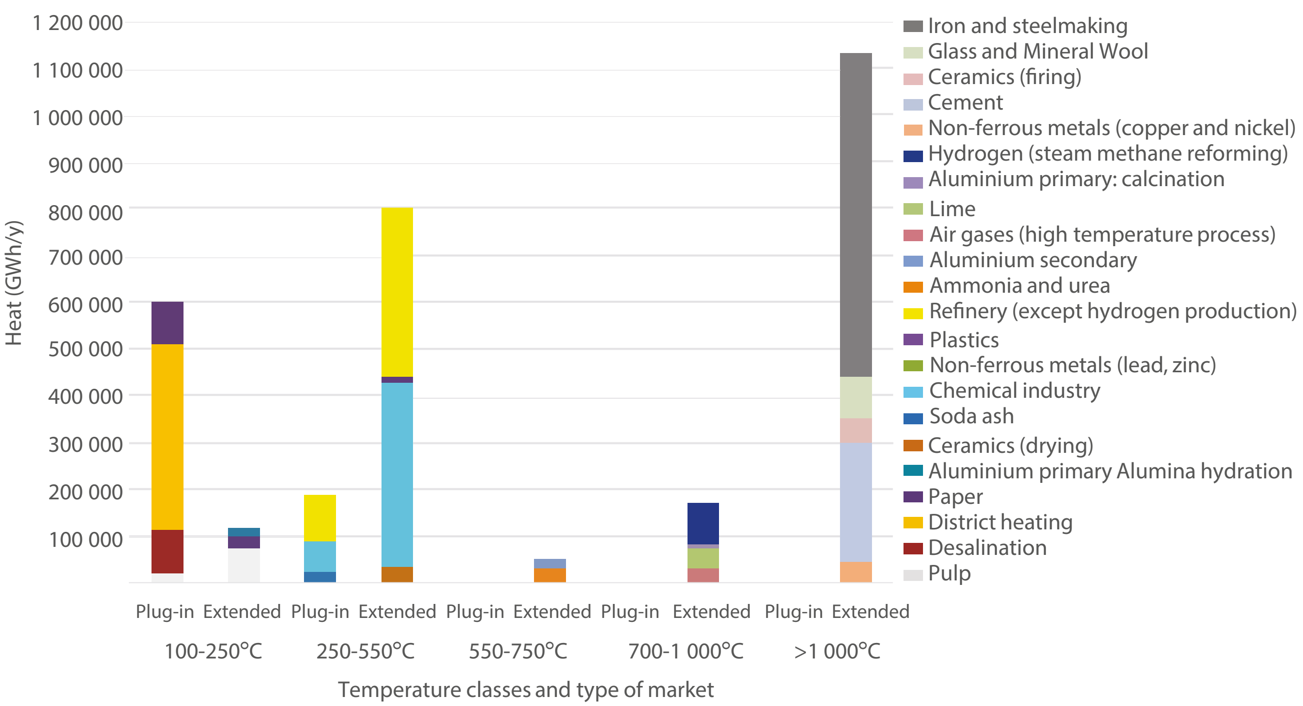

Figure 20: Distribution of the European heat market by temperature class and sector

Source: Bredimas (2011).

2. Canadian Small Modular Reactor Roadmap Steering Committee (2018), *A Call to Action: A Canadian Roadmap for Small Modular Reactors*, Ottawa, Ontario, Canada, https://smrroadmap.ca.

5. Barriers and enabling policies

In countries that wish to rely on nuclear power as part of their future low-carbon energy mixes, current electricity market designs create a number of barriers that can impact existing nuclear plants and hinder the development of new build. Developing a level playing field is therefore key to foster the competiveness of nuclear power.

In addition, considering that the costs of nuclear new build are dominated by the capital costs, access to low cost financing will play a critical role, as is the case for other low-carbon technologies that have similar cost structures.

Finally, government have a central role to play to support the development of innovative reactor designs – such as SMRs – and to foster international licensing framework that are expected to play an increasingly important role for the deployment of these new nuclear technologies.

5.1. Electricity market reforms to support low-carbon technologies

Supporting the competitiveness of LTO in existing electricity markets

Despite the advantages of the existing reactor fleet in terms of carbon management and total cost of electricity provision, there are still several barriers to its life extension.

