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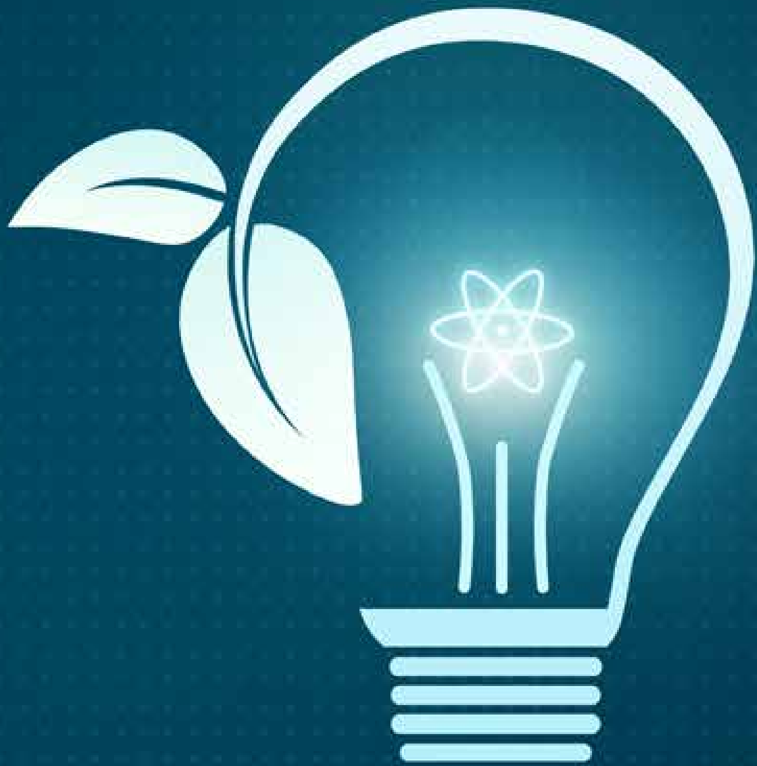
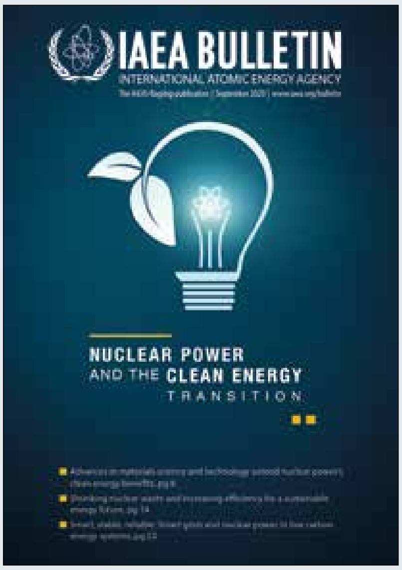


NUCLEAR POWER AND THE CLEAN ENERGY TRANSITION



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Office of Public Information
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International Atomic Energy Agency
Vienna International Centre
PO Box 100, 1400 Vienna, Austria
Phone: (43-1) 2600-0
iaeabulletin@iaea.org

Managing Editor: Nicole Jawerth
Editor: Miklos Gaspar
Design & Production: Ritu Kenn

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IAEA

The International Atomic Energy Agency's mission is to prevent the spread of nuclear weapons and to help all countries — especially in the developing world — benefit from the peaceful, safe and secure use of nuclear science and technology.

Established as an autonomous organization under the United Nations in 1957, the IAEA is the only organization within the UN system with expertise in nuclear technologies. The IAEA's unique specialist laboratories help transfer knowledge and expertise to IAEA Member States in areas such as human health, food, water, industry and the environment.

The IAEA also serves as the global platform for strengthening nuclear security. The IAEA has established the Nuclear Security Series of international consensus guidance publications on nuclear security. The IAEA's work also focuses on helping to minimize the risk of nuclear and other radioactive material falling into the hands of terrorists and criminals, or of nuclear facilities being subjected to malicious acts.

The IAEA safety standards provide a system of fundamental safety principles and reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from the harmful effects of ionizing radiation. The IAEA safety standards have been developed for all types of nuclear facilities and activities that serve peaceful purposes, as well as for protective actions to reduce existing radiation risks.

The IAEA also verifies through its inspection system that Member States comply with their commitments under the Nuclear Non-Proliferation Treaty and other non-proliferation agreements to use nuclear material and facilities only for peaceful purposes.

The IAEA's work is multi-faceted and engages a wide variety of partners at the national, regional and international levels. IAEA programmes and budgets are set through decisions of its policymaking bodies — the 35-member Board of Governors and the General Conference of all Member States.

The IAEA is headquartered at the Vienna International Centre. Field and liaison offices are located in Geneva, New York, Tokyo and Toronto. The IAEA operates scientific laboratories in Monaco, Seibersdorf and Vienna. In addition, the IAEA supports and provides funding to the Abdus Salam International Centre for Theoretical Physics, in Trieste, Italy.

Building a clean energy future

By Rafael Mariano Grossi, Director General, IAEA

Nuclear power has a vital role to play in helping to address the global climate emergency.

It already contributes one third of all low carbon electricity generated in the world. Nuclear power offers a steady, reliable supply of power and its use can help to both reduce greenhouse gas emissions and meet the needs of the world's growing population, not least in developing countries.

Nuclear power plants produce almost no greenhouse gas emissions or air pollutants during their operation. Emissions over their entire life cycle are very low. It provides a vital complement to renewables such as wind and solar power, which are intermittent sources of energy.

The great contribution that nuclear power has already made — for example, avoiding the production of the equivalent of 55 gigatonnes of carbon dioxide emissions over the past 50 years — and the enormous potential of innovative technologies now in the pipeline deserve to be better known.

That is why I decided to devote the first IAEA Scientific Forum since I became Director General of the IAEA to "Nuclear Power and the Clean Energy Transition". Leading scientists and experts from around the world will meet over two days to examine how nuclear power's science-based solutions can play a pivotal role in paving the way for a sustainable future.

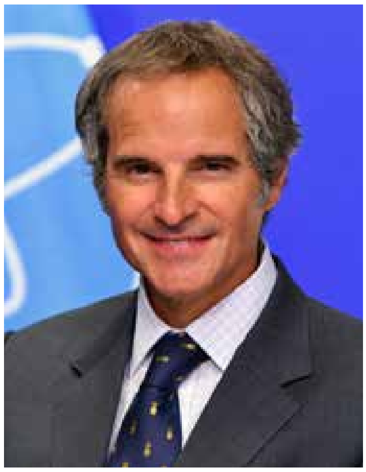
This edition of the *IAEA Bulletin* will provide you with a closer look at the clean energy transition and how nuclear power fits in (page 4). You will learn how, during extreme events such as a pandemic or severe weather caused by climate change, nuclear power's resilience can help to ensure continuous energy supplies (page 6).

You will get a glimpse of the innovations driving the future of nuclear energy. Advances in materials science, for example, are helping nuclear power plants to operate safely, sustainably and cost-effectively for far longer than originally planned (page 8). Thanks in part to new concepts, technologies and materials, fast reactors promise more efficient energy production with far less waste (page 14). With enhanced designs and safety features, large advanced nuclear reactors (page 11), as well as small modular reactors and microreactors (page 16), offer countries a wider array of options for nuclear power to meet their energy and climate needs.

The impact of innovation goes beyond nuclear power production. Forward-looking financing policies are helping to overcome the economic barriers to new nuclear power projects (page 24). 'Smart' technology, such as artificial intelligence and the 'Internet of Things', when combined with nuclear power, is making energy grids with a high share of renewables more efficient, stable and reliable (page 22). Non-electric applications using nuclear power facilities, such as hydrogen production, are extending the low carbon benefits of nuclear energy to sectors such as industry and transport (page 18).

Advances in nuclear power technology must be accompanied by progress in nuclear safety, security and safeguards. A new, technology-neutral regulatory framework is being established to enable innovation in nuclear power technologies without compromising safety (page 26). One technology in development for safeguards are neural networks to help analysts more effectively and efficiently use their time when reviewing surveillance data collected as part of verification activities to help prevent the spread of nuclear weapons (page 28).

Achieving sustainable development and meeting climate goals will be a huge challenge. Nuclear power is a proven, mature technology with a great deal to contribute. The IAEA will continue to do everything it can to assist the transition to a clean energy future for the world through the use of nuclear technology.



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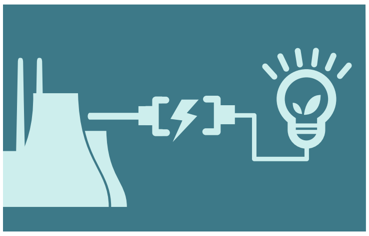
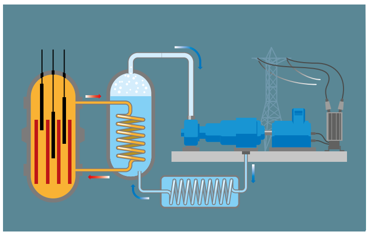




World View

IAEA Updates

What is the clean energy transition and how does nuclear power fit in?

