WORLD NUCLEAR ASSOCIATION

World Nuclear Performance Report 2017

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Contents

Preface

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More than 9 GWe of new nuclear capacity came online in 2016, the largest annual increase for over 25 years. By the end of 2016 there were 448 reactors around the world, up from 441 at the start of the year. Ten reactors started to supply electricity and three were closed down, resulting in a net increase in nuclear capacity of just over 8 GWe. The amount of electricity supplied by nuclear globally increased by 35 TWh to 2476 TWh. This increased generation is the result of both additional generation from new reactors coming online and continued performance improvements from the existing fleet.

The number of reactors being built remains high, with 61 under construction at the end of 2016. There were only three construction starts last year and, with ten units having completed construction, the number of reactors under construction has fallen from 68 at the start of 2016. There has been a pause in new reactor construction starts in China; however, the pouring of first concrete for Tianwan 6 in September marked the resumption of reactor construction.

The first Korean-designed APR-1400, unit 3 at the Shin Kori nuclear power plant, was connected to the grid by Korea Hydro and Nuclear Power in January. Construction of four APR-1400 reactors at Barakah in the United Arab Emirates continued to make good progress and the first reactor is due to start-up next year. In Russia the first VVER-1200 at Novovoronezh II, was connected to the grid in August.

2016 saw the start-up of Watts Bar 2, the first reactor connected to the grid in the United States in 20 years. But it also saw continuing challenges to the operation of some reactors in deregulated markets and the ongoing construction of four reactors at VC Summer and Vogtle. More must be done to ensure nuclear plants can compete in a fair electricity market.

The process of gaining regulatory approval for the restart of reactors in Japan is proving to be protracted and extensive and some restarts have been delayed by legal challenges. However, five reactors have now restarted and a further 19 have applied to do so.

In the UK in 2016, the go-ahead was given for Hinkley Point C, the first of a planned new generation of nuclear power plants in that country. Nuclear remains the largest single source of low carbon generation in Europe, but political pressure in some countries is threatening this.

The world's nuclear power plants have performed well this year, making a significant contribution to meeting the need for clean, reliable and affordable electricity. But more will need to be done to ensure this contribution grows as it will need to over the coming decades in order to meet the Harmony goal of supplying 25% of the world's electricity by 2050.

1 Recent Industry Highlights

Three large reactor projects commenced construction in 2016, while ten achieved grid connection and three units were permanently shut down.

Asian countries continue to dominate the market for new nuclear build and the industry is growing overall, albeit slowly. At the end of 2016, 20 of the 61 power reactors under construction around the world were in China, with a further 15 spread across India, Pakistan and Russia. In the USA and Europe, premature retirements of reactors continue to outstrip the rate of capacity addition.

The years since the 2011 accident at Japan's Fukushima Daiichi nuclear plant have been some of the most challenging for the industry. The slow reinstatement of Japan's nuclear fleet, combined with new challenges that have arisen – most notably the bankruptcy of the Toshiba-owned reactor designer Westinghouse – present significant headwinds. Despite this, industry prospects are brighter than they have been for a while, with major nuclear new build programmes under way in several parts of the world.

North America

The Tennessee Valley Authority announced that its Watts Bar 2 unit entered commercial operation in October 2016 – the first new nuclear power reactor in the country for 20 years. Despite this success, the number of operable reactors in the USA stood at 99 at the end of 2016, down from 104 in 2012.

Closures have been brought forward by a combination of cheap gas, market liberalization (in some states), over-subsidy of renewable sources and political campaigning. During 2016, Omaha Public Power District's Fort Calhoun 1 closed, and operator Exelon warned that it will have to close plants that remain unprofitable.

Four reactors are under construction in the USA at two sites in regulated markets. The future of these Westinghouse AP1000 units is unclear due to the vendor's bankruptcy, but construction work has continued.

Several reactors were upgraded and uprated having operated for 25-35 years.

In Canada, all but one of 19 power reactors are in Ontario. In the first part of 2016 the government signed major contracts for the refurbishment and life extension of six reactors at the Bruce generating station. The programme begins in 2020 and will extend the units' operating lifetimes by 30-35 years. Similar refurbishment work enabled the province to phase out coal in 2014 and achieve one of the cleanest electricity mixes in the world.

South America

A full operating licence was issued to Argentina's Atucha 2 in May 2016 replacing a conditional one on which the unit had operated since starting up in 2015. Construction of Argentina's fourth reactor is set to start in 2017 after China and Argentina reaffirmed their plans to build two new reactors through the signing of a memorandum of understanding in August 2016.

West & Central Europe

In July 2016 EDF's board passed its final investment decision on Hinkley Point C in the UK. After delaying its final approval, prime minister Theresa May's cabinet signed all supporting agreements in September 2016. The placement of some structural concrete has begun, ahead of full construction. At Wylfa Newydd, Horizon Nuclear Power's plans to build an Advanced Boiling Water Reactor to replace the recently closed Wylfa 1 are progressing. In April 2017, the company applied for a nuclear site licence.

In France, which has the largest European fleet of 58 operable reactors, a 2015 energy policy aims to reduce the country's share of nuclear energy from 75% of electricity today to 50% by 2025 and the government of President Emmanuel Macron is set to continue this. Through to 2030 the government also aims to reduce greenhouse gas emissions by 40%, though it remains to be seen how this will be achieved while scaling back the contribution of nuclear power. The construction of the Flamanville 3 EPR unit continued through 2016.

In Spain, the owner of the Garoña nuclear power plant, Nuclenor, continued to work towards its restart after stopping the reactor in 2012 due to new taxes and regulatory hurdles. In February 2017, regulatory approval for restart was granted, conditional on certain safety upgrades.

In Finland, infrastructure work commenced early in 2016 at Fennovoima's Hanhikivi site – the most northerly nuclear site outside of Russia – and is expected to be completed by the end of 2017.

Eight nuclear reactors continue to operate in Germany, providing about 14% of electricity in 2016. Increasingly they operate in load-following mode, accommodating the country's push for variable renewable sources and coping with the negative pricing that often results.

In Switzerland, a proposal to force older nuclear power plants to close on an accelerated schedule was rejected in a referendum in November 2016. All five reactors can continue to operate according to their planned lifetimes.

In Belgium, the European Commission has approved government plans to support the long-term operation of Doel 1&2 and Tihange 1. After clearing lengthy investigations of their reactor pressure vessels in late 2015 Doel 3 and Tihange 2 operated routinely through 2016, restoring nuclear's contribution to Belgian electricity to about half the total.

A significant number of other European countries are looking to build new nuclear reactors, including: Bulgaria, Czech Republic, Hungary, Poland and Romania.

East Europe & Russia

Russia connected to the grid its first VVER-1200, Novovoronezh II unit 1. It went on to enter commercial operation in March 2017. The Beloyarsk 4 fast reactor entered commercial operation in November 2016.

A government decree in late 2016 specified the construction of 11 new nuclear power reactors in Russia by 2030. These units will be in addition to the units already under construction at Leningrad, Novovoronezh and Rostov, as well as the floating plant, *Academician Lomonosov*.

The strength of Russia's nuclear industry is reflected in its dominance of export markets for new reactors. The country's national nuclear industry is currently involved in new reactor projects in Belarus, China, Hungary, India, Iran and Turkey, and to varying degrees as a potential investor in Algeria, Bangladesh, Bolivia, Indonesia, Jordan, Kazakhstan, Nigeria, South Africa and Tajikistan among others.

In Ukraine, ambitious plans are in place to start supplying electricity to the European Union by 2019 via its planned 'energy bridge'.

Site preparations at Hanhikivi: Image Fennovoima

Asia

China continues to dominate nuclear new build activity globally. In 2016 new reactors were connected to the grid at Changjiang, Fangchenggang, Fuqing, Hongyanhe and Ningde, adding some 4.6 GWe, and representing about 50% of all new nuclear capacity additions worldwide.

The country continues to benefit from series nuclear construction, with all new reactors connected in 2016 built within six years.

The strong impetus for developing new nuclear power in China comes from the need to improve urban air quality and reduce greenhouse gas emissions. The government's stated long-term target, as outlined in its *Energy Development Strategy Action Plan, 2014-2020*, is for 58 GWe nuclear capacity by 2020, with 30 GWe more under construction.

China continued its nuclear expansion in 2016, with large units at Fangchenggang and Tianwan commencing construction. At the time of writing, the country has a total capacity of 23 GWe under construction. In March 2017 the National Energy Administration announced that it would complete construction of five units in 2017, and begin construction of eight more.

In Japan, 2016 saw muted progress in reactor restarts. By the end of the year, five reactors had passed Japan's Nuclear Regulation Authority (NRA) inspections confirming that they met post-Fukushima standards, and a further 19 reactors had applied for clearance. However, of Japan's 42 operable reactors, only Kyushu Electric's Sendai 1, Shikoku's Ikata 3 and Kansai Electric's Takahama 4 are currently online.

The International Energy Agency, the Institute of Energy Economics and the Japan Atomic Industry Forum have all called for a sustained effort in 2017 to reinstate production from idled reactors, reiterating the essential role that nuclear power needs to play in enabling the country to meet its climate obligations. Since the start of 2017 regulatory approval rates appear to have picked up pace, with the NRA clearing two reactors in Genkai for restart in January, and the Osaka High Court lifting an injunction that had prevented the restart of units 3&4 at Takahama following NRA clearance in 2015.

In 2016, Kansai Electric Power became the first operator to be granted extended, 60-year operating licences under the revised regulations at its Takahama and Mihama plants.

The first Korean-designed APR-1400, unit 3 at the Shin Kori nuclear power plant, was connected to the grid by Korea Hydro and Nuclear Power in January 2016. The unit officially entered commercial operation on 12 December 2016. It is the reference plant for the Barakah project, the UAE's first nuclear power plant, and a further three APR-1400 reactors in Korea are scheduled to be online within six years.

Unit 2 of India's Russian-built Kudankulam nuclear power plant was connected to the grid in August 2016, taking the country's total number of operating reactors to 22. The Indian government is committed to growing its nuclear power capacity as part of its massive infrastructure development programme, and shortly after the successful commissioning of Kudankulam 2, India and Russia launched the second phase of the nuclear power plant's construction in October.

Over the course of 2016 the Indian government took a series of steps designed to catalyse sector investment. In January the country signed a preliminary deal with EDF to build six EPR reactors in Jaitapur; in February the country removed joint venture restrictions stipulated in its Atomic Energy Act to help the state-owned operator Nuclear Power Corporation of India Ltd (NPCIL) secure funding for new projects; and in March the government's new budget included an additional $442 million of support for new nuclear power projects over the next 15-20 years. In May 2017 ten indigenous design units won cabinet approval for construction.