Extensions of operating licences for nuclear plants require regulatory approval from the national competent safety authority. This decision is taken after the evaluation of the technical evidence and actions plans provided by the licencees to ensure that the facility will perform safely during the extended period. In parallel, operators will also assess the economic viability of the necessary investments taking into account expected market conditions as well as their internal capabilities. However, even if all the previous dimensions yield a positive output, there are several risks and uncertainties out of reach of operators that may lead to early closures. This is for instance the case of sudden political shifts in some countries and acute market downturns.

Policy-driven decisions are the main reason of early closure of nuclear power plants, particularly in Europe. From all the nuclear power plantsthat have shut down since 2012 and those that are expected to close before 2026 according to stated policies, almost 50% are for policy reasons. In Europe, nuclear closures for policy reasons are greater than 80%.

At the same time, due to the combined effect of increased renewable penetration and stagnating energy demand, several regions are facing degraded market conditions. In the US, this negative market context has been amplified by the presence of abundant cheap shale gas. While operators have made significant efforts to reduce plant-level costs and optimise operations, this has not prevented some plants from being forced out from the market earlier than expected, especially single-unit plants that cannot spread their fixed costs among several units (NEA, 2019b). Nuclear power plant closures in the US between 2012 and 2026 for purely economic reasons represent approximately 70% of all closures. The previous examples illustrate that some conditions cannot be effectively controlled by utilities and additional policy actions are required.

More specifically, an enabling policy framework for LTO is based on two pillars: long-term policy commitment and addressing specific market risks. In contrast to the case of new nuclear projects, LTO does not encounter financing issues that may require some sort of government support or guarantee. With more than 100 projects already completed, lower investment levels and a simpler scope, LTO projects face lower construction and financing risks.

Long-term policy commitment for LTO implies sending positive policy signals on nuclear energy activities to both industry and society as a whole while providing stability and long-term visibility. Like any other capital intensive industrial activity, LTO requires long-term visibility, not only to improve its economic viability, but also to properly optimise the underlying industrial plans that could ultimately lead to additional cost savings. To become economically attractive, and in line with the periodicity of major safety reviews, major LTO refurbishment require at least 10 years without any major political shifts. Of course, longer periods will further improve the business case of this type of investments.

From a market perspective, Figure 21 illustrates the different areas that can be addressed by policies in order to enable LTO. They emerge from both the revenue (system value) and technology cost side.

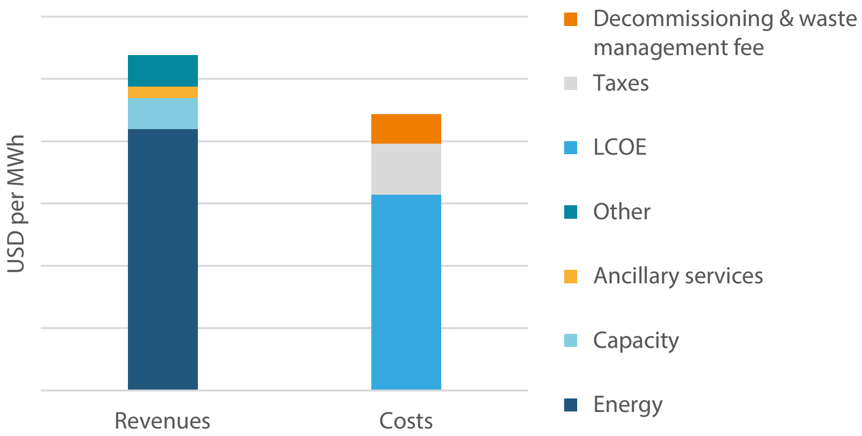

Figure 21: Qualitative representation of the system value and technology costs of LTO

The cost side includes the main components of the LCOE (capital, operation and maintenance and fuel costs) as well as country-specific taxes and decommissioning and waste management fees.[1] Changes in the taxation regime of nuclear power provide a quick and efficient way to sustain continuing operation of the plants in adverse market conditions. There is evidence coming from countries such as Sweden and the US:

- In 2018, the Swedish government abolished the Nuclear Capacity Tax representing an amount of USD 7.7 per MWh (more than 20% of an average LTO LCOE of a nuclear power plant).[2]
- The US has more experience in the utilisation of production tax credits. Similarly to the renewable energy credits (RECs) that are generated by wind and solar generators and sold to utilities, zero emission credits (ZECs) are credits generated by the low-carbon electricity produced by nuclear power plants. Several ZEC frameworks have been granted in states such as New York, New Jersey and Illinois enabling continuing operation of nuclear generation in a short time. Between the period of 2016-2019, the closure of 12 reactors has been prevented with this mechanism. Idaho National Laboratory's research suggests that with additional USD 15 per MWh on top of current average wholesale electricity prices, it would be possible to close the

1. These cost items can also be included in a standard LCOE calculation but, for the sake of clarity, they have been considered as a separate category.
2. Which can be considered as USD 35 per MWh.

revenue gap for around 70% of the US reactor fleet (INL, 2016). Currently ZECs are enacted at approximately USD 17 per MWh. Furthermore, and assuming that projected decommissioning and waste management costs remain constant, extending the lifetime of a nuclear power plant provides additional funding thus reducing the financial burden of these associated fees.