By Nicole Jawerth

The world needs energy to support everyday life and drive human and economic development. In 2019, over 26 000 terawatt-hours of electricity were produced worldwide. This electricity is being produced by a range of energy sources, mostly fossil fuels but also nuclear power and renewables such as solar, hydro and wind.

Energy production and use are the largest source of greenhouse gas emissions around the world. As greenhouse gases are a driving force behind climate change, countries worldwide are actively working on a clean energy transition by changing how energy is produced.

Here's a closer look at the clean energy transition and what role nuclear power plays.

What is the 'clean energy transition'?

The clean energy transition means shifting energy production away from sources that release a lot of greenhouse gases, such as fossil fuels, to those that release little to no greenhouse gases. Nuclear power, hydro, wind and solar are some of these clean sources.

The direction of the global transition to clean energy was agreed in the Paris Agreement, an international deal between over 180 countries that are part of the United Nations Framework Convention on Climate Change (UNFCCC). The agreement's central aim is to limit the increase in global average temperatures to well below 2°C relative to pre-industrial levels by encouraging the use of low carbon energy sources to reduce greenhouse gas emissions.

With around two thirds of the world's electricity still coming from burning fossil fuels, reaching these climate goals by 2050 will require at least 80% of electricity to be shifted to low carbon sources, according to the International Energy Agency (IEA).

What are greenhouse gases, global warming and climate change?

Greenhouse gases are gases in the Earth's atmosphere that trap and let off heat. These gases include carbon dioxide, methane, water vapour, nitrous oxide and ozone. As they absorb and radiate heat back to Earth, it causes the planet's average temperature to go up.

Although some greenhouse gases come from natural sources, most now come from people. Since the Industrial Revolution in the late 1800s, greenhouse gas emissions have gone up owing to an increase in human activities, primarily from burning fossil fuels, such as when driving a gasoline-fuelled car or burning coal to produce heat. When fossil fuels burn, they let off carbon dioxide.

For over 100 years, greenhouse gases have been accumulating much faster than they can dissipate, which, according to the most accredited scientific theories, has sped up the increase in the average global temperature. This is called global warming.

Global warming is causing environmental changes, such as more extreme weather patterns, erratic rainfall, drought and unpredictable season changes. These changes are known as climate change. With the current fast pace of global warming, climate change and its effects are expected to become more extreme and make it more difficult to live on Earth.

How does nuclear power fit into the clean energy transition?

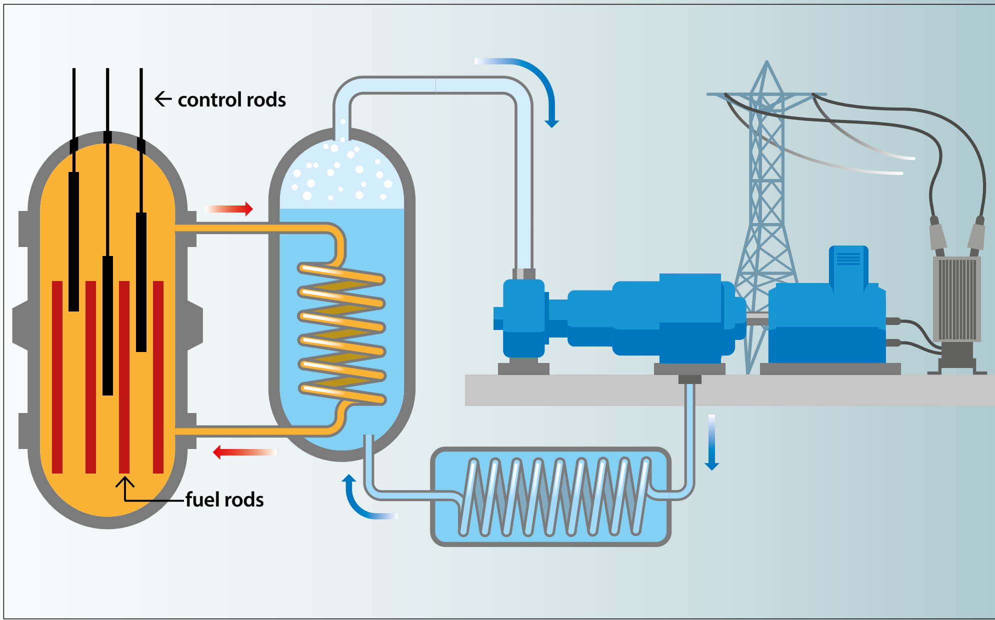
Nuclear power is the second-largest source of low carbon energy used today to produce electricity, following hydropower. During operation, nuclear power plants produce almost no greenhouse gas emissions. According to the IEA, the use of nuclear power has reduced carbon dioxide emissions by more than 60 gigatonnes over the past 50 years, which is almost two years' worth of global energy-related emissions.

Nuclear power accounts for around 10% of the world's electricity and for around one third of global low carbon electricity. Currently, there are 440 nuclear power reactors in operation in 30 countries. There are 54 reactors under construction in 19 countries, including 4 countries that are building their first nuclear reactors.

As they can operate at full capacity nearly uninterrupted, nuclear power plants can provide a continuous and reliable supply of energy. This is in contrast to variable renewable energy sources, such as solar and wind, which require back-up power during their output gaps, such as when the sun sets or the wind stops blowing.

Nuclear power plants can also operate flexibly to meet fluctuations in energy demand and provide stability to electrical grids, particularly those with high shares of variable renewable sources (see page 22). Some nuclear power plants are now being designed to also provide non-electric services, such as hydrogen production. These services can help to decarbonize other sectors, in addition to electricity production (see page 18).

As progress on nuclear power technologies continues, it has led to innovative, advanced and next generation reactor designs that are helping to make nuclear power a more efficient, affordable and attractive option for decarbonization (see page 11). A new era of smaller, more flexible, and, in some cases, transportable reactor designs are also expected to help make nuclear power and its non-electric applications more accessible and cost-effective, especially for remote and hard-to-reach parts of the globe (see page 16).



A simplified diagram of a pressurized water reactor.
(Graphic: iStock.com/jack0m)

How does nuclear power work?

Nuclear power is electricity produced through the controlled release of nuclear energy, which is the energy that holds the centre of atoms together. These centres are called nuclei. Nuclear energy is released, ultimately as heat, by nuclear fission, which is the process of splitting the nuclei of specific materials. The most commonly used material is uranium, a weakly radioactive heavy metal found naturally in the Earth's crust.

The uranium is normally loaded into fuel rods, often after it has been enriched to increase its capability to fission. These rods are placed inside a nuclear reactor.

When used in a pressurized water reactor, which is the most common type of nuclear power reactor currently in operation worldwide, the fuel rods are placed inside the reactor's vessel, which is filled with water. There, the fuel rods are bombarded with nuclear particles called neutrons, which are initially generated by a device (neutron source) inside the reactor. These neutrons cause the uranium nuclei in the fuel rods to split, releasing energy and neutrons. These newly released neutrons cause other uranium nuclei in the fuel rods to split, and so on, creating a nuclear fission chain reaction.

In pressurized water reactors, the energy released during nuclear fission heats up the fuel rods and the surrounding water. The water is kept pressurized to prevent boiling, and the heat is instead piped off to boil water in a nearby vessel. The boiling water produces steam, which is used to turn a giant turbine at very high speeds. The turbine is connected to a generator that also spins, producing electricity. The electricity then flows to a power grid, which is an interconnected network for delivering electricity from producers to consumers.

Nuclear fission continues until control rods made of materials that absorb neutrons without generating additional fissions, such as cadmium, are inserted between the fuel rods. This stops the nuclear fission chain reaction.

The resilience and safety of nuclear power in the face of extreme events

By Matt Fisher

Nuclear power plants are built to last. But as the prospect of extreme global events grows — from natural disasters and intensifying climate change-driven weather patterns that could affect a plant, to a rise in infectious diseases that could affect its workforce — nuclear power plants' adaptable workforces and robust designs will be essential to staying resilient and contributing to a low carbon path to the future.

"For the world to mitigate climate change in the next 20 to 30 years, the energy sector needs to fundamentally transform into a low carbon energy supply system," said Loreta Stankeviciute, an energy systems analyst at the IAEA. "But to do that, the sector also needs to be able to withstand and adapt to extreme events and changes in the environment. Nuclear power's resilience and safety records make it well positioned to help the global community overcome these challenges."

Pandemics

A recent test of resilience emerged during the unprecedented COVID-19 pandemic.