Africa

In South Africa, applications from companies interested in building new nuclear plants are being solicited by utility Eskom, with the government aiming to increase capacity by about 6.8 GWe by 2041. At present South Africa is the only African nation that generates electricity from nuclear energy – its two Koeberg reactors have been operational since the mid-1980s.

Elsewhere, a number of African countries have taken steps that signal a growing interest across the continent to utilize nuclear as a source of low carbon power: Algerian officials have held discussions with the Russian foreign ministry; IAEA director general Yukia Amano has lent his support to Ghana in the event that the country decides to embark on a nuclear power programme; and Sudan has signed a framework agreement with China ahead of the proposed construction of its first nuclear power plant.

Middle East

The UAE's first nuclear unit at Barakah reached several construction milestones during 2016, including installation of the first reactor vessel at unit 3 in June. The plant remains on target to have all four units in operation by 2020. Cooperation between the Emirates Nuclear Energy Corporation (ENEC) and Korea Hydro and Nuclear Power (KHNP) has been extended beyond the commissioning of the first unit at Barakah, with the two companies signing a services agreement to support the Korean-designed plant's first ten years in operation.

Developments elsewhere demonstrate the growing interest in nuclear power across the Middle East. In the first half of the year, Saudi Arabia and China signed a memorandum of understanding on the construction of a high-temperature gas-cooled reactor, whilst King Abdullah II of Jordan stated the importance of moving ahead with the country's plan for nuclear energy and went on to open the region's first particle accelerator in May 2017.

Oceania

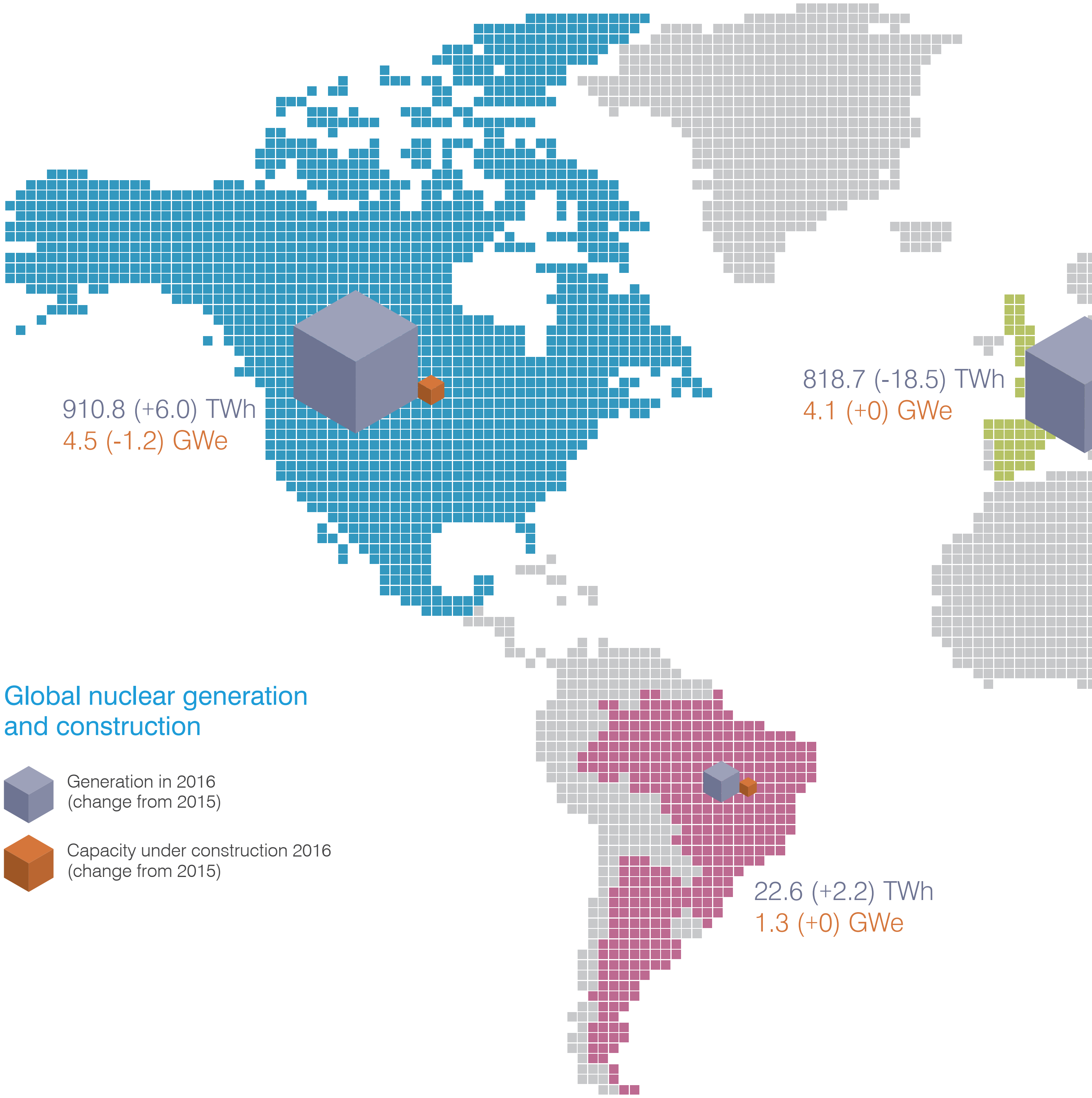
In May 2016, South Australia's Royal Commission delivered its final report into the country's potential participation in the nuclear fuel cycle, recommending that the government should support plans to establish a multi-national storage and disposal facility in South Australia. Whilst the country has not considered a nuclear energy programme since the 1970s, it is a major producer of uranium.

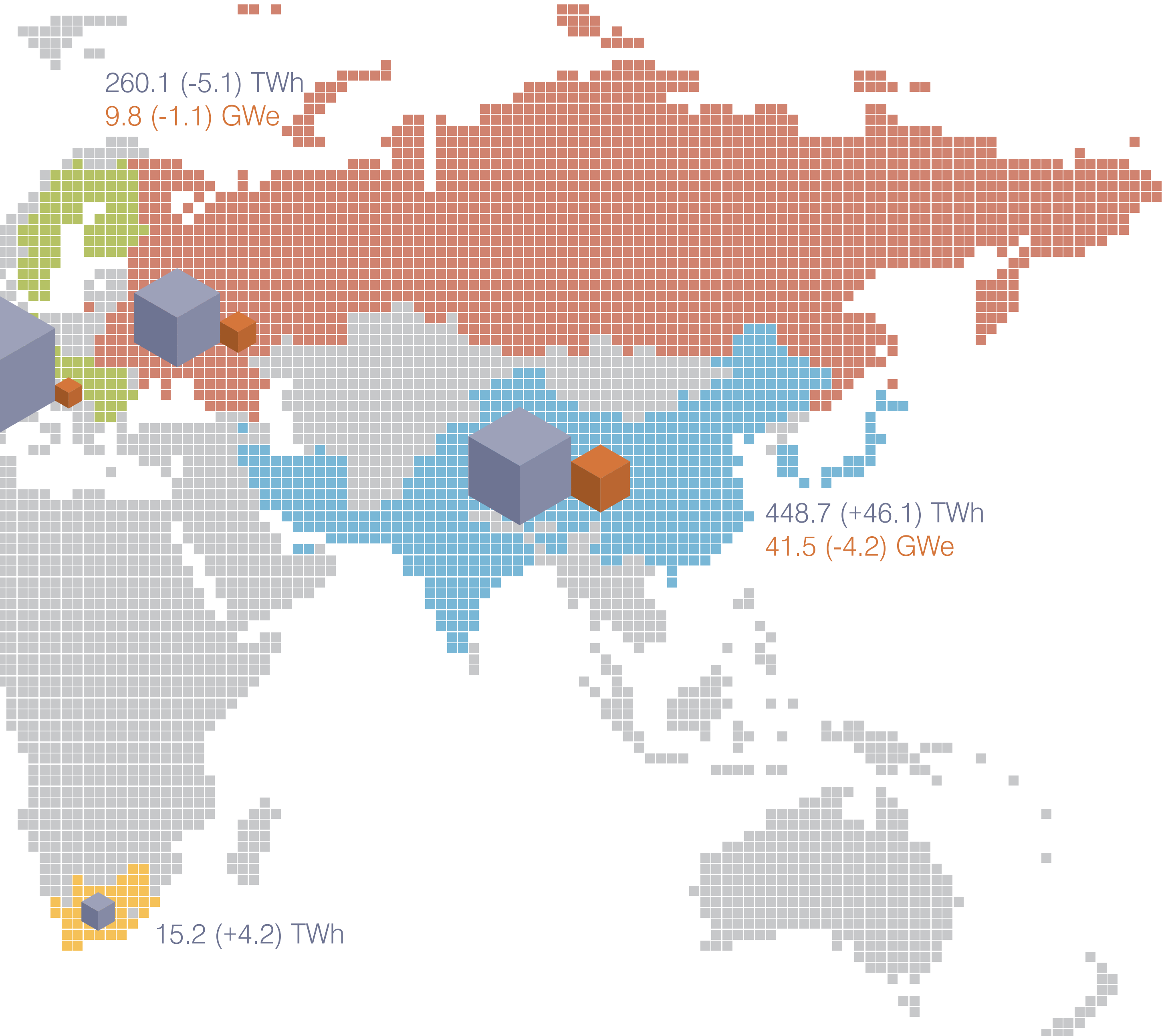
A citizens' jury – set up by the South Australian government to gauge public sentiment towards the idea – rejected the proposal by a significant two thirds majority in November 2016. However, the government continues to support the commission's proposal and following the result announced plans for a state-wide referendum on the issue.

The strong impetus for developing new nuclear in China comes from the need to improve urban air quality and reduce greenhouse gas emissions.