Structural electricity market reforms to foster the decarbonisation of the power system

In parallel, revisited market designs can be envisioned in order to address structural market flaws and risks to properly remunerate different low-carbon technology for the value they provide to the system. Nowadays, most power plants, regardless of their technology, get most of their revenues from energy-only markets. Some of these plants, in particular those with dispatchability attributes such as fossil fuel and nuclear power plants, also provide additional value to the system with round-the-clock capacity and the so-called ancillary services (i.e. inertia, frequency control, etc.). These markets however represent a small portion of the total revenues. In addition, their "size" is system specific and depends on aspects such as the structure of the existing generating portfolio and the number of interconnections, among others. On top of these markets (or revenue streams), additional regulations may be necessary in particular when it comes to reconciling low emissions, affordability and capacity adequacy in the electricity systems in the long-term. In fact, current electricity markets fail to provide long-term price signals to invest on low-carbon capacity.

All low-carbon technologies are characterised by large proportions of fixed costs and low marginal costs. This type of cost structure is not well-suited to withstand the volatility of current deregulated electricity markets. The 2019 NEA system costs study identified that decarbonising the electricity sector in a cost-effective manner while maintaining high levels of electricity security requires five complementary policy measures. These structural reforms should be prioritised to support cost-effective investments in the power system.

Box 1: Key electricity market reform recommendations from the NEA report: The true costs of decarbonisation: System costs with high shares of nuclear and renewables

- Recognise and allocate the system costs to the technologies that cause them: For countries to make the most economic decisions regarding their future electricity supply, they must achieve a full understanding of the costs of each option. Just as nuclear waste costs are best internalised into prices for nuclear-generated electricity, the price of VREs should reflect the costs they introduce into the overall system. Exposure to electricity prices would internalise profile costs, and remunerate each unit of electricity generated at its true value for the system.
- Implement carbon pricing, as the most efficient approach for decarbonising the electricity supply: For countries pursuing policies to reduce carbon emissions, this approach would increase the cost of high-carbon generation technologies, reduce greenhouse gases and enhance the competitiveness of low-carbon technologies such as nuclear power and VRE. However, it will also produce losses for some stakeholders – in particular, fossil fuel producers and their customers. The OECD has highlighted the need for appropriate policies to facilitate a "fair transition" for affected businesses and households, particularly for those in vulnerable regions and communities.
- Encourage new investment in all low-carbon technologies by providing predictable and stable conditions for investors: In order to create modern sustainable and resilient low-carbon electricity systems, major investment in all low-carbon technologies will be needed. However, their high capital intensity requires specific financing solutions as investment will be incentivised solely on the basis of marginal cost pricing in competitive markets. Policymakers need to strike the appropriate balance between out-of market support and exposure to wholesale market prices for low-carbon technologies with high fixed costs such as nuclear energy and variable renewables. Feed-in tariffs (FITs), long-term power purchase agreements (PPAs), contracts for difference (CFDs), regulated electricity tariffs, feed-in premiums (FIPs) or even direct capital subsidies through, for instance, loan guarantees, are all appropriate instruments to achieve long-term cost effective security of supply with low-carbon technologies.

- Enable the development of adequate levels of capacity and flexibility, as well as transmission and distribution infrastructure: Generation is at the heart of any electricity system, but the electricity system requires frameworks for the provision of capacity, flexibility, system services and adequate physical infrastructures for transmission, distribution and interconnections. The variability of variable renewables and new technological developments make these complementary services increasingly important. It is also important to recognise the positive contribution to system stability and inertia of large centralised units such as nuclear power plants or hydroelectric stations and to value them appropriately.
- Maintain truly competitive short-term markets for the cost-efficient dispatch of resources: Marginal cost pricing based on short-term variable costs is an appropriate mechanism to ensure the optimal utilisation of existing resources. It is however, not sufficient to incentivise sufficient investment in low-carbon generation technologies and grid infrastructure. Mechanisms such as capacity remuneration could recognise the value of dispatchability. In OECD countries, the deployment of large amounts of VREs has been successful partly because it was done over an amortised, relatively robust and over-dimensioned electricity system. Even in these conditions, the wholesale price of electricity is not sufficient to cover the cost of producing electricity. And clearly, current markets do not have price signals that may incentivise the investment in the renewal of ageing electricity system infrastructures (NEA, 2019b).