As the COVID-19 virus spread to every corner of the globe in the first part of 2020, societies and economies were turned upside down. Numerous restrictions, including lockdowns, were adopted to control the spread of the virus.

"Despite these worldwide constraints, nuclear power plants around the world continued to operate safely. Operators seamlessly implemented contingency plans, including a variety of emergency measures, to maintain operations and keep personnel safe," said Greg Rzentkowski¸ Director of the IAEA's Division of Nuclear Installation Safety. "Operators took the necessary precautions and carefully implemented operational and organizational changes, while continuing to ensure safety and security of nuclear power plants."

While no country has reported the enforced shutdown of a nuclear power reactor due to the effects of COVID-19, some scheduled maintenance outages have had to be, with regulatory approval, either shortened or postponed as part of protective health measures that have temporarily scaled back non-critical work, according to operator reports. There are also concerns that pandemic-related supply chain disruptions, such as delayed services and temporary closures of manufacturers, could lead to delays in new builds and major refurbishment projects.

"It remains to be seen how much of an impact these pandemic-related disruptions will have on the industry," said Dohee Hahn, Director of the IAEA's Division of Nuclear Power. "The input we continue to receive provides us with crucial insight as to the pandemic's impact on the nuclear industry and will help operators and regulators alike learn from each other's experiences."

Nuclear power has not only proven its resilience during the pandemic but has

(Photo: G. Desipris/P

also shown that it is safe and well suited to meet changing energy needs. Since the pandemic began, the share of nuclear power has increased in some countries, including Brazil, India and South Korea. In the United Kingdom, for example, nuclear power has played a significant role in drastically reducing the amount of coal burning for electricity; the pandemic-induced lower demand for electricity allowed the UK to temporarily close coal plants in favour of an increased use of nuclear power.

Climate change

Just as the resilience of a plant's workforce has been necessary to continue operations unimpeded during the ongoing pandemic, their resilience and a nuclear power plant's robust design are also required in the face of extreme weather events, including those driven by climate change.

Caused by the global mean temperature increase, climate change is altering the severity and frequency of weather events, such as temperature extremes, periods of heavy rainfall, high winds and major sea level rises. These changes are expected to continue to increase in the near to long term.

"While rising water and air temperatures may pose challenges to the continuity of reactor operation by limiting its cooling capacity, it's the extreme floods and winds that may affect reactor safety by posing threats to the installation's design," said Rzentkowski. "One of the challenges with climate change is that, as it continues to progress and make conditions more extreme, past observations and predictive models become less reliable. We should thus start anticipating these events and periodically reassess the relevant risks to ensure that accident prevention and mitigation measures remain adequate."

Natural events

Nuclear power plants may also be affected by extreme natural events, such as earthquakes, tornados, volcanic activity, ice storms and flooding. In rare circumstances, these events can be extreme enough to exceed the design capacity of a nuclear power plant.

An example of this is the accident at the Fukushima Daiichi Nuclear Power Plant in Japan on 11 March 2011, which was triggered by a tsunami that followed a massive earthquake. While the nuclear power plant was damaged by these events and the consequent hydrogen explosions, no lives were lost due to the accident.

In the aftermath of the Fukushima Daiichi accident, concrete steps have been taken to further enhance safety at existing nuclear power plants and refine the designs of new plants against extreme events. These measures include, for example, alternative cooling options, environmentally qualified back-up generators, shields and seals to guard against wind, and dykes and other embankments to protect sites against flooding.

All types of external events that may affect a nuclear site or the safety of nuclear installations are also addressed by the IAEA safety standards, including site evaluation and design and safety assessment. These standards reflect the current state of practice and are used to ensure safety throughout a plant's lifetime. The IAEA also provides guidance through its Nuclear Energy Series and other technical publications such as Adapting the Energy Sector to Climate Change.

Advances in materials science and technology extend nuclear power's clean energy benefits

By Carley Willis

Advances in materials science and technology are helping to extend the lives of nuclear power plants, so countries can continue reaping their clean energy benefits.

"The cost of refurbishing a nuclear power plant for long term operation is much lower than building a new nuclear power plant," said Ed Bradley, Team Leader in Nuclear Power Plant Operation and Engineering Support at the IAEA. "Long term operation of a nuclear power plant is an excellent opportunity to improve the sustainability of the current nuclear generation, since it is one of the most cost-effective sources of low carbon electricity. With the materials and technology that we have today compared to in the past, this has become an attractive and competitive option for many countries that are trying to decarbonize."

Most nuclear power reactors were initially built to have an operating life of between 30 and 40 years. Extending the life of a nuclear power plant involves assessing an existing plant and determining if it can safely, securely and cost-effectively continue operating past its assumed retirement date. When a plant's life is extended, operations can often continue for an additional 20 to 40 years.

"Given the extensive and thorough work done during a nuclear power plant's initial siting, design and construction, as well as ageing management throughout operations, with certain upgrades and refurbishments, many nuclear power plants are capable of continuing to operate safely far past the original expected operation timeline," said Robert Krivanek, Senior Safety Officer at the IAEA. However, some nuclear power plants have certain components and designs that cannot be easily or cost-effectively updated, which means they aren't suitable for long term operation, he added.

An overhead view of two Unit 2 turbines at the Darlington Refurbishment Project.
(Photo: R. Radell/Ontario Power Generation)

One of the major challenges with an ageing nuclear power reactor is degradation. As a plant operates, its structures and components must withstand high temperatures, intense conditions and continuous operation, which, over time, can wear them down.

"Routine evaluation and replacement of parts can mitigate degradation, but, over time, this may not be the best approach economically, especially in the case of long term operation," said Bradley.

New techniques and materials

The development of new techniques such as laser beam welding and friction stir welding, and materials such as duplex stainless steel, which provide better corrosion resistance, means some components are now able to safely last longer, making it more economically feasible for a nuclear power plant to continue operation.

Researchers are also developing a better understanding of how different operating conditions at a nuclear power plant can affect components and structures. For example, in the case of the CANDU reactors in Ontario, Canada, which went into service between 1970 and 1993, materials science research and component inspection has enabled some components to safely operate for an additional 10 years beyond their expected 30 years. A US $18.5 billion refurbishment programme will further extend operation for a second cycle of up to an additional 40 years. This means that some reactors built in the 1980s will be safely operating into the 2060s.

"Our reactors were built at a time when we didn't have a lot of history with nuclear power plants, and the original expected lifetime of our design was conservatively estimated at 30 years," said Fred Dermarkar, President and Chief Executive Officer at the CANDU Owners Group, an industry group of nuclear operators in seven countries using CANDU reactors. "As we operate these machines and get to know them and understand how they age, we can realize the tremendous benefit in continuing to operate long term."

Dermarkar explained how state-of-the-art materials science is being used to predict material properties many years into the future. "CANDU reactors use components called pressure tubes to cool the fuel. In the reactor environment, pressure tube properties change with time due to high neutron flux, high temperature and pressure, and corrosion from the cooling water. To predict the changes from corrosion, for example, we start with irradiated pressure tubes that have been