Kudankulam nuclear power plant

2 | Nuclear Industry Performance

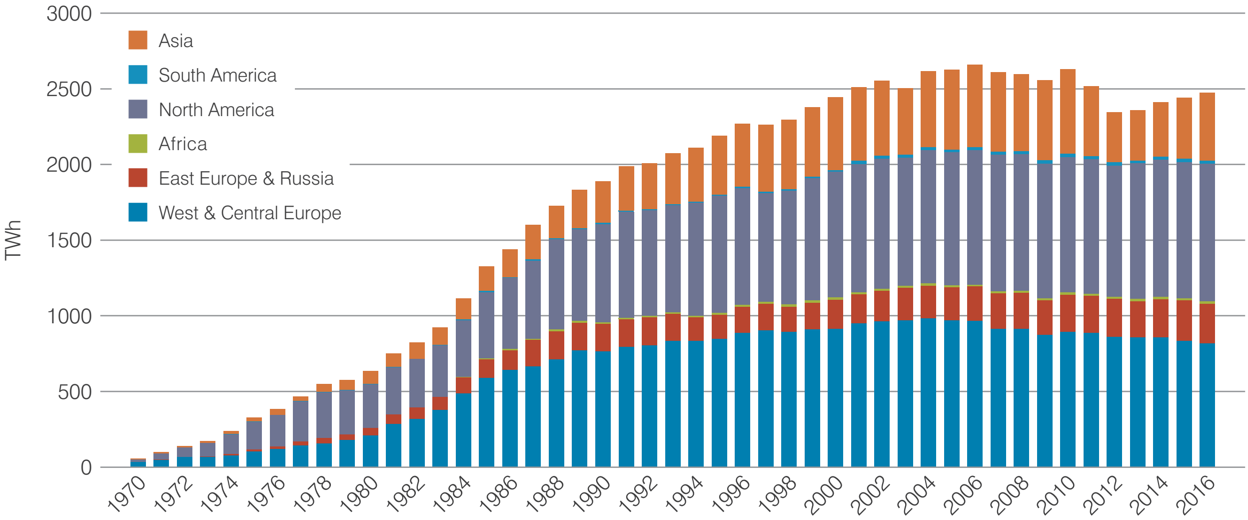



260.1 (-5.1) TWh
9.8 (-1.1) GWe
448.7 (+46.1) TWh
41.5 (-4.2) GWe
15.2 (+4.2) TWh

2.1 Global highlights

Nuclear plants supplied 2476 TWh of electricity in 2016, up from 2441 TWh supplied in 2015. This is the fourth consecutive year that global nuclear generation has risen, with output 130 TWh higher than in 2012.

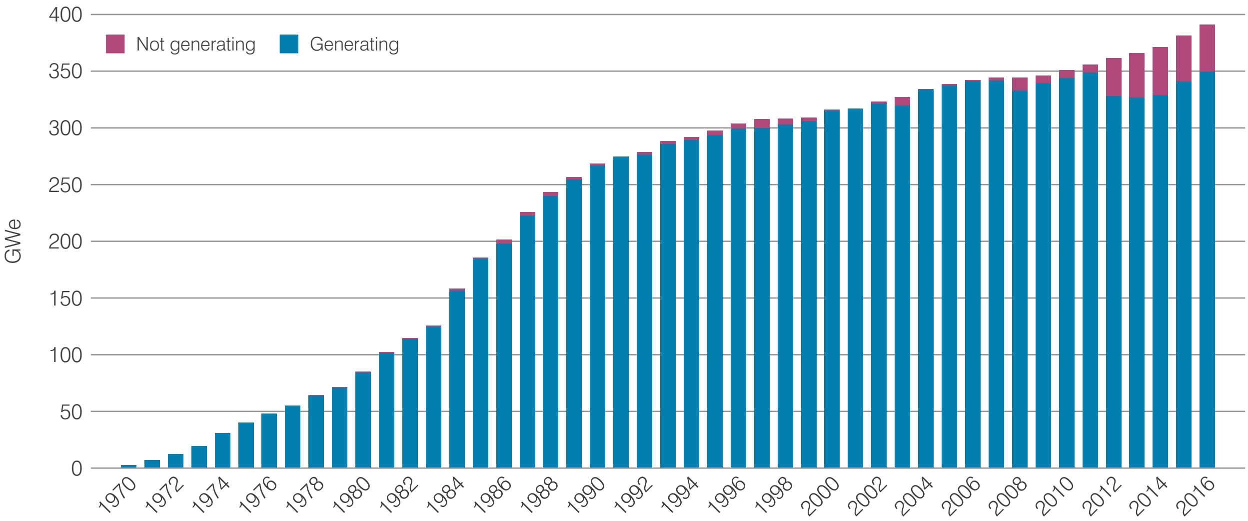
Figure 1. Nuclear electricity production



Source: World Nuclear Association, IAEA Power Reactor Information Service (PRIS)

Global operable nuclear capacity has grown every year since the start of nuclear generation in 1954. In 2016 global net capacity reached 391 GWe.

Figure 2. Nuclear generating capacity



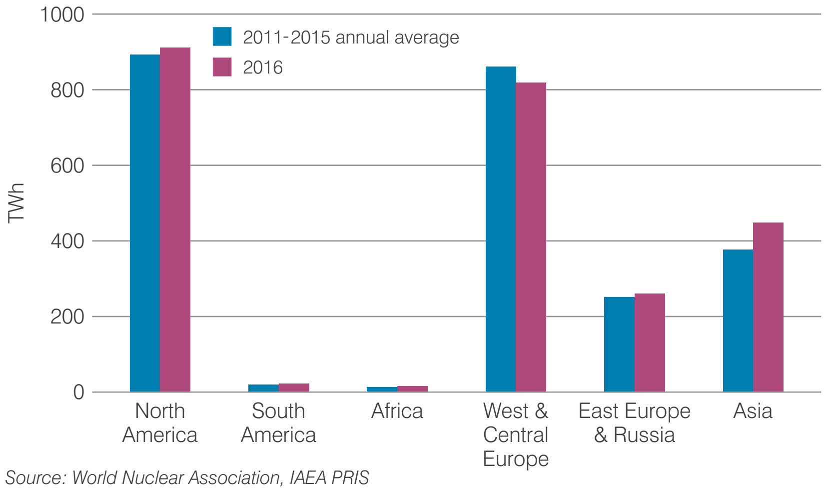
Source: World Nuclear Association, IAEA PRIS

Usually, only a small fraction of operable nuclear capacity is out of service awaiting restart. However, since the 2011 Fukushima accident most of the Japanese reactor fleet has been awaiting restart. Nevertheless, the total capacity of reactors supplying electricity has grown each year since 2013, exceeding 350 GWe for the first time in 2016.

In 2016 nuclear generation was higher in all regions except West & Central Europe, compared to the average annual generation in the preceding five years. Nuclear output rose most markedly in Asia, with generation 72 TWh higher than the 2011-2015 average.

Nuclear output in Asia was 72 TWh higher than the 2011-2015 average.

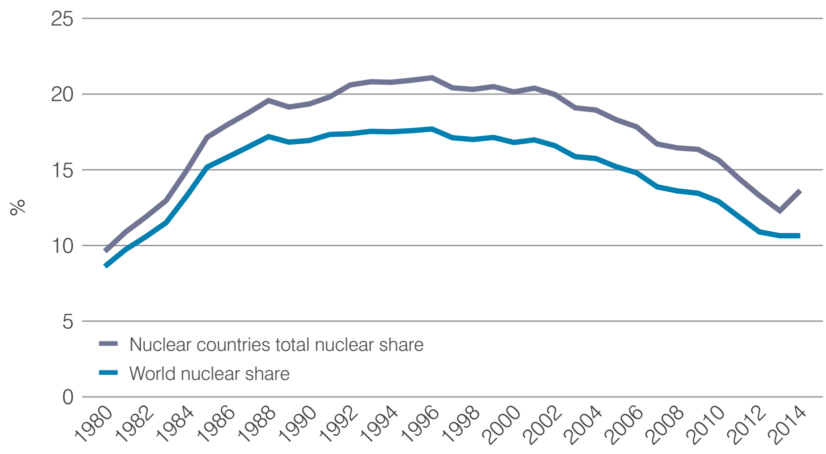
Figure 3. Regional generation



Source: World Nuclear Association, IAEA PRIS

In 2014 the share of nuclear generation in the global electricity generation mix held steady at 10.6%, unchanged from 2013. In those countries that have nuclear generation the share supplied by nuclear rose from 12.3% in 2013 to 13.6% in 2014.

Figure 4. Share of nuclear generation in total electricity supply



Source: International Energy Agency, IAEA PRIS, World Nuclear Association

Since 1996 the share of nuclear generation in the global energy mix has fallen from a peak of around 17% to just over 10%. This decline in the overall share is in part due to an increase in global electricity supply and in part because of a decline in nuclear generation, particularly in 2011 and 2012, in response to the Fukushima accident.

However, as nuclear generation started to increase again from 2012 the share of nuclear generation in the total electricity supply has stabilized.

At the end of 2016 there was a total of 448 operable reactors, up from 441 operable reactors at the end of the previous year. In terms of reactor types used, the pressurized water reactor (PWR) remains predominant. Of the 39 reactors that have been connected to the grid since 2011 all except four have been PWRs, with the remainder consisting of two pressurized heavy water reactors and two fast reactors.

Table 1. Nuclear power reactors at end of December 2016

	Boiling water reactor	Fast reactor	Gas cooled reactor	Light water graphite reactor	Pressurized heavy water reactor	Pressurized water reactor	Total
Operable	78	3	14	15	49	289	448 (+7)
Africa						2	2
Asia	28	1			25	83 (+7)	137 (+7)
East Europe & Russia		2		15		33	50
North America	36				19	65	120
South America					3	2	5
West & Central Europe	14		14		2	104	134

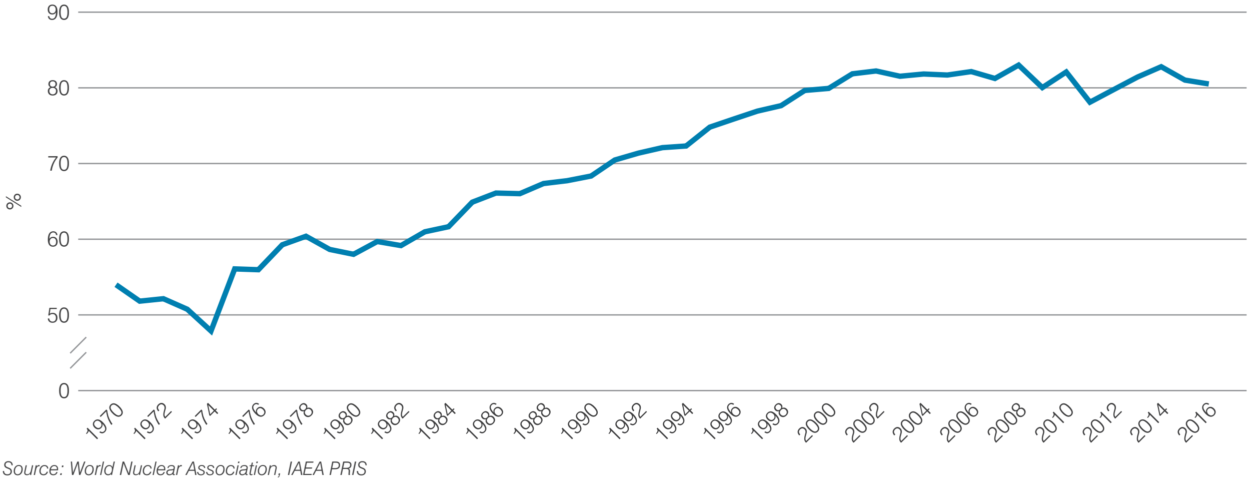
Source: World Nuclear Association, IAEA PRIS

2.2 Operational performance

Capacity factors in this section are based on the performance of those reactors that generated electricity during each calendar year.