5.2. The role of government in supporting the financing of new nuclear projects

The financial gap for nuclear new build in a liberalised electricity market

Financing conditions directly affect the levelised cost per kWh and therefore the competitiveness of nuclear new build. These conditions are strongly influenced by both the nature of the risks (higher risks leading to a higher expected rate of return on investment and, therefore, a higher cost of capital), and the organisational and ownership arrangements that allocate risks among stakeholders. Figure 22 illustrates the impact of the cost of capital on the levelised cost of nuclear power. An increase from 6 to 9% on the nominal weighted average cost of capital (WACC) would translate in an increase in about 50% of the levelised cost, under a reference scenario with an overnight cost of 4 500 USD/KWe and a lead time of 7 years. Such a reduction of the nominal WACC to 6% would be in line with the social discount rates that are typically used to assess public investments, such as infrastructure projects. Assuming a 2.5% inflation rate, this equates to a 3.5% real WACC – in line with normative estimates of the social discount rate.

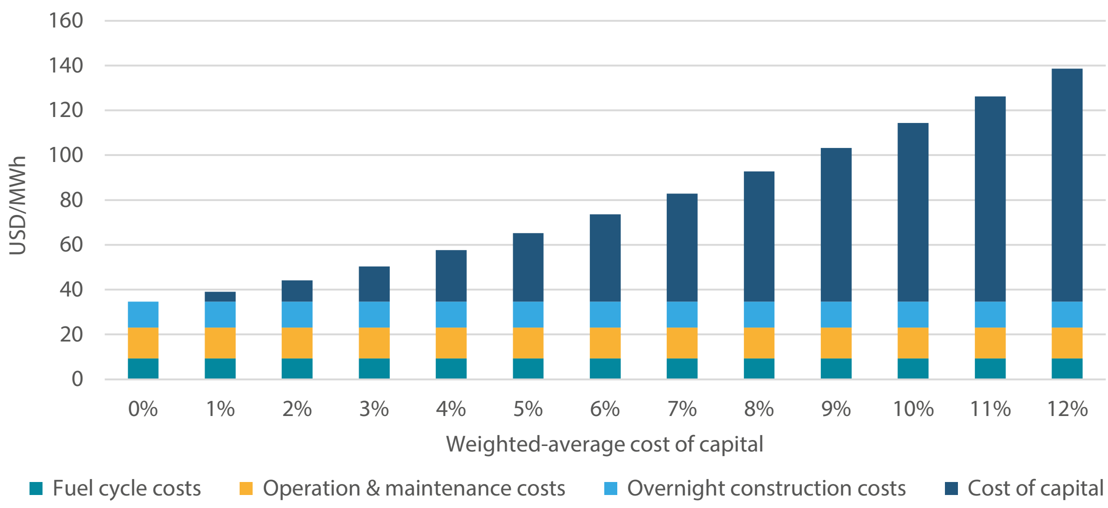

Figure 22: Illustrative LCOE of a new nuclear power plant project according to the cost of capital

Source: NEA (2020b).

Governments have a central role to play to support low cost financing of nuclear power. These direct or indirect government interventions are especially important to address a number of market failures, in particular:

- The contribution of nuclear power to electricity security, energy diversification, as well as climate change mitigation are positive externalities that will typically not be appropriately valued by markets.
- The short-term horizon of electricity markets, as well as equity providers, hinders the development of long-lived assets such as nuclear power plants that are more exposed to market risks. This is reinforced by the failure of current electricity markets to deliver the long-term price signals needed to match the lifetime of nuclear reactors.

In addition, the current macroeconomic environment with persistent low interest rates in many G20 countries is dramatically changing the potential impact that government support schemes can have on the cost of capital. More specifically, the volume of global private equity has been growing rapidly over the last decade and in excess of private investments resulting in a reduction in the cost of equity. However, investors continue to require relatively high risk premium when considering investment in infrastructure-like assets with time horizons beyond 10-15 years. There is therefore a strong rationale for government policy intervention to steer private capital toward infrastructure projects that would contribute to long-term growth, in particular as part of post-COVID-19 recovery plans in G20 countries.