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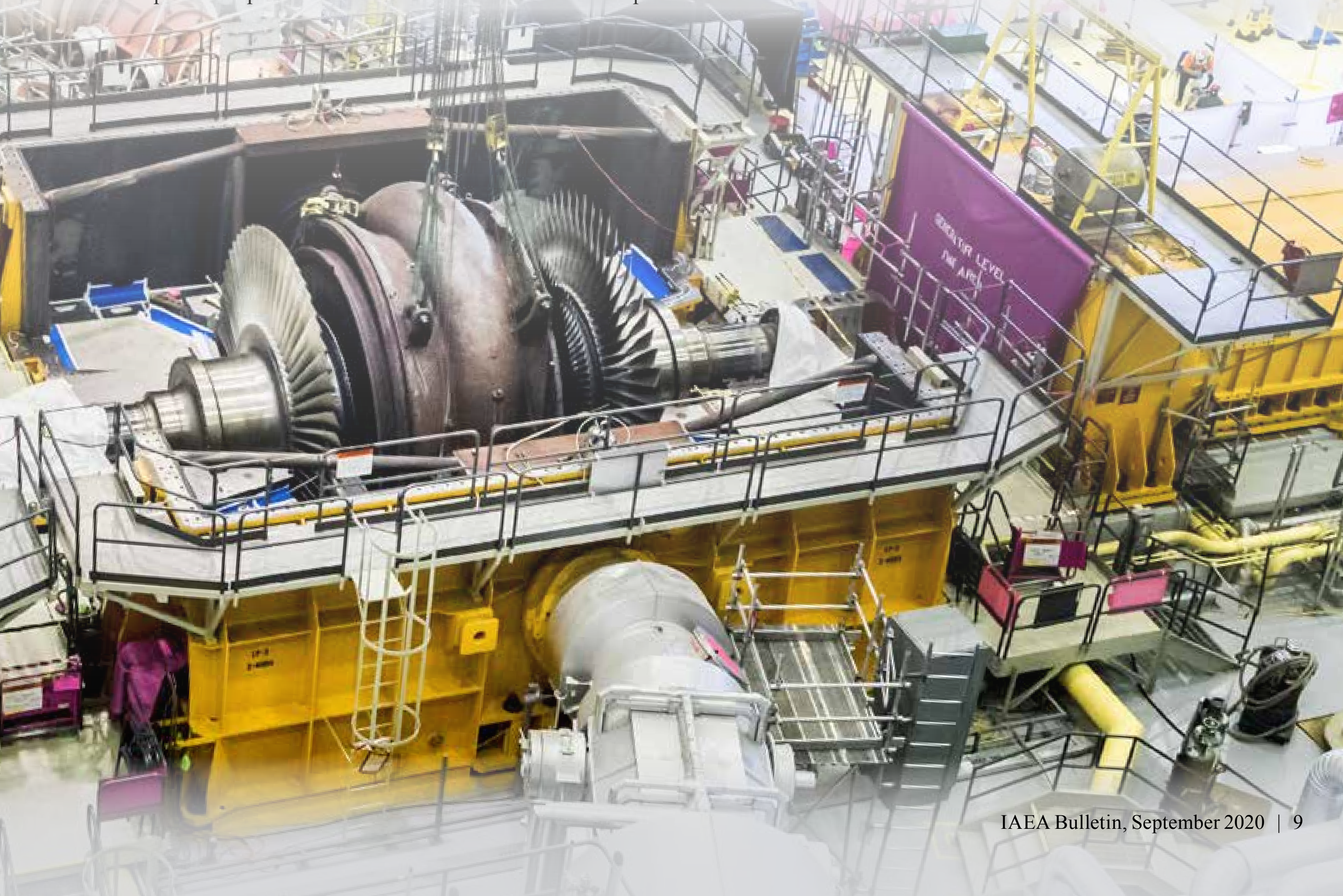
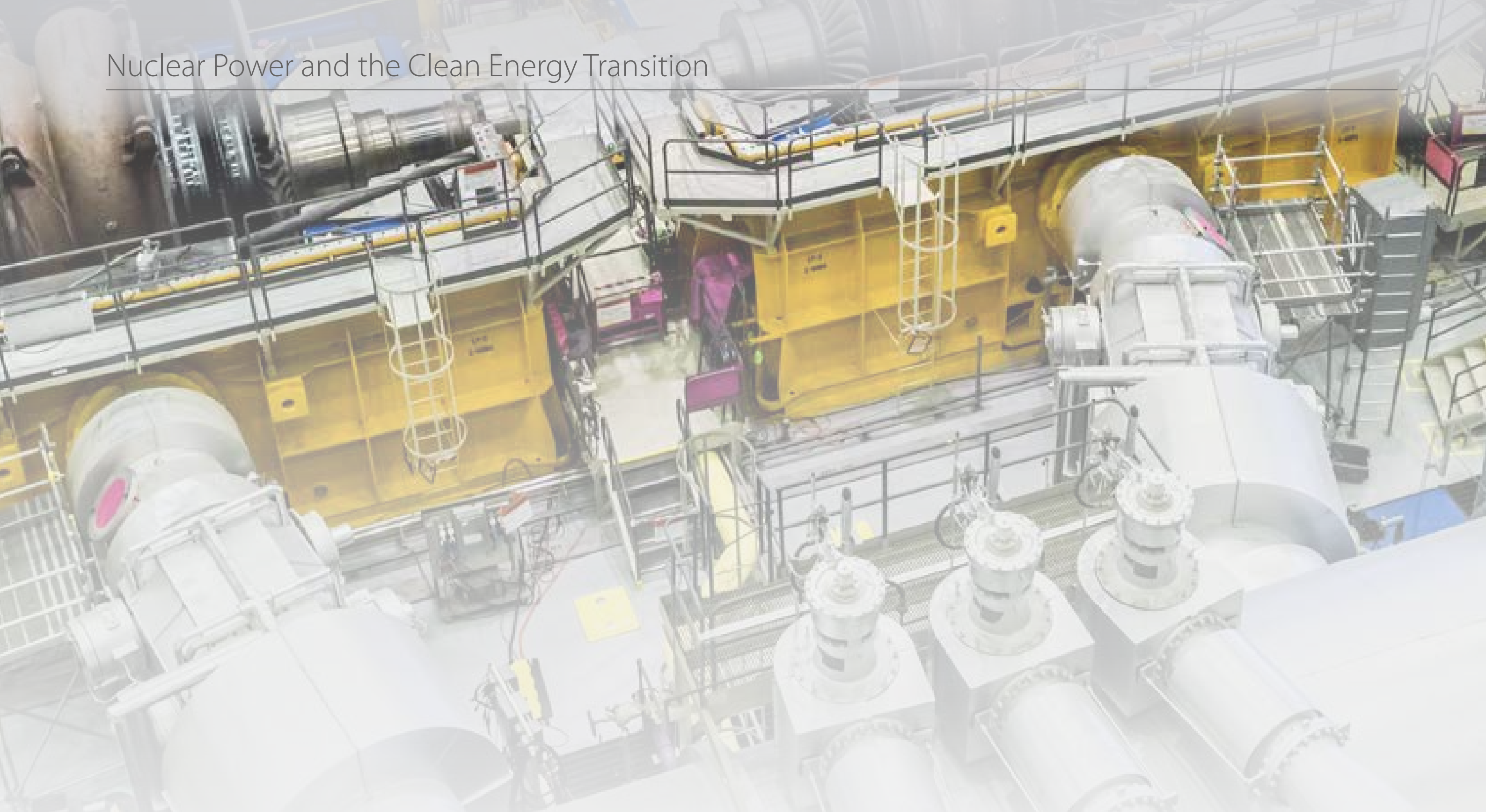
— Fred Dermarkar, President and Chief Executive Officer, CANDU Owners Group





removed from operating reactors. We then apply techniques to artificially accelerate corrosion, and then perform extensive tests to determine the material properties of these artificially aged components. In this way, we are able to demonstrate how far we can take these components. Being one step ahead in the laboratory is how we are giving ourselves confidence that these components will continue to operate safely and reliably until their scheduled refurbishment date," he said.

Big data and nuclear power

Researchers are now also exploring how to use big data to assess and determine the feasibility of long-term nuclear power plant operation. Big data is a term used to describe the analysis of extremely complex and large amounts of data collected very quickly and often in real time to identify trends and patterns and to predict outcomes and behaviours.

For the long term operation of a nuclear power plant, millions of data points are collected from a plant's operation, including operating logs, reactor measurements and reported events. By mining these data using nuclear-related big data software, researchers can predict, using simulation tools, how a plant's systems, structures and components may age under different conditions, and determine what may need replacing and roughly when that replacement would need to happen.

"Big data is not just the future; it's happening now, and it's gaining momentum," said Dermarkar. "Our power plants are modernizing, and they are being equipped with more instruments that are portable and can be easily mounted to collect data and anticipate problems early on, enabling us to take early corrective actions. We are seeing real benefits: our plants are performing better today than at any time in their history."

Helping countries to navigate the long term operation of nuclear power plants is part of the IAEA's work. It develops internationally recognized safety standards, provides guidance through technical publications, such as the Ageing Management for Nuclear Power Plants: International Generic Ageing Lessons Learned publication, and shares expertise through the Safety Aspects of Long Term Operation (SALTO) peer review missions. The IAEA also coordinates a working group for operators, regulators and decision makers from around the world to discuss their experience and share good practices.

"The primary challenge with long term operation is to maintain the highest safety standards and to do this economically," said Garry G Young, Director of Licence Renewal Services at Entergy Nuclear and Chair of the IAEA's working group on long term operation. "Our working group is continually exploring ways to ensure efficiency and safety and to spread the results and advances that are being made in the field so that research and development is most beneficial to all."

Advanced reactors help pave the way for nuclear power to meet climate goals

By Matt Fisher

Advanced reactors are helping to make nuclear power a more accessible, sustainable and affordable low carbon energy option. With enhanced safety features and designs optimized for cost-effectiveness, these reactors are expected to open the door to better economics, streamlined licensing processes and greater public acceptance, ultimately helping countries to consider nuclear power towards achieving their climate goals.

"Designed to operate for six decades or more and expected to streamline licensing processes, advanced reactors fit the bill for climate change mitigation, which requires both quick implementation and long-term sustainability," said Stefano Monti, Head of the IAEA's Nuclear Power Technology Development Section. "Public engagement and acceptance are crucial for the future of nuclear power, and, as reactor designs continue to improve from both a safety and economic perspective, so too will the global community's perception of this vital source of low carbon electricity."