In 2016 the global average capacity factor was 80.5%, in comparison to 81.0% in 2015. Despite this small reduction, this maintains the high level of performance achieved by the world's nuclear reactors since 2000, following the significant improvement in capacity factor achieved in the preceding 30 years.

Figure 5. Global average capacity factor

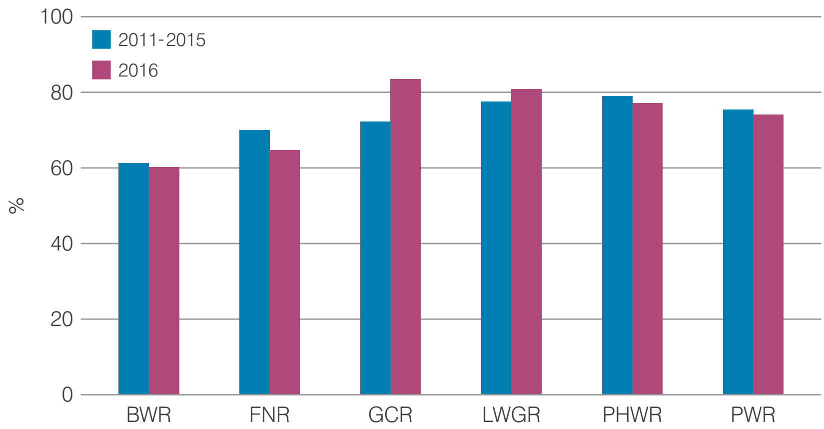


Source: World Nuclear Association, IAEA PRIS

Capacity factors for different types of reactor are broadly consistent with the average achieved in the preceding five years. Greater variation is seen in those reactor types represented by a smaller number of reactors.

Overall capacity factors have remained at the high levels achieved over recent years.

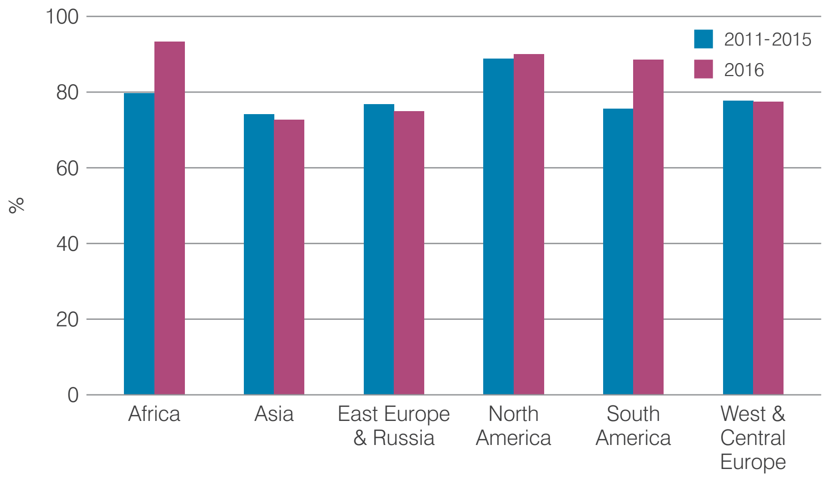
Figure 6. Capacity factor by reactor type



Source: World Nuclear Association, IAEA PRIS

Capacity factors are also broadly consistent with the average achieved in the preceding five years for reactors in different regions. Again, the greatest variation is seen in regions represented by a smaller number of reactors.

Figure 7. Capacity factor by region

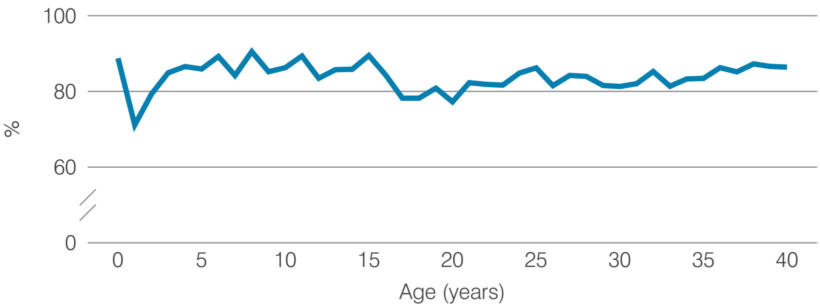


Source: World Nuclear Association, IAEA PRIS

Median capacity factor remains consistently high throughout the lifetime of the reactor.

There is no significant age-related trend in nuclear reactor performance. The median capacity factor for reactors over the last ten years shows no significant age-related variation.

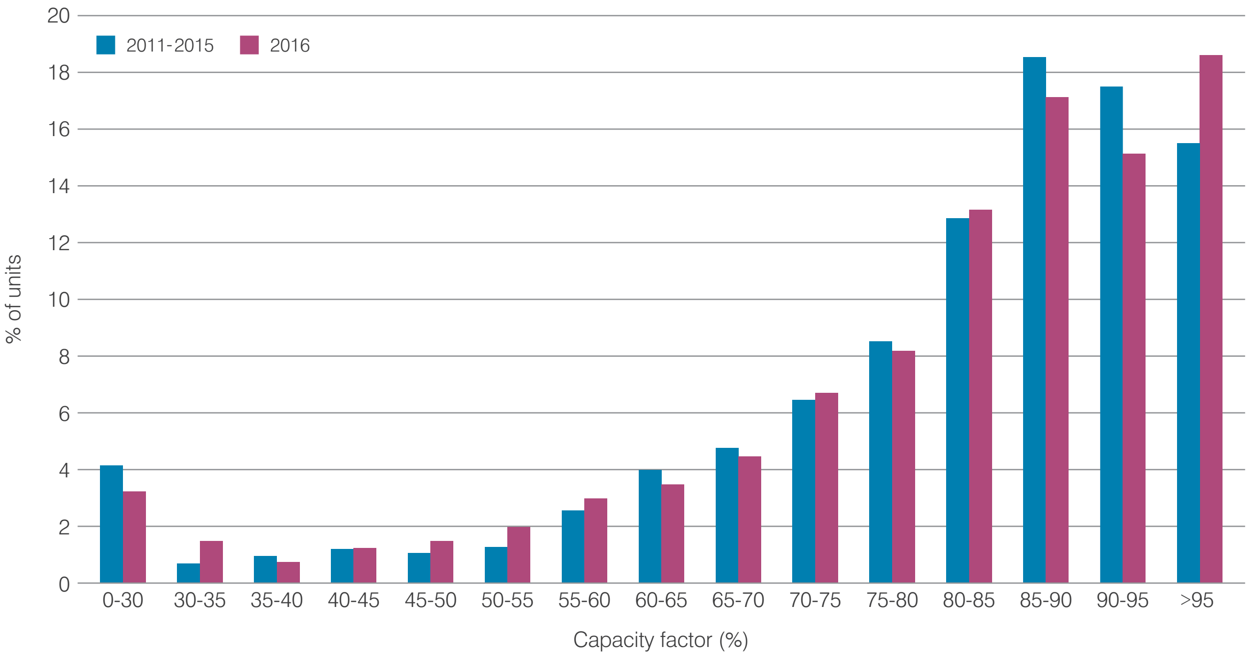
Figure 8. Median capacity factor 2007-2016 by age of reactor



Source: World Nuclear Association, IAEA PRIS

The global average capacity factor has remained fairly consistent over the last decade and there has been no significant change to the spread of capacity factors achieved across the fleet either.

Figure 9. Percentage of units by capacity factor

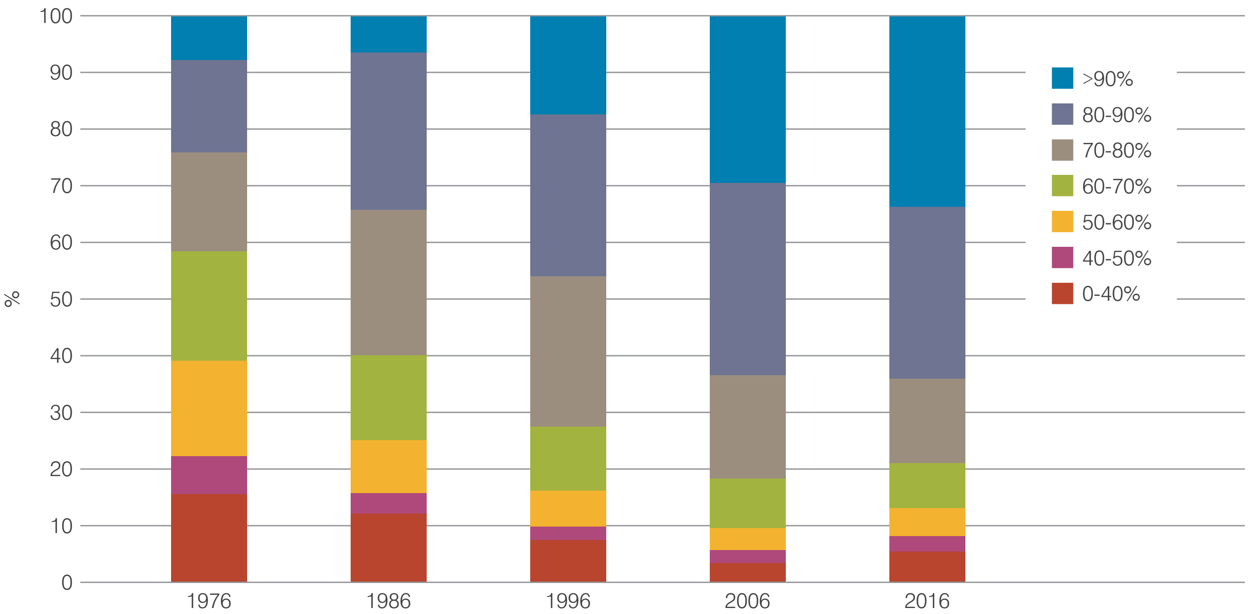


Source: World Nuclear Association, IAEA PRIS

There remains some scope for improvement in the performance of those reactors with lower than average capacity factors. However, in some cases reactors are being used in a load-following mode, which means their output is reduced to help balance variations in supply from other generators, with a resulting reduction in capacity factor.