The role of government in supporting the financing of nuclear new build

Government commitment and political consensus to having nuclear power as part of the long-term energy strategy is a prerequisite for any nuclear new build project. The role of government will also be central to build an effective regulatory framework for the licensing of the reactor, and to secure the "social licence" from society.

In this evolving context, government can support financing conditions through a number of nonexclusive policy support schemes:

- direct government financial support (equity or debt);
- indirect government support through long-term power purchase agreements; and
- indirect government support through regulated models (e.g. Regulated Asset Base).

The choice of financial support will be in large part determined by the national context and project characteristics. In particular, the role of government in the area of financing will be particularly important for countries restarting their nuclear energy programmes. However, they should also be viewed as transitional, as improvement in industrial maturity will drive both risk and cost down, reducing the need for government financial support in the long run (see Figure 23 below).

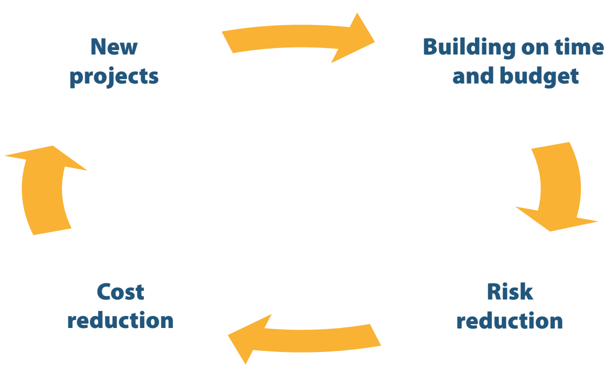

Figure 23: Positive loop between cost and risk with nuclear new build projects

Source: NEA (2020b).

The different policy support schemes highlighted above are not exclusive and their combination can further improve the effectiveness of government action. Doing so can reinforce the degree of certainty regarding government commitment to nuclear new build which further mitigates the risks profile faced by private investors. This is of central importance for attracting new sources of financing as part of public-private partnerships. This would be especially the case of financial institutions – such as pension funds – that may not have specific expertise in infrastructure assets and are looking for long term investments to match the time horizon of their liabilities.

Beyond measures aimed specifically at supporting financing, the role of electricity market reforms highlighted in the previous section will also play a significant role for providing some long term price signals. For example, greater certainty regarding long term CO_2 price trajectories will go in this direction. Policies can also be designed to incentivise corporate power purchase agreements for large energy intensive users, as it is the case in Finland with the Mankala model.

Box 2: Environmental, Social and Governance (ESG) Criteria and investments in nuclear energy projects

ESG Criteria are used by investors to assess the environmental and societal impact of an investment in a company:

- Environment criteria have to do with a company's energy and resource use, pollution and waste generation. Broadly, this set of criteria are used to assess a company's stewardship of and impact on the natural environment.
- Social criteria have to do with a company's treatment of its employees, its supply chain partnerships and its relationship with its local communities as well as society at large.
- Governance criteria have to do with the transparency and ethical soundness of a company's operations, governance and accounting practices.

There is no single set of globally accepted ESG criteria. Instead consulting and investment firms typically develop their own ESG criteria and update them frequently. Based on these criteria, coal and oil companies typically carry low ESG ratings and are excluded by funds that use ESG criteria to guide investment decisions. Conversely, renewable companies typically have high ESG ratings.

Though many funds use ratings based on ESG criteria to guide investment decisions, the ESG criteria themselves are often not technologically neutral and, in many cases, explicitly exclude nuclear energy. Some funds, although acknowledging the positive role of nuclear energy towards decarbonisation of the energy sector, nevertheless exclude it from their ESG criteria citing the management of nuclear waste, the potential for accidents and corresponding damages as reasons for excluding nuclear energy. As a result, some analyses call for excluding nuclear energy from funds focused on sustainability and call for case by case analyses of nuclear energy investments for non-sustainability funds (Robeco 2020).

On the other hand, still other analyses on the possible inclusion of nuclear energy in ESG funds argue for nuclear energy's significant contributions towards achieving at least three of the UN Sustainable Development Goals: Affordable and Clean Energy, (2) Industry, Innovation and Infrastructure and (3) Climate Action and advocate for the inclusion of nuclear energy in ESG criteria (CBIC 2018). Such analyses also cite the strong regulatory oversight of nuclear energy facilities and their consistent safety performance as reasons for inclusion (Morningstar, 2017). The deliberate exclusion of nuclear energy from ESG criteria may be detrimental to attracting private investments in future nuclear energy projects.