Advanced reactors and associated fuel and fuel cycles represent the cutting edge of nuclear power technology. Their designs build on over six decades of research, development and lessons learned in nuclear power.

The IAEA works together with countries to identify and address challenges associated with the development of advanced reactors, such as technological innovation and safety design criteria. This support includes collaborative research projects and activities such as workshops with international experts, as well as cooperation with the Generation IV International Forum (GIF), an international cooperative endeavour that now includes 13 countries. Since its establishment in 2000, GIF has been carrying out research and development activities to support next generation nuclear energy systems.

Some distinguishing features of advanced reactors include enhanced thermal efficiency, waste minimization, optimized use of natural resources and the ability to address both electricity production and non-electric applications of nuclear power, such as hydrogen production (see page 18). These features expand operating potential and vastly improve nuclear power plant economics.

Sophisticated designs

There are two main categories of advanced reactors: 'evolutionary' and 'innovative'. Evolutionary reactors offer a sturdy and immediate bridge to low carbon energy production, while the innovative reactors of tomorrow will further help countries on a low carbon path while significantly reducing high level radioactive waste and expanding non-electric applications of nuclear power.

At present, there are 15 evolutionary reactors in operation, with more on the horizon. Both South Korea's APR1400 reactor and Russia's VVER-1200 reactor offer pressurized water reactor designs with bolstered efficiency and advanced safety characteristics. In addition to the APR1400 reactor being deployed in South Korea, another reactor of this type is currently under construction in the United Arab Emirates, with the first unit set to go online in 2020.

Three VVER-1200 units are currently in operation in Russia and others are under construction in Bangladesh, Belarus, Russia and Turkey, with further units in Belarus expected to be commissioned in late 2020. The French-designed EPR reactor, which has two operational units in China and further units under construction in Finland, France and the United Kingdom, is designed to simplify plant operations while boosting generation capacity.

China's 1090 MW(e) HPR1000 reactor, also known as the Hualong One, is under construction at sites across China and is planned for export to other countries, including Argentina and the United Kingdom, with the first units expected to begin operation in late 2020. It incorporates sophisticated passive and active safety systems, such as control rods that are inserted by gravity alone in the event

of a loss of power, and a new containment structure that can withstand higher pressure, minimizing the chance of leaks in the event of a nuclear accident.

The AP1000, an 1157 MW(e) pressurized water reactor, is in operation at two nuclear power plants in China. This reactor's relatively simple design includes fewer valves and has features that take advantage of natural forces, such as pressurized gas, gravity flow, natural circulation flow and convection, which have safety-related functions. Additional AP1000 units are under construction in the United States, with plans to begin generating electricity by 2022.

Innovation for sustainability

Innovative reactors are still under development, with construction on some designs potentially beginning around 2030. Their common design features include high operating temperatures necessary for both electricity production and other non-electric applications, such as hydrogen production, as well as highly robust inherent safety features, enhanced sustainability via waste minimization and optimized use of natural resources and special provisions to improve physical protection and proliferation resistance.

Some designs are also expected to include new types of coolants, such as liquid metal or molten salt, which allow the reactors to operate at ambient pressure and at much higher temperatures for greater efficiency. Some designs may also operate with a closed nuclear fuel cycle, with the aim of reducing the volume, toxicity and lifespan of radioactive waste.

A glimpse into the future of innovative reactors is offered by the BN-800 sodium cooled fast reactor, which is one of three fast reactors currently in commercial operation, along with an earlier version known as the BN-600, and the China Experimental Fast Reactor. Operating in Russia since October 2016, the BN-800 is powered by mixed oxide fuel, which is a combination of plutonium and uranium. Many innovative reactor designs are expected to operate using a similar physical principle, pushing the limits of nuclear power technology to the next level. Learn more about fast reactors on page 14.

"While the next generation of nuclear power reactors may be quite a few years away from entering commercial operation, the progress that continues to be made in research and development initiatives is highly encouraging," said Dohee Hahn, Director of the IAEA's Division of Nuclear Power. "As we strive towards a clean energy future, it is clear that nuclear power will play a significant role in getting us to where we need to be."

The Taishan Nuclear Power Plant in China features EPR reactors.

(Photo: Taishan Nuclear Power Joint Venture Co. Ltd)

New fuels for more energy and less waste

Researchers are working on new ways to fuel nuclear reactors. The aim is to minimize the impact of nuclear waste and reduce operating and maintenance costs, while also improving nuclear plant performance and further strengthening nuclear safety.

One approach is through multi-recycling leftover uranium and plutonium from spent fuel — nuclear fuel after it has been irradiated. This recycled fuel can power the next generation of nuclear reactors and more efficiently use resources while reducing the volume and radiotoxicity of nuclear waste. With multi-recycling, reactors could potentially operate almost only on recycled spent fuel, rather than newly mined natural uranium resources.

Accident tolerant fuel (ATF) is a new, promising type of fuel being developed for current and future reactor designs. Using new and improved materials for the fuel and cladding (the outer tube surrounding the fuel), ATF can better withstand temperature changes and extreme conditions in a reactor. This means, for example, that it can endure the loss of active cooling in a reactor core for much longer than currently used fuels.

For advanced reactors, new types of fuels are being developed to last longer in the reactor core, meaning that they produce more energy and less waste. They use a mix of uranium and plutonium with a higher atomic density in different ceramic compounds, as well as in metals and alloys, to improve reactor performance. This makes the fuel more well suited for breeding, or producing, new fuel in fast reactors during operation. As the types of materials used in these fuels are also more efficient at transferring heat, the fuels' overall temperature reduces and becomes more uniform, which increases safety.

Shrinking nuclear waste and increasing efficiency for a sustainable energy future

By Jeffrey Donovan

Fast neutron reactors can increase efficiency of nuclear energy and shrink the environmental footprint of radioactive waste. Several countries are looking to these innovative reactors to help ensure a sustainable energy future.

Fast reactors use neutrons that are not slowed down by a moderator, such as water, to sustain the fission chain reaction. While only a fraction of natural uranium is used as fuel in existing thermal reactors, fast reactors can use almost all uranium contained in the fuel to extract up to 70 times more energy, reducing the need for new uranium resources.

Fast reactors also operate in what is known as a closed nuclear fuel cycle. A closed fuel cycle is when spent fuel — nuclear fuel after it has been irradiated — is recycled and reused. Such an energy system could potentially be sustainable for thousands of years. This contrasts with an open fuel cycle, where nuclear fuel is used once and the spent fuel is declared as waste for eventual underground disposal in geological repositories.

Fast reactors can also produce or 'breed' more fuel than they consume and burn off some of the waste contained in spent fuel, such as minor actinides, which thermal reactors cannot do efficiently. Burning them off significantly reduces the volume, toxicity and lifespan of the longest-living radioactive waste.

"The environmental footprint of an energy source, such as its waste, is a big question for many countries as they look for sustainable ways to deliver clean energy," said Amparo Espartero Gonzalez, Technical Lead for the Nuclear Fuel Cycle at the IAEA. "The ability to shrink that footprint, while also getting more out of nuclear fuel is a big part of the growing appeal of fast reactors for many countries and what is driving their technological development."

Making a comeback

Fast reactors were among the first technologies deployed during the early days of nuclear power, when uranium resources were perceived to be scarce. But as technical and materials challenges hampered development, and new uranium deposits were identified, light water reactors (LWRs) eventually became the industry standard. Five fast reactors are now in operation: two operating reactors (BN-600 and BN-800) and one test reactor (BOR-60) in Russia, India's Fast Breeder Test Reactor (FBTR) and the China Experimental Fast Reactor (CEFR).

New concepts, technologies and advances in materials research, combined with a long-term vision of nuclear power as part of sustainable energy, are now reviving the fast reactor option. These advances generally feature innovative upgrades, such

as enhanced safety features and improved and more compact designs that address economics. New designs also include alternative coolants, such as molten salt, lead, lead–bismuth and gas.

“Fast reactors have been under development for decades primarily as fuel breeders and, in recent years, also as long-life battery-type small modular reactors and even microreactors,” said Vladimir Kriventsev, Team Leader for Fast Reactor Technology Development at the IAEA. “Fast reactors can make nuclear power a sustainable energy source for thousands of years and provide significant improvements in nuclear waste management.”

Fast reactors in progress

Fast reactors are under development around the world. The IAEA plays a central role in supporting their development and deployment as well as in sharing information and experience, including through coordinated research projects, technical publications, technical working groups and international conferences.

Already operating two sodium cooled fast reactors, Russia plans to deploy a next generation 1200 megawatt (MW)(e) commercial fast reactor after 2035 as part of a self-sustaining system alongside light water reactors. With help from the fast reactor, spent fuel from the thermal reactors will be reprocessed and reused, with a final waste footprint up to ten times smaller than that of regular nuclear fuel.