There has been continuous improvement in the proportion of reactors reaching higher capacity factors over the last 40 years. For example, 64% of reactors achieved a capacity factor higher than 80% in 2016, compared to 24% in 1976, whereas only 8% of reactors had a capacity factor lower than 50% in 2016, compared to 22% in 1976.

Figure 10. Long-term trends in capacity factors



Source: World Nuclear Association, IAEA PRIS

Three reactors shut down in 2016. Fort Calhon 1 closed after 43 years of operation. The reactor owners said that the shutdown had occurred due to economic considerations, with the reactor having been the smallest commercial reactor in the USA at the time. Ikata 1, in Japan, was due to end its 40-year operating period in September 2017. Novovoronezh 3, in Russia, was the oldest VVER-440 reactor in operation, first producing electricity 45 years previously.

Table 2. Shut down reactors in 2016

Reactor	Capacity (MWe)	Electricity generated (TWh)	Date of closure	Type of reactor
Japan				
Ikata 1	538	125.68	May 2016	PWR
Russia				
Novovoronezh 3	385	109.26	Dec 2016	PWR
USA				
Fort Calhon 1	482	130.68	Oct 2016	PWR

Source: World Nuclear Association, IAEA PRIS

2.3 New construction

With three reactor construction starts and ten reactors being grid-connected, the total number of reactors under construction fell by seven, compared to the end of December 2015. The number of reactors under construction has been at least 60 since December 2010, a level of construction not seen since the early 1990s.

Table 3. Reactors under construction by region end of December 2016 (change since 2015)

	BWR	FNR	HTGR	PHWR	PWR	Total
Asia	4	1	1	4	30 (-5)	40 (-5)
East Europe & Russia					11 (-1)	11 (-1)
North America					4 (-1)	4 (-1)
South America					2	2
West & Central Europe					4	4
Total	4	1	1	4	51 (-7)	61 (-7)

Source: World Nuclear Association, IAEA PRIS

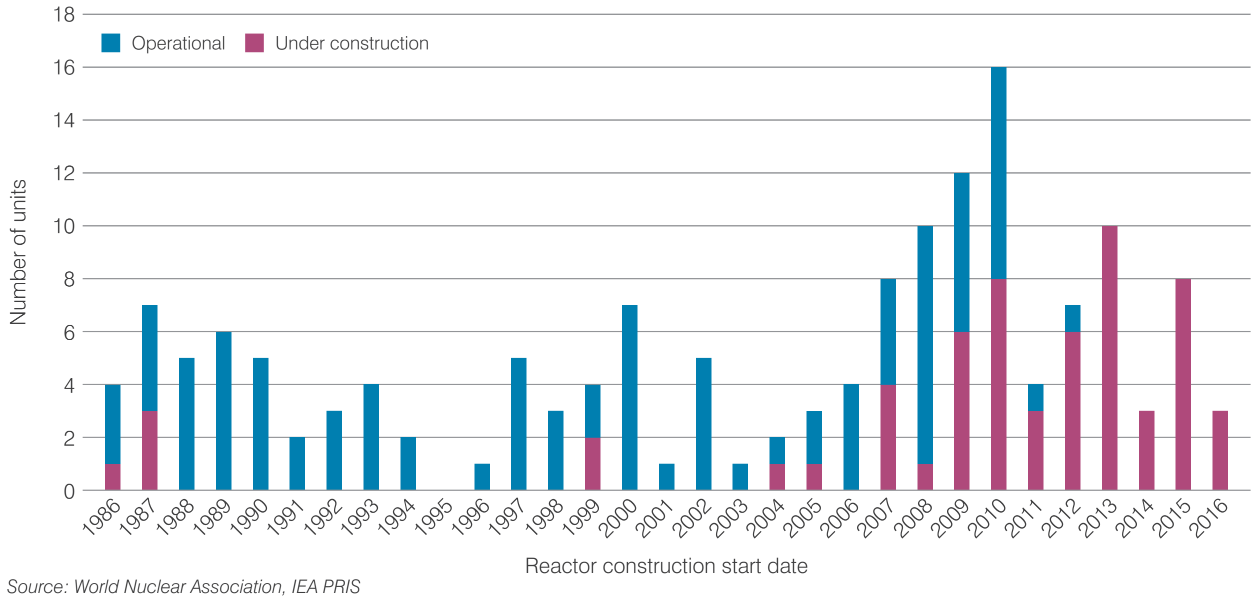
The three reactor construction starts during 2016 are listed in Table 4.

Table 4: Reactor construction starts 2016

Reactor	Capacity (MWe)	Start of construction	Type of reactor
China			
Fangchenggang 4	1150	Dec 2016	PWR
Tianwan 6	1080	Sept 2016	PWR
Pakistan			
Karachi Coastal 3	1014	May 2016	PWR

Source: World Nuclear Association, IAEA PRIS

Figure 11. Operational status of reactors with construction starts after 1985

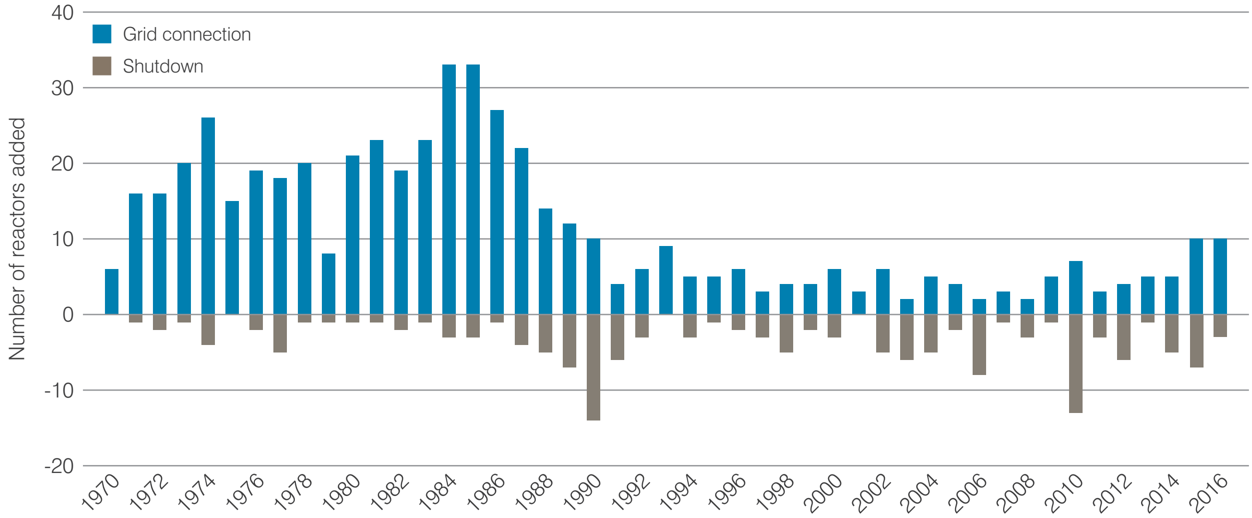


Source: World Nuclear Association, IEA PRIS

Most reactors under construction today started construction in the last ten years. A small number of reactors have been formally under construction for a longer period. Mochovce 3&4, in Slovakia, started construction in 1987, but work was suspended in 1991. The projects were restarted in 2008 and are expected to be completed before 2020. Two units at Khmelnitskiy, Ukraine, started construction at a similar time and were suspended in 1990. Similar plans to recommence construction have been in development but are less advanced.

In 2016, ten units started up and three units closed down. This was the second year that ten new reactors commenced operation, a number of grid connections not seen since 1990. Reactor starts remain lower than their mid-1980s peak, when more than 30 reactors were connected to the grid in both 1984 and 1985.

Figure 12. Reactor grid connection and shutdown 1980-2016



Source: World Nuclear Association, IAEA PRIS

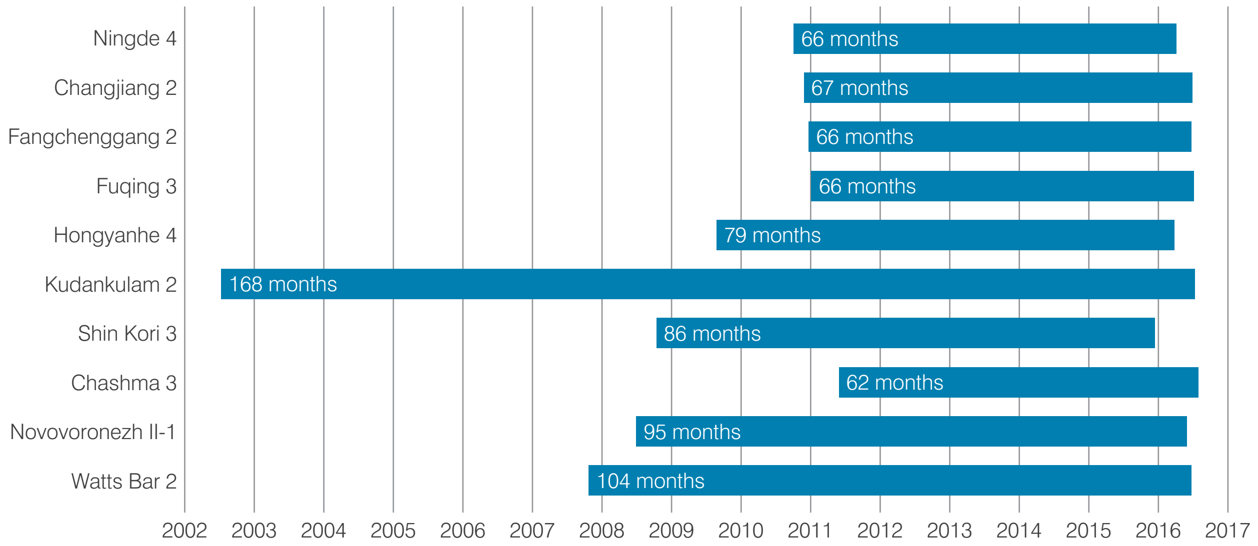
Table 5. Reactor grid connections in 2016

Reactor	Capacity (MWe)	Start of construction	Grid connection	Type of reactor
China				
Changjiang 2	610	Nov 2010	Jun 2016	PWR
Fangchenggang 2	1020	Dec 2010	Jul 2016	PWR
Fuqing 3	1020	Dec 2010	Sept 2016	PWR
Hongyanhe 4	1060	Aug 2009	Apr 2016	PWR
Ningde 4	1018	Sept 2010	Mar 2016	PWR
India				
Kudankulam 2	917	Jul 2002	Aug 2016	PWR (VVER)
South Korea				
Shin Kori 3	1340	Oct 2008	Jan 2016	PWR
Pakistan				
Chashma 3	315	May 2011	Oct 2016	PWR
Russia				
Novovoronezh II-1	1114	Jun 2008	Aug 2016	PWR (VVER)
USA				
Watts Bar 2	1165	Oct 2007	Jun 2016	PWR

Source: World Nuclear Association, IAEA PRIS

Five of the ten reactors connected to the grid in 2016 were constructed in China, with one reactor grid-connected in each of India, South Korea, Pakistan, Russia and the USA. Watts Bar 2 first started construction in 1973, but this was suspended in 1985, before restarting in 2007.