The lack thus far of an industry-wide standard for ESG may present an opportunity for creating technology-neutral ESG criteria that create a true level playing field for all low-carbon sources of energy. Such technology-neutral ESG criteria could enable investments in new nuclear energy projects when found to be both financially, socially and environmentally sound investments.

5.3. Innovation and investments in nuclear R&D

The nuclear industry is confident that today's larger Gen III/III+ light water reactors can be built on-time and on-budget and become economically competitive in all markets with all other low-carbon technologies. At the same time, given the major changes that are expected in the energy sector, both technological and market related, the nuclear industry is investing in other concepts and new technologies that may help nuclear energy secure its role as a flexible, reliable and dispatchable source of electricity and heat.

Support for small modular reactor demonstration projects

As stated before, significant efforts are ongoing for the development of small modular reactors (SMRs). Countries such as Canada, the UK and the US are investing public funds to energise research and to incentivise private investment. Public-private partnerships in these countries have resulted in the development of innovative reactor concepts, streamlined frameworks for the validation of new operational and safety approaches, and revised regulatory paradigms more aligned with the new reactor concepts. Several demonstration projects are currently underway, aimed at showing the technical and financial feasibility of these reactor concepts.

Support for non-nuclear application demonstration projects

There is significant focus in the decarbonising all energy sectors, particularly those that cannot be easily electrified. Since nuclear energy is one of the few low-carbon sources of energy capable to produce heat at the same time as electricity, there is a lot of interest in optimising the use of this heat, particularly for hard to abate energy sectors. Existing nuclear power plants can provide power for district heating and desalination applications, and significant research is currently taking place in their use for the production of hydrogen. At the same, advanced designs such non-LWR SMRs, designed for higher operational temperatures, could supply process heat for industrial sectors where substituting carbon-intensive sources of energy would otherwise not be possible, including synthetic fuels for air and marine transportation.

Support for advanced fuels

Another area of major interest is the development of advanced nuclear fuels. These fuels are designed to have an improved performance under the most challenging conditions and to produce fewer and more manageable fission products, thus allowing better operational and safety margins. There are several approaches to these advanced fuels, including metallic fuels, carbon based fuels and claddings or advanced coatings. Significant investment has taken place in many countries, often as public-private collaborations, to develop these new fuels, validate them and test them in real operating conditions. The first test assemblies for some of these advanced fuels have already been installed in commercial nuclear power plants, and are undergoing assessment.

An additional type of nuclear fuel that has gained a lot of interest recently is the High Assay Low Enrichment Fuel (HALEU), which is being proposed for several advanced reactor concepts. HALEU fuel has enrichment levels between 5 and 19.75%, which results in new challenges throughout the entire nuclear fuel cycle.

5.4. Supporting international licensing frameworks for innovative nuclear technologies

Harmonising different licensing approaches is a fundamental determinant in the deployment of SMR technologies. However, as illustrated in Table 4, the advances introduced by innovative nuclear technologies and reactor designs such as SMRs may deviate from the current licensing regimes. The limited regulatory experience base with novel designs poses a significant challenge in demonstrating and approving their safety case.

From a technical perspective, it may be advantageous defining an architecture, or SMR technology taxonomy, capable of identifying common licensing aspects among different concepts while minimising adjustments for current frameworks. This taxonomy may provide higher regulatory predictability and facilitate the licensing activities from both the vendor and regulator sides.

SMRs could be viewed as an opportunity for the early development of international collaborative approaches for the harmonisation of licensing frameworks and codes and standards. These topics have already been extensively discussed for large reactors and the experience gained could be applied to SMRs. For instance, at the level of industrial codes and standards harmonisation, the World Nuclear

Association CORDEL working group has made significant progress inspired by the example of the aircraft industry. More generally, these issues are currently discussed by the IAEA SMR Regulators Forum and the Multinational Design Evaluation Programme (MDEP) administered by the NEA encourages multinational convergence of codes, standards and safety goals.

At the international regulatory level, building on recent initiatives, the nuclear sector is moving towards multi-national licensing in a stepwise manner. For instance, dedicated licensing of SMR modules are applicable to different sites, and are approved in different countries under reciprocal agreements. This would foster the benefits of standardisation, both in terms of learning by doing from serial production, as well as for the reduction of the fixed (non-recurrent) costs associated with licensing.

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