India is commissioning the sodium cooled 500 MW(e) Prototype Fast Breeder Reactor, the first of several industrial fast reactors the country is planning. China, which operates a 20 MW(e) experimental fast reactor, is building a large demonstration fast reactor and plans to eventually deploy commercial fast reactors.

In North America, several fast reactor designs using different coolants, including molten salt, are under development. The United States plans to build a test fast reactor to facilitate the technology’s further development as well as a 1.5 MW(e) demonstration micro fast reactor, which will also demonstrate a new type of reprocessed fuel suitable for use in future innovative reactors.

Since the 1950s, the technological viability of fast reactors has been amply demonstrated. France operated the 1200 MW(e) Superphenix commercially for 12 years until 1998 and continues to do research and development on the technology, as do South Korea as well as Japan, which plans to restart an experimental fast reactor.

Still, wider industrial deployment of fast reactors will largely depend on improved economics.

“In a resource-constrained world where the price of uranium is expected to be much higher than now and a greater premium to be put on waste minimization, innovative and compact fast reactors may become more economically competitive compared with traditional thermal reactors,” said Stefano Monti, Head of the Nuclear Power Technology Development Section at the IAEA. “With several countries actively developing fast reactors, we expect them to make an important contribution to clean energy systems in the coming decades.”

The BN-800 reactor at the Beloyarsk Power Station in Russia.
(Photo: Rosenergoatom)

Small reactors, great potential

By Irena Chatzis

The Aurora powerhouse is an advanced fission plant design.
(Photo: Oklo)

Hearing the words 'nuclear power' usually conjures up images of huge power plants and cooling towers, but with small modular reactors (SMRs) and microreactors (MRs) starting to become a reality, the face and reach of nuclear power is changing.

"SMRs and MRs provide low carbon energy like large nuclear reactors do, but they are smaller, more flexible and more affordable, so they can be used on smaller power grids and be built in hard-to-reach places where large reactors wouldn't be practical," said Frederik Reitsma, Team Leader for SMR Technology at the IAEA. "Many are designed to provide non-electrical services in addition to electricity production, adding to their clean energy benefits and cost-effectiveness."

SMRs are expected to generate up to 300 megawatts (electrical) (MW(e)) of power and MRs up to 10 MW(e), depending on their designs. In addition to their modularity, some other common features are passive and built-in systems that enhance safety, the ability to efficiently and flexibly generate energy to meet fluctuating demands, and simpler designs that are faster and less complex to construct than current reactors. They also have more factory-based manufacturing possibilities, which can reduce on-site construction time and makes them easier and more cost-effective to reproduce for additional deployment.

"Large nuclear reactors are a major undertaking and require substantial long-term investment, which is feasible and appropriate for some situations. For others, however, SMRs and MRs can be a more realistic and faster approach and sometimes the only way to cost-effectively access nuclear power," said Reitsma. "When you combine this with effective financing and market policies, it opens up nuclear power to a wider range of users and makes it a more competitive and attractive option on the energy market." Learn more about financing and market policies in nuclear power on page 24.

An SMR first

The world's first advanced SMR was connected to the grid in 2019 and started commercial operation in May 2020.

Akademik Lomonosov floating nuclear power plant, located just off Russia's Arctic coast, houses two 35 MW(e) KLT40S SMR units that are now generating enough energy to power a city of about 100 000 people. The plant also has a heat capacity of 50 gigacalories per hour, and it is used for seawater desalination, producing up to 240 000 cubic metres of fresh drinking water per day.

"With the help of small nuclear reactors, the Arctic can achieve net zero emissions as early as 2040," said Anton Moskvin, Vice President for Marketing and Business Development at Rusatom Overseas. "Akademik Lomonosov will replace a plant that burns brown coal. Besides contributing to the elimination of harmful emissions in the Arctic ecosystem, it will provide guarantees that the region's inhabitants will not be left without light and heat in the freezing Far North."

Other SMRs at the most advanced stage of construction are the 30 MW(e) CAREM reactor in Argentina and the 210 MW(e) HTR–PM in China. Several are also far along in the regulatory process, including the NuScale Power SMR in the United States and several in Canada. In total, there are more than 70 SMR designs worldwide at various stages of development.

The IAEA has several activities related to SMRs to support research and development worldwide. It facilitates cooperation in SMR design, development and deployment and serves as a hub for sharing SMR regulatory knowledge and experience.

Micro powerhouses

While SMR designs are generally based on well-known reactor systems, MRs are the sort of thing you would expect to see in a science fiction movie. They are small enough for the whole plant to be built in a factory and transported by a truck. With self-regulating passive safety systems, they only require a small workforce to run. Operating independently from the electric grid, they can be moved around and used in different locations. They can generate up to 10 MW(e) of power — around 10 years or more of electricity for more than 5 000 homes, 24 hours a day, 7 days a week.

These compact, movable reactors can serve as backup power supplies for places like hospitals, or replace power generators that are often fuelled by diesel and are the only source of electricity for remote communities as well as industrial and mining sites.

More than a dozen MRs are now under development by private companies and research groups worldwide.

One close to deployment is the Aurora 1.5 MW(e) fast spectrum reactor being developed by Oklo, a US-based start-up company. Now going through the regulatory process, Aurora is designed to function and self-regulate primarily using natural physical phenomena, meaning it has very few moving parts, which increases safety. It is also expected to be able to operate for decades without refuelling, using high assay low enriched uranium fuel.

"The fission reaction can be used in many formats: small and large, different fuels, different ways to cool, and enable many different ways for business models and community interaction and ownership," said Caroline Cochran, Chief Operating Officer of Oklo. "The novel use of fission and the implementation of distributed, smaller plants can enable human development while minimizing resource use."

Other MRs at advanced stages include a 4 MW(e) reactor developed by U-Battery, a URENCO-led company based in the United Kingdom that is expected to begin operation in 2028.

Large-scale deployment

Despite advances, SMRs and MRs are still far from deployment on a large scale.

"It is a 'chicken and egg' situation," said Reitsma. "On the one hand, investment to develop and deploy SMRs requires a secured market and demand for the product, but on the other, one cannot secure the market without funding to develop and demonstrate, or even to do the necessary research or build test facilities that may be required for licensing. Potential investors are hesitant to invest in new technology if they are unsure about the market risks."

One of the other major obstacles for deployment is applying regulations to the wide range of SMR and MR designs. The diverse combination of systems, structures and components means standard regulatory approaches, which were set up for conventional nuclear power plants, have to be re-evaluated and eventually adjusted to ensure an adequate level of safety. Learn more about the SMR regulatory process on page 26.

"At this point, many first of a kind advanced SMRs have been going through the regulatory process and, once that's done, we generally expect at least another four to five years until they are constructed and operating," Reitsma said. "But as SMRs and MRs become mainstream, we can expect to see this timeline shrink as the deployment processes should become faster, more cost effective and easier."

"The novel use of fission and the implementation of distributed, smaller plants can enable human development while minimizing resource use."