Figure 13. Construction times of new units connected to the grid in 2016



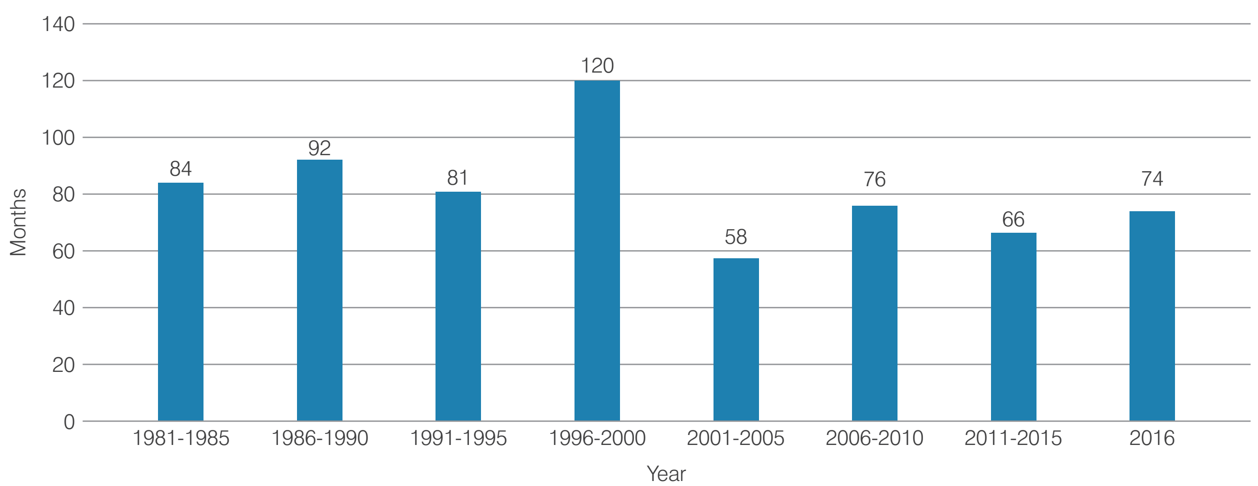
Source: World Nuclear Association Reactor Database, IAEA PRIS

The best performance for construction times for those reactors grid-connected in 2016 are all associated with China. Five of the six reactors built in the shortest time were built in China, and the sixth, Chashma 3, is a Chinese-designed and built reactor, constructed in Pakistan.

The construction time listed for Watts Bar 2 is based on the restart date for construction, in October 2007.

The median construction time for reactors grid-connected in 2016 was 74 months, higher than for the average in the preceding five years, but little changed from 2015. Construction times have remained below the levels seen prior to 2000.

Figure 14. Median construction times for reactors since 1981



Source: World Nuclear Association, IAEA PRIS

Capacity uprates allow existing reactors to generate more power. They may involve changes to the plant's operation and maintenance and accident response procedures – including a corresponding licensing effort – as well as its components.

Table 6. Reactor capacity uprates in 2016

Reactor	Previous capacity (MWe)	Uprate (MWe)	Type of reactor
Finland			
Loviisa 1	496	6	PWR
Loviisa 2	496	6	PWR
USA			
Catawba 1	1146	20	PWR
Peach Bottom 3	1283	72	BWR

Source: World Nuclear Association

Nine reactors, in Japan and the USA, had operating licence extensions approved in 2016. In all cases, the licence extensions granted were for an additional 20 years.

Table 7. Extension of licences approved in 2016

Reactor	Capacity (MWe)	Licence extension (years)	End of licence	Type of reactor
Japan				
Mihama 3	780	20	2036	PWR
Takahama 1	780	20	2034	PWR
Takahama 2	780	20	2035	PWR
USA				
Braidwood 1	1194	20	2046	PWR
Braidwood 2	1160	20	2047	PWR
Fermi 2	1122	20	2045	BWR
Grand Gulf 1	1419	20	2044	BWR
La Salle 1	1137	20	2042	BWR
La Salle 2	1140	20	2043	BWR

Source: World Nuclear Association

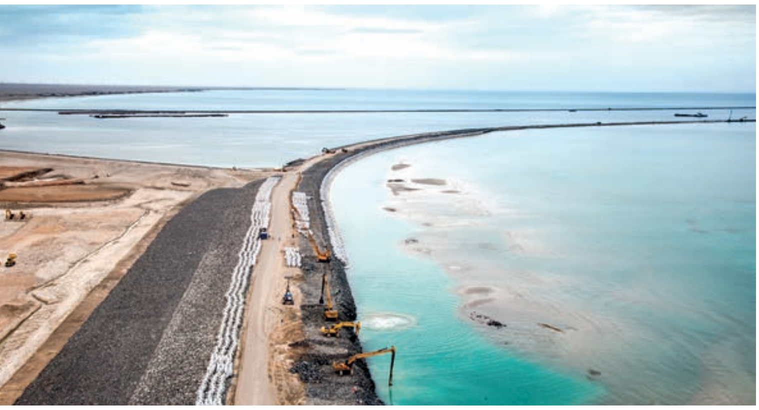
Licensing conditions for nuclear reactors vary from country to country. For example, in the USA, reactors were originally licensed for a period that related to estimates of how long it would take to amortize the costs of construction.

Requirements for extending the licence also vary from country to country. Regulatory bodies may insist on additional checks on older plants, and may require upgrades to be carried out.

The lack of any age-related reduction in performance, as shown in figure 8, indicates the technical capability of reactors to operate efficiently and effectively for much longer than originally anticipated, with reactor licences to 60 years not uncommon.

3 | Case Studies

Barakah: Innovative plant cooling water system



Breakwater at Barakah: Image ENEC

Construction of the first nuclear energy plant in the United Arab Emirates (UAE) is underway at Barakah. The Barakah Nuclear Energy Plant consists of four nuclear power generating units with a combined capacity of approximately 5,600 MWe.

One of the earliest and most critical tasks for the Barakah project was the design for the tertiary plant cooling water system. This system provides for the removal of thermal heat generated from power generation sources such as the turbine-generator condenser steam exhaust and a host of energy plant support system heat exchangers, as well as other sources. The unique climate conditions of the Arabian Gulf and the UAE required specific parameters and criteria to be set up in order to ensure that the cooling system was able to operate at optimal efficiency.

Some of the unique aspects that required consideration for the development of the cooling water system for the Barakah plant included:

- Assessment of cooling water options, including natural draft cooling towers and once-through cooling with water intake and discharge from the adjacent Arabian Gulf. It was concluded that a once-through cooling arrangement was a better option than the cooling tower option due to the extreme ambient air characteristics, among other considerations.
- Environmental impact assessment requirements mandated by government agencies such as the Environment Agency - Abu Dhabi (EAD) for protection of aquatic and biological species in the Arabian Gulf region. This included limitations for water intake flow velocities and discharge effluent temperature rises.
- Evaluation of Arabian Gulf ambient water and air temperature histories and flow patterns coupled with wave patterns to minimize thermal recirculation from discharge plume to cooling water intake in order to maintain optimum power generation and shutdown safety functions.

A final plant cooling water breakwater and dredging arrangement was agreed at the end of December 2010 to allow for construction to begin and to support the overall project schedule. The initial thermal modelling results for this configuration showed that environmental and operational requirements would be met for the planned four units once they are operational. The breakwater layout was optimized, resulting in a combined total length of 15 kilometres, making it one of the longest breakwaters in the global nuclear energy industry. By comparison, the breakwater of Shin Kori 3, the reference plant for Barakah, is only one kilometre long.

ENEC had to implement several design modifications to adapt to the UAE's climate conditions. The Arabian Gulf generally has higher temperatures than the waters off the coast of South Korea, for which the original APR1400 design was prepared. These changes include:

- Larger pumps, heat exchangers and pipes to increase the water flow rate of the cooling systems to deal with higher seawater temperatures in the Gulf.
- Each unit's condenser has 85,000 titanium and super stainless steel tubes that will have a volume of 6000m^3 of seawater per minute passing through them. The amount of water withdrawn from and returned to the Arabian Gulf during operation for cooling is estimated at 105 m^3/second per unit.
- A modified breakwater to ensure that the discharge and intake structures are at an increased distance from each other to avoid recirculation of warmer water. A limited intake temperature increase of less than 1°C was considered to be acceptable.
- Seawater intake and plant cooling systems were designed to ensure compliance with EAD standards for changes in Gulf water temperature near the plants.
- A refined intake screen designed to help protect local fish populations during operations.
- A seawater bypass system not in the original design mixes seawater with cooling water to reduce the effects of discharging warm water to the Arabian Gulf.

Interview

Ricky Rice, Senior Civil Engineering Manager at ENEC

Barakah units 1-4 under construction: Image ENEC

Why is this cooling system being used at Barakah?

Other cooling options such as cooling towers were considered during the environmental impact assessment. Due to extreme ambient air and seawater temperatures, the cooling capability of those systems would be less effective for removing plant system heat loads. The use of cooling towers (natural draft or mechanical draft) would still require a make-up water facility near the shoreline and a large overall facility footprint. The combined effects of system efficiency, complexity, environmental impact and system maintenance made a once-through cooling option more desirable.

Have there been any challenges during development and construction of the system and how were they overcome?

During the investigation and subsequent conceptual and final design of the cooling system, many challenges were encountered and overcome. One specific challenge was the validation of the breakwater design to withstand extreme waves characterized for the site, despite the fact that the Arabian Gulf is not an area with a history of tsunami activity and has a very low probability of earthquakes. To support the computer modelling and analytical calculations, scale model prototypes of various breakwater cross-sections were built in European test facilities and extreme design waves were applied to demonstrate structural integrity. In addition, analyses were performed to confirm breakwater structural integrity for a postulated distant seismic event creating a tsunami that may propagate to the Barakah site.

These activities along with design studies for postulated oil spills, biofouling due to sea grass or jellyfish and sediment transport were necessary to demonstrate to regulatory agencies that the ultimate heat sink cooling source from the Arabian Gulf would remain reliable.

From the construction standpoint, a major challenge included the need to obtain large quantities of rock materials to construct the breakwater. This issue was minimized by using of a portion of the dredged sand (from the intake/discharge channels) to build the inner core for parts of the breakwater. Rock materials were then placed around the sand core for protection and construction time and material supply was optimized.

Could this technology have applications at other nuclear power plants?

This technology could be beneficial and applicable at other nuclear power plants located near large bodies of water used as cooling sources. The careful consideration of thermal heat load and local site characterization, such as water source bathymetry, currents, temperatures, wind patterns and air temperatures is critical to ensure that the safety and efficiency of the plant facility is maintained.

The Barakah site is somewhat unique due to the more shallow water and extreme temperature characteristics, which had implications on the time needed for the design of the breakwater and its subsequent construction.

Beloyarsk: Start up of the BN-800 sodium-cooled fast reactor

Unit 4 of the Beloyarsk plant: Image Rosenergoatom

Reactor type	Fast neutron reactor
Model	BN-800
Owner	Rosenergoatom
Operator	Rosenergoatom
Construction start	18 July 2006
First criticality	27 June 2014
First grid connection	10 December 2015
Commercial operation	31 October 2016
Capacity net	789 MWe
Capacity gross	864 MWe
Capacity thermal	2100 MWt

The BN-800 sodium-cooled fast reactor at Beloyarsk, Russia, was connected to the grid in December 2015. In February 2016, all power tests were completed and commercial operation began on 31 October 2016.

Fast reactors are able to considerably enhance the utilization of nuclear fuel and minimize radioactive waste as part of the closed nuclear fuel cycle. Fast reactors make possible the burning of long-lived radioactive isotopes, with half-lives of thousands or hundreds of thousands years, transforming them into short-lived products. A closed nuclear fuel cycle with fast reactors will make it possible to burn plutonium and some minor actinides in the fuel cycle, as well as allowing for the utilization of natural uranium-238, which is abundant in nature.

The BN-800 reactor design includes a number of advanced features; an emergency cooling system with an air heat exchanger connected to the secondary circuit; a core with sodium bubble volume coefficient close to zero; passive hydraulically suspended absorber rods; and a tray under the pressure vessel to catch corium if the core melts in case of a severe accident (the so-called 'core-catcher').

These improvements have ensured the compliance of the BN-800 project to the safety requirements for innovative nuclear power units, under the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) term.

Russia launched the production of MOX fuel for the BN-800, comprising a mixture of uranium oxide and plutonium oxide in autumn 2015, at the Mining and Chemical Combine in Zheleznogorsk.

The use of MOX provides the possibility of using the plutonium extracted from spent nuclear fuel and high-level radioactive waste in a new cycle of energy generation while bringing the world closer to the absolute nuclear cycle closure. Due to the launch of the BN-800 and MOX fuel production, Russia will be able to meet its obligations to convert 34 tonnes of weapons-grade plutonium into peaceful nuclear fuel under the USA-Russia Plutonium Management and Disposition Agreement of 2000.

Interview

Ivan Sidorov, Deputy Director General of JSC "Concern Rosenergoatom"
Director of the Beloyarsk Nuclear Power Plant, subsidiary of JSC "Concern Rosenergoatom"

What specific problems did the project face and what were the solutions?

During the construction there has been a continuous improvement in the requirements of rules and regulations, including after the events at Fukushima. To bring the existing project in line with the requirements of the rules and regulations it was necessary to adjust a number of decisions taken in the project. There was a need to design, manufacture and use new types of equipment and technologies. Implementation of the BN-800 project was therefore accompanied by a continuous increase in the safety level of the power unit being built.

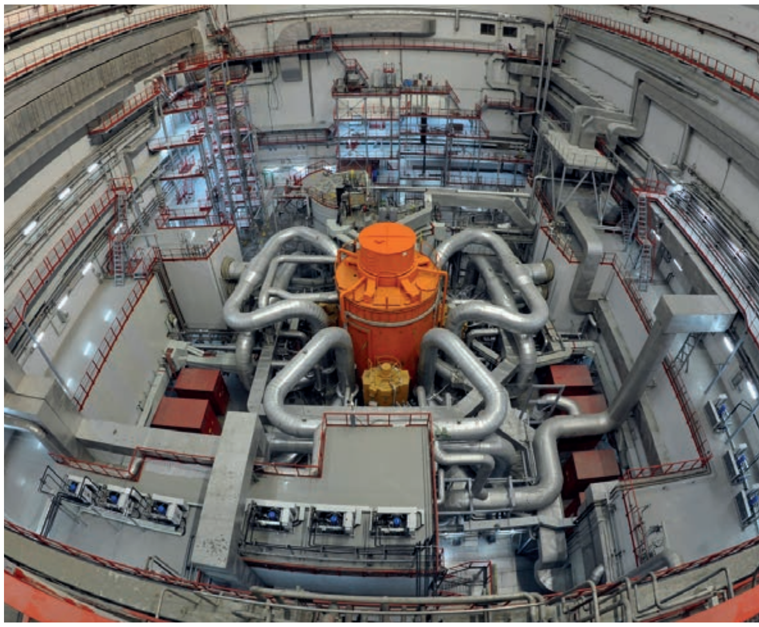
Are there any measures used or planned to improve the operation of the power unit?

At present, work is planned on the diagnosis of heat-exchange equipment in the steam generator. The aim of the work is to increase the heat transfer from the second sodium circuit to the third steam-water circuit, which will increase the efficiency of the steam generator and the power unit as a whole.

What are the further stages in the development of fast reactor technology?

The main further stages in the development of fast reactor technology are:

- Development of technology for closing the nuclear fuel cycle.
- Increase in fuel burn-up with the use of improved and new structural materials for fuel claddings.
- Carrying out studies to justify the safety and reliability of the new BN-1200 commercial power fast reactor.



BN-800 fast reactor: Image Rosenergoatom

Yangjiang 4: Optimized construction through series build experience

Reactor Type	Pressurized water reactor
Model	CPR-1000
Owner	China General Nuclear Power Group
Operator	Yangjiang Nuclear Power Company
Construction start	17 November 2012
First criticality	30 December 2016
Hot tests	22 August 2016
First grid connection	8 January 2017
Commercial operation	15 March 2017
Capacity net	1000 MWe
Capacity gross	1080 MWe
Capacity thermal	2905 MWt

Yangjiang 4 is the fourth CPR-1000 reactor to be built at Yangjiang, in western Guangdong province, China. Two more reactors at Yangjiang, based on the ACPR-1000 design, are under construction as units 5 and 6.

Construction on unit 1 began in December 2008 and it was connected to the grid five years later in December 2013. The following three units began construction during this period, with unit 4 beginning construction in November 2012.

This series build enabled lessons to be learned during the construction process, allowing issues to be identified during construction that could be applied to later units. Unit 4 was grid connected in January 2017, 1531 days (just over four years) after construction start, compared to 1840 days required for unit 1.

Yangjiang nuclear power plant: Image CGN

Interview

Wu Jiang Tao, Assistant General Manager and Operational Team Chief of Yangjiang 4

Yangjiang 4 achieved first concrete to grid connection in just 50 months. What contributed to this?

First this is an achievement of the whole team that worked on Yangjiang 4. We always adhere to the basic principles of ‘safety first, quality first, the pursuit of excellence’ and the values of ‘doing things right in one go’ and ‘integrity and transparency.’

We have established an internal feedback system to ensure it is shared between the various units and projects so that the lessons learned can be implemented in a timely manner. At the same time we have established an effective channel of business communication with domestic and international counterparts to share construction experience.

The owners of Yangjiang Nuclear Power Company were actively involved in dealing with the supply chain, ensuring that components and equipment met compliance requirements and that any problems with the construction and installation process were dealt with in an early and timely way.

Throughout the design, equipment manufacturing, construction and installation and commissioning the production manager must manage safety and quality at the same time.

We have been adopting a series of technical innovations and improvements, such as self-compacting concrete, modular construction of steel structures, automatic welding of main pipelines, which lay the foundations for further optimization of the critical path duration.

The start of the main Yangjiang 4 project was delayed by 18 months because of the Fukushima nuclear accident in Japan. We made good use of this time to carry out the design drawings, equipment procurement and other preparatory work. When formal construction began in 2012, 96% of civil drawings were complete and 94% of procurement contracts were in place. This created favourable conditions for uninterrupted construction.

Yangjiang 4 is the fourth CPR-1000 to be built at Yangjiang. Did experience with construction of units 1-3 help?

The accumulated construction experience of previous CPR-1000 units, including the experience of Yangjiang 1-3, was a valuable asset for the construction of unit 4. We were able to identify and rectify 912 important issues during the construction of units 1-3 which could be applied to unit 4 to help ensure a smooth construction process.

Were there any issues during construction and how were they overcome?

In the engineering aspect the biggest challenge was the increased time interval between construction of units 3 and 4 (due to the delay to the start of construction of unit 4). Yangjiang units 3 and 4 are a twin unit layout. There should be continuous construction between the two units.

For this reason we carried out the design evaluation analysis to screen out the impact on unit 3 through physical isolation, construction logic optimization, additional temporary control systems, and temporary ventilation and fire prevention measures to ensure the safety of unit 3.

Yangjiang 5 & 6 will be ACPR-1000 reactors. Will construction still benefit from the experience of building the earlier CRP-1000 reactors?

The ACPR-1000 design is an advanced version of the CPR-1000 design, with improvements to the design principles, plant layout and construction logic. Through CPR-1000 series construction, the accumulation of feedback, technical improvements, scheduling optimization, and so on, will be conducive to the subsequent construction of units 5 & 6. Not only that, these experiences and techniques will also be applied to the follow-up Hualong One construction process.

Heysham II-2: Longest continuous operation of a nuclear power reactor

Heysham II turbine hall: Image EDF Energy

Location	Lancashire, United Kingdom
Reactor type	Advanced gas-cooled reactor
Owner	EDF Energy
Operator	EDF Energy
Start of construction	1 August 1980
First grid connection	11 November 1988
Current planned end of generation	2030
Net capacity	610 MWe
Employment	Approximately 520 full time EDF Energy staff plus 250 full time equivalent contract partners

On 16 September 2016 the second unit of the Heysham II nuclear power plant set a new world record for continuous operation of a commercial nuclear power reactor, by running for 941 days. The reactor generated around 14 TWh of electricity during this period of continuous operation.

Speaking at the time of this achievement, station director John Munro said the performance of the reactor "represents world class, safe and reliable nuclear plant operation, achieving 0.3% unplanned capability loss factor for the period."