— Caroline Cochran, Chief Operating Officer, Oklo, United States

More than just a power source

Hydrogen production using nuclear energy for a low carbon future

By Matt Fisher

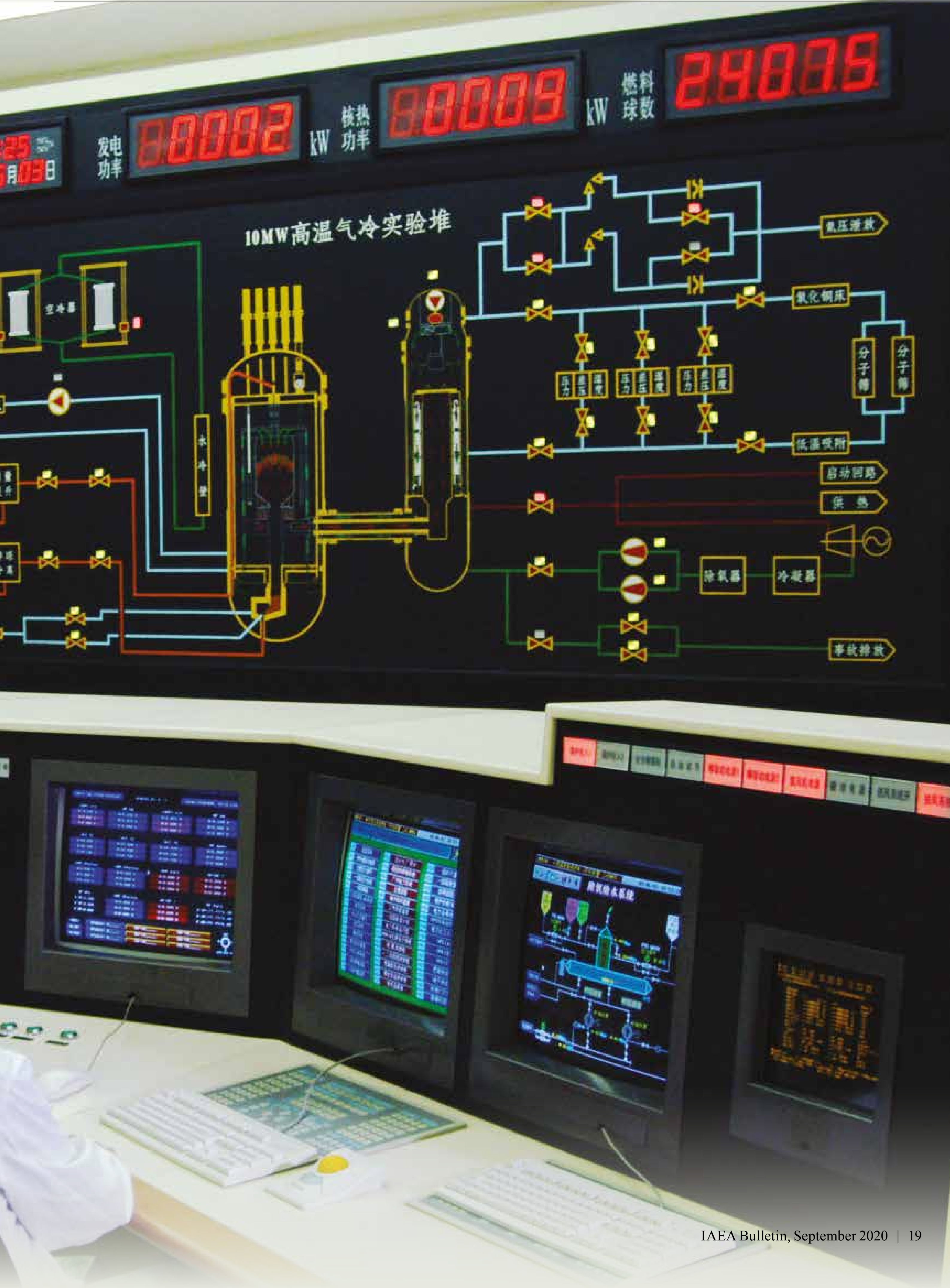
Hydrogen is the most abundant chemical element in the universe, but producing it in pure form for a range of industrial processes is energy intensive, with a significant carbon footprint.

"Almost 95% of current hydrogen demand is met by utilizing carbon-intensive production processes such as steam methane reforming. This is unsustainable in light of the global clean energy transition, particularly considering that demand is already quite high and continues to grow," said Ibrahim Khamis, a senior nuclear engineer at the IAEA. Hydrogen demand has more than tripled since 1975, according to the International Energy Agency.

Hydrogen is used in industrial processes ranging from producing synthetic fuels and petrochemicals to manufacturing semiconductors and powering fuel cell electric vehicles. In order to decrease the environmental impact of the annual production of over 70 million tonnes of hydrogen, some countries are looking to nuclear power.

"If, for example, just 4% of current hydrogen production were to be shifted to nuclear-generated electricity, this would result in as much as 60 million tonnes of carbon dioxide emissions being abated each year," Khamis said. "And if all hydrogen were to be produced using nuclear energy, then we are talking about eliminating over 500 million tonnes of carbon dioxide emissions annually."

The control room of the HTR-10 reactor at Tsinghua University in Beijing.
(Photo: P. Pavlicek/IAEA)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> **“Hydrogen production through nuclear energy offers an opportunity to drastically cut carbon emissions while also boosting the profitability of the nuclear power industry.”**
>
> *— Anton Moskvin,*
> *Vice President for Marketing and Business Development,*
> *Rusatom Overseas, Russia*

Nuclear power reactors can be coupled with a hydrogen production plant to efficiently produce both energy and hydrogen as a cogeneration system. For hydrogen production, the cogeneration system is fitted with components for either electrolysis or thermochemical processes. Electrolysis is the process of inducing water molecules to split using a direct electric current, producing both hydrogen and oxygen. Water electrolysis operates at relatively low temperatures of around 80°C to 120°C, while steam electrolysis operates at much higher temperatures and is therefore more efficient. Steam electrolysis could be ideal for integration with advanced high temperature nuclear power plants, as the process requires heat input at around 700°C to 950°C.

Thermochemical processes can produce hydrogen by inducing chemical reactions with specific compounds at high temperatures to split water molecules. Advanced nuclear reactors capable of operating at very high temperatures can also be used to produce heat for these processes.

“Hydrogen production using the sulphur–iodine cycle in particular has great potential to be scaled up for sustainable, long term operation,” said Khamis. “The development of this method using Japan’s HTTR reactor design and China’s HTR–PM 600 and HTR-10 designs is very promising, and other research initiatives continue to make excellent progress.”

Several countries are now implementing or exploring hydrogen production using nuclear power plants to help decarbonize their energy, industrial and transportation sectors. It is also a way to get more out of a nuclear power plant, which can help to increase its profitability.

The IAEA provides support to countries interested in hydrogen production through initiatives including coordinated research projects and technical meetings. It has also developed the Hydrogen Economic Evaluation Programme (HEEP), a tool for assessing the economics of large-scale hydrogen production via nuclear energy. The IAEA also released an e-learning course on hydrogen production through nuclear cogeneration in early 2020.

“Hydrogen production using nuclear power plants has great potential to contribute to decarbonization efforts, but there are a number of challenges that must first be addressed, such as determining the economic viability of incorporating hydrogen production into a broader energy strategy,” said Khamis. “Hydrogen production through thermochemical water splitting processes requires innovative reactors operating at very high temperatures, and these reactors remain some years away from deployment. Similarly, the sulphur–iodine process still requires more years of research and development to reach maturity and achieve commercial scale-up status.” The licensing of nuclear energy systems incorporating non-electric applications can also be a challenge, he added.

Studying and testing feasibility

The ‘H2@Scale’ initiative, launched in early 2020 by the United States Department of Energy (DOE), is examining the feasibility of developing nuclear energy systems that produce hydrogen in tandem with low carbon electricity. Among the dozens of projects funded through this initiative, one will be implemented by three US commercial electric utility companies in cooperation with the DOE’s Idaho National Laboratory. The project will include technical and economic assessments, as well as pilot demonstrations of hydrogen production at several nuclear power plants around the US.

One of the utility companies involved in the project, Exelon, the largest producer of low carbon power in the US, is now taking steps to install a one-megawatt polymer electrolyte membrane electrolyzer and associated infrastructure at one of its nuclear power plants. The system, which could be in service by 2023, will be used to demonstrate the economic viability of electrolytically-produced hydrogen to supply onsite needs of electric generation-related systems as well as future scalability opportunities.

“This project will be instrumental in helping us determine the prospects for nuclear-driven hydrogen production, including how financial considerations may affect any long term, large-scale production of hydrogen,” said Scot Greenlee, Senior Vice President of Engineering and Technical Services at Exelon Generation. “The introduction of hydrogen production with nuclear power can go a long way towards enhancing the sustainability of nuclear power as we plan for a low carbon future.”

More than hydrogen

Nuclear power has a variety of non-electric applications in addition to hydrogen production. Some of these include district heating for homes and businesses, heating and cooling for industrial purposes, and desalination of seawater to boost the availability of drinking water.

The potential adoption of these applications is also expanding as new nuclear energy systems are designed to optimize the combined electric and non-electric uses as well as the integration with renewable sources. New reactor designs are also being developed, such as small modular reactors, to provide more flexible operation, allowing their power output to be adjusted according to demand. This makes them especially well-suited for such applications because energy normally used for electricity production can be rerouted for non-electric applications.

The Davis-Besse Nuclear Power Station in Ohio will produce hydrogen using nuclear energy.

(Photo: B. Rayburn/Davis-Besse Nuclear Power Station)

Assessments are also under way in the United Kingdom. The Energy Systems Catapult, a non-profit initiative in the UK, is modelling the whole energy system and now includes the option for advanced nuclear technologies for hydrogen production. This provides a look at the potentially lowest-cost energy mix that could deliver net zero greenhouse gas emissions by 2050, and the output indicates that advanced nuclear could play a role in hydrogen production alongside other technologies.

"While the exact role of hydrogen in the United Kingdom is still to be determined, analysis done by the Committee on Climate Change and the Department for Business, Energy and Industrial Strategy suggests that we may need to deploy around 270 terawatt-hours of low carbon hydrogen by 2050, although this could increase considerably depending on which applications across the heat, power and transport sectors hydrogen is ultimately used for," said Philip Rogers, Senior Strategic and Economic Advisor at the United Kingdom's Nuclear Innovation and Research Advisory Board.