The long operation was in part due to the features of the AGR (advanced gas-cooled reactor) design. AGRs are cooled with carbon dioxide, graphite-moderated, fuelled with enriched uranium and designed to be refuelled online.

The previous holder of this record was unit 7 of the Pickering plant in Ontario, Canada, a Candu design that can also be refuelled during operation, which ran uninterrupted for 894 days.

The world record for continuous operation of light water reactors, which need to be shut down for refuelling, resides with Exelon's LaSalle 2 boiling water reactor. In February 2007 this unit was shut down after a run of 739 days, shortly after unit 1 at the plant completed 711 days of uninterrupted generation. Calvert Cliffs 2 set a world record for continuous operation of a pressurized water reactor in February 2009, having operated without interruption for 693 days.

Interview

John Munro, Heysham II Station Director

How did this world record-breaking run help plant performance?

The world record creates a virtuous cycle. Steady plant operation at full load delivers business results and targets as well as giving staff time and space to think, mitigate risks up-field in a timely manner. Basically this record moves you from a reactive to a proactive organization creating opportunities to excel.

What determines the optimum continuous period of operation for a plant?

The optimum continuous operation is determined by the need to fuel and statutory regulations such as pressure vessel inspection requirements.

Were there any particularly notable challenges involved in achieving this record and how were they overcome?

The plant is dynamic and there were many challenges throughout the run, most notably preserving the balance between through-life management and managing the operational risk day-to-day.

On two occasions we disconnected quadrants to back flush small pieces of debris that had accumulated in our boiler tubes. Had we left them we would have incurred hot spots which would have lessened boiler tube life. However to physically undertake the operation is challenging and complex and could very quickly lead to a reactor shut down.

What should the performance improvement plans be focussed on?

Our culture has been grown over the last few years to ensure that we all understand our part in contributing to what we describe as ‘organizationally aligned operational focus’. Step 1 of operational focus is equipment reliability, so day-to-day rigour in understanding and correcting the health of the plant coupled with a fine-tuned sensible investment plan to improve it where necessary is an essential foundation.

Having established improving levels of equipment reliability it is important to then organizationally understand and aggressively eliminate operational risk (erosion of margins) at every turn.

A quality workforce and good leadership are obviously key ingredients and performance improvement plans should therefore be closely linked to training. The objective is to have a very well-trained and engaged workforce fully focussed on the fundamentals of nuclear power plant operation (from plant manoeuvres through to senior leadership) and skilled in the application of error prevention techniques. Running through all of this is a culture that is humble and seeking to improve with a strong bias for organizational learning and a willingness to benchmark.

Heysham II: Image EDF Energy

4 Director General's Conclusions

The global nuclear fleet continued high levels of performance in 2016, with an average capacity factor of 80.5%. The industry has maintained high capacity factors of around 80% for the last 20 years, a substantial increase on around 50% achieved in the 1970s.

In recent years, US reactors have regularly achieved an average capacity factor of around 90%. However, increasing requirements in some countries for nuclear generation to operate to compensate for intermittent renewable generation means that in those countries capacity factors will be lower than their availability.

Nuclear generation has continued to grow. The last four years have each seen an increase in electricity produced from nuclear generation. The global nuclear capacity has also continued to grow, as it has done each year since the start of nuclear generation in the 1950s. This year saw the capacity of reactors supplying electricity to the grid reach an all-time high of 350 GWe.

The restart of reactors in Japan has taken longer than expected. The process of gaining regulatory approval and support from local authorities is proving to be an onerous task. Nevertheless we can expect more reactors to resume generation over the coming months and years, as many have carried out upgrades in accordance with the new regulations and have applied for restart.

The level of new build remains high, with 61 reactors under construction at the end of 2016. There have been more than 60 reactors under construction for the past six years, a level of new build not seen since the early 1990s.

Western Europe and North America led the way in nuclear construction in the 1970s and 1980s and nuclear power is a significant component of the generation mix as well as being the largest low carbon energy source. But new build activity in these regions is currently low and some construction projects have faced delays and uncertainty. This low level of new build is in part because of the excellent performance of the existing nuclear fleet. Not only have the capacity factors increased and reactors been uprated to deliver more electricity, but also many reactors have successfully applied to operate for longer than initially planned. The expectation is that operating lifetimes in excess of 60 years will be achievable for much of the existing nuclear fleet. With reactors able to operate longer and with higher output the need for new build has been deferred.

The time taken to construct new reactors has, on average, been falling. However, new nuclear construction projects have faced delays in some countries. The process of gaining approval for reactor construction is frequently long; legal challenges, although usually unsuccessful, cause delay and uncertainty.

Building first-of-a-kind reactors in countries where nuclear new build may not have taken place for decades adds to the challenge. Establishing supply chains and developing local expertise takes time. There needs to be a 'critical mass' of construction in these regions to bring the benefits of series build and construction experience that will help deliver reactors on time and within budget.

With ten reactors coming online in both 2015 and 2016 – double the average for the preceding 25 years –

nuclear generation worldwide has continued its recent growth. This growth is being led by China, where five of the ten reactors grid-connected in 2016 are sited. This pattern is likely to continue in the coming years, with around a third of reactors currently under construction being located in China.

The number of reactors coming online in the last two years has met the requirements of Harmony, the global nuclear industry's vision designed to meet the world's growing energy needs sustainably.

The Harmony goal is to have 1000 GWe of new nuclear build by 2050, enabling nuclear generation to supply 25% of the world's electricity by that date. This would be part of a global drive to reduce dependence on fossil fuel generation as much as possible whilst meeting the electricity needs of the world's growing population.

To achieve this aim, it will require a ramping up of nuclear construction. About 10 GWe of nuclear capacity needs to be grid connected each year until 2020. An average 25 GWe then needs to be connected each year from 2021 to 2025, and an average 33 GWe from 2026 to 2050.

This is a practical and achievable target, with build rates similar to those achieved in the mid-1980s. But to achieve it will require action on three key areas: establishing a level playing field in electricity markets; building harmonized regulation; and creating an effective safety paradigm.

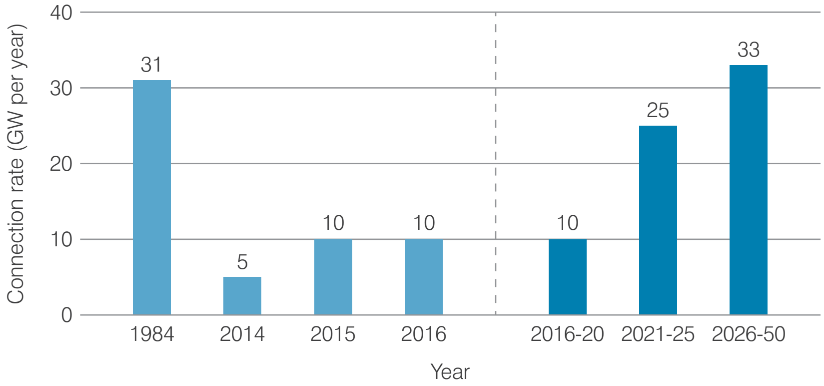
Most electricity markets are distorted and do not recognize the full costs of different forms of electricity generation. Even when carbon pricing is included they do not represent the true long-term costs of climate change. There are also significant system effects and costs associated with unpredictable and intermittent renewable generation that are not reflected in the market price. Reliable and dispatchable energy, such as nuclear, is not valued by many liberalized markets.

The current nuclear regulatory regime has provided a high level of safety. However development of nuclear regulations and standards remains fragmented, and has not kept pace with the growth of recent international new build projects, limiting global civil nuclear trade and investment.

The current energy system fails to consider safety from a holistic society perspective. The health and environmental benefits of nuclear energy are not valued on an equitable basis with alternative energy sources. The current preoccupation with the safety first message is driving the nuclear debate to focus on nuclear safety issues alone, ignoring other factors such as economics, industrial, social, public health and environment.

Addressing these issues will enable nuclear energy to expand its already substantial contribution towards a global generation mix, meeting the needs of the world's population for affordable, reliable and sustainable electricity.

Figure 15. Historic construction rates and future requirements for the Harmony target



The Harmony goal is to have 1000 GWe of new nuclear build by 2050.

Abbreviations

AGR	Advanced gas-cooled reactor
BWR	Boiling water reactor
EAD	Environment Agency – Abu Dhabi
FNR	Fast neutron reactor
GCR	Gas-cooled reactor
GWe	Gigawatt (one billion watts of electric power)
HTGR	High temperature gas-cooled reactor
IAEA	International Atomic Energy Agency
LWGR	Light water gas-cooled reactor
LWR	Light water reactor (a BWR or PWR)
MOX	Mixed uranium and plutonium oxide fuel
MWe	Megawatt (one million watts of electric power)
MWh	Megawatt hour (one million watt hours of electricity)
NRA	Nuclear Regulation Authority – Japan
PHWR	Pressurized heavy water reactor
PRIS	Power Reactor Information System (IAEA)
PWR	Pressurized water reactor
RBMK	Reaktor Bolshoy Moshchnosti Kanalniy (an LWGR)
TWh	Terawatt hour (one trillion watt hours of electricity)
UAE	United Arab Emirates
UN	United Nations
VVER	Vodo-Vodyanoi Energetichesky Reactor (a PWR)

Geographical Categories

Africa
South Africa

Asia
Armenia, China mainland and Taiwan, India, Iran, Japan, Kazakhstan, Pakistan, South Korea, United Arab Emirates

East Europe & Russia
Belarus, Russia, Ukraine

North America
Canada, Mexico, United States Of America

South America
Argentina, Brazil

West and Central Europe
Belgium, Bulgaria, Czech Republic, Finland, France, Germany, Hungary, Italy, Lithuania, Netherlands, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom

Further Reading

World Nuclear Association Information Library
http://world-nuclear.org/information-library.aspx

The Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2015-2035
http://world-nuclear.org/shop.aspx

The World Nuclear Supply Chain: Outlook 2035
http://world-nuclear.org/shop.aspx

World Nuclear News
http://world-nuclear-news.org

The Harmony programme
http://world-nuclear.org/our-association/what-we-do/the-harmony-programme.aspx

International Atomic Energy Agency Power Reactor Information System
https://www.iaea.org/PRIS/home.aspx

We are grateful for access to IAEA PRIS data used in the preparation of this report.

The World Nuclear Association is the industry organisation that represents the global nuclear industry. Its mission is to promote a wider understanding of nuclear energy among key international influencers by producing authoritative information, developing common industry positions, and contributing to the energy debate, as well as to pave the way for expanding nuclear business.

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