New programmes

In 2019, Russia launched its first nuclear-driven hydrogen production initiative. The programme, run by the country's State Atomic Energy Corporation "Rosatom", will use nuclear-driven electrolysis as well as thermochemical generation using high temperature gas cooled reactors. The aim is to produce large quantities of hydrogen each year and shift production away from carbon-intensive production methods such as steam methane reforming.

The hydrogen it produces will be for domestic use and exports. A feasibility assessment is under way on exporting some of the hydrogen to Japan.

"As hydrogen demand continues to grow, driven in part by the expansion of industries such as metalworking, hydrogen production through nuclear energy offers an opportunity to drastically cut carbon emissions while also boosting the profitability of the nuclear power industry," said Anton Moskvin, Vice President for Marketing and Business Development at Rusatom Overseas.

Smart, stable, reliable

Smart grids and nuclear power in low carbon energy systems

By Sinead Harvey

Nuclear power combined with smart power grids — the two-way networks that connect producers to consumers and use new technologies to do so — can help countries transition to low carbon electricity sources and ensure reliable, stable and sustainable energy supplies.

Many countries are diversifying their mix of low carbon energy sources to help them decarbonize their economies and achieve their climate goals. This has led to a global shift towards renewable energy sources; however, these sources alone are not able to fully and reliably meet demand.

"Low carbon renewable energy sources are climate friendly but are not always readily controllable or able to meet energy demand due to the intermittent nature of solar and wind, and the absence of massive energy storage capacities. This means the power grid often requires supplementary energy sources," said Henri Paillere, Head of the IAEA's Planning and Economic Studies Section. "With more diverse energy sources feeding into the networks, power grids have had to become more flexible and adaptable in order to ensure a reliable and resilient energy supply."

Nuclear power can generate low carbon energy 24 hours a day, 7 days a week. It provides the energy security countries need to move to low carbon energy systems. By operating flexibly, nuclear power plants can complement the variable generation of energy by renewables, and with the inertia of their large steam turbines, these plants can also help stabilize grids and ensure a clean and reliable power supply.

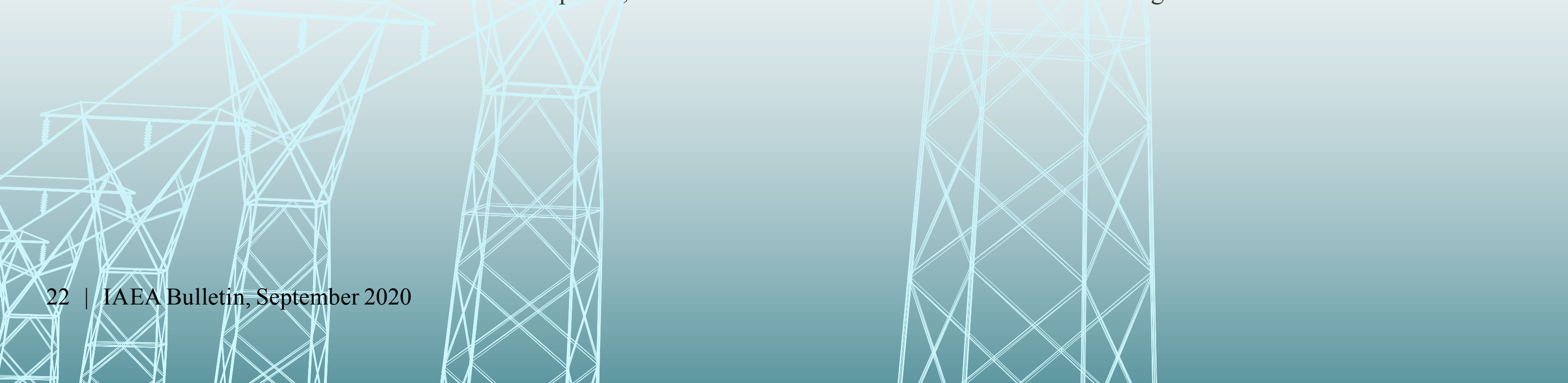
Traditionally, power grids have relied on fossil fuel plants, such as coal and natural gas, to be turned on and off to meet energy demand when it outpaces supplies.

Smart power grids, on the other hand, can accept many different energy sources and dynamically switch between them, unlike traditional power grids, which are less flexible. Although smart grids have existed for some time now, advances in technology have taken them to the next level. Smart grids can use recent technology such as artificial intelligence (AI) and the Internet of Things (IoT) — a system of computers and devices connected through the Internet that can dynamically share and act on data — to gather information, increase operating efficiency and automate processes.

For example, a smart power grid can use forecasts generated by AI to anticipate a cloudy and windless day and dynamically switch from solar and wind-based production to alternatives, such as nuclear power, for an uninterrupted supply. AI can also forecast where a storm may hit and how long it may last, signalling the grid to scale up and diversify production in the event of damage to transmission lines.

If there is a broken transmission line or a power outage, the sensors and devices of the grid's IoT system can inform grid operators of the need for repair work and reroute electricity or retrieve it from a different source.

With traditional power grids, the impact of a storm could only be assessed in its aftermath. So living downstream from a broken power line has often meant being without electricity until that line was repaired. With the ability to find alternative solutions for electricity production and delivery, smart grids are more resilient and can reduce outages for consumers.



At Electricite de France (EDF), one of the world's largest producers of electricity, for example, some of the innovative smart grid technologies now under development include the use of 5G — the new generation of mobile Internet technology — to bolster the IoT and the development of more efficient hybrid networks for electrical currents. Blockchain technologies, which offer a highly secure way to track and handle transactions, are also being introduced to certify where and how much clean energy is being produced. EDF is using a method called 'digital twinning' to build virtual environments for predicting grid maintenance needs and reducing repair expenses.

"Our research and development on smart grids focuses on a range of challenges. We are also taking into account society's expectations for greener electrical infrastructure and preparing for risks, such as the impact of climate change, cyber risk and ensuring networks are resilient to potential crises," said Bernard Salha, Director of Research and Development at EDF. "Of course, any new method made possible by the increase in computing power will be tested on existing models to enhance their accuracy."

Assessing the impact of these technological advances is an essential part of the process, said Dian Zahradka, Senior Nuclear Safety Officer at the IAEA. "New technology is beneficial only if it's safe. In line with IAEA safety standards, any design modifications, including the use of AI and IoT technologies, undergo a rigorous safety assessment to evaluate any impact these changes and modernizations could have on nuclear power plants and how they interact with the power grid. The IAEA organizes technical meetings to discuss the potential implications and to share experience in the use of these technologies at nuclear power plants."

Grid inertia and nuclear power

Smart power grids allow for more energy sources to be actively connected and used dynamically. However, this has also opened the door for greater fluctuations in electrical frequency and therefore more instability.

A power grid operates at a specific frequency and is designed to stay within a certain range to ensure a steady supply of energy. Changes in frequency happen constantly as people turn electrical devices on and off. These are usually absorbed by an energy source's electricity-generating moving parts, such as a rotating turbine in a nuclear power plant or a fossil fuel plant.

This heavy, rotating mass can turn slightly faster or slower to act like a shock absorber, helping to balance out frequency fluctuations and buffer against rapid changes. The way these parts move and their influence on energy in the grid is called grid inertia.

However, renewable energy sources like solar do not have these moving parts. Other renewables that do have such moving parts, such as wind turbines, these moving parts are not directly connected to the grid but operate through a frequency converter, which means they do not have the necessary grid inertia.

"Without inertia, the grid has a limited ability to absorb fluctuations and can become unstable," said Shannon Bragg-Sitton, National Technical Director of Integrated Energy Systems at Idaho National Laboratory in the United States. "It also becomes particularly vulnerable to big changes, such as a sudden disconnect of an energy source, a large change in net load or a severe transmission event. These changes could cause sudden overloads or shortages of electricity and possible eventual electricity blackouts. Nuclear power can assist in meeting this challenge and provide some of the stability required to the grid."

The IAEA supports countries in assessing electric grid reliability and resilience, including with the use of nuclear power, through publications, workshops and technical meetings. The IAEA also connects nuclear industry and grid system stakeholders, enabling them to exchange information, present good practices and discuss common challenges and opportunities. These activities help countries to chart out their energy strategies towards achieving energy security and sustainability.

Investing in the clean energy transition

Financing and economic support for nuclear power

By Shant Krikorian

Innovative financing and market policies are one way that investment in new build nuclear power plants is becoming more attractive, which may help to pave the way for a clean energy future.

Nuclear power — which produces no greenhouse gas (GHG) emissions during operation — has been widely recognized by many countries for its important role in reducing GHG emissions and mitigating climate change. Its flexible and continuous stream of energy can also supplement supplies when other energy sources, such as variable renewables like wind or solar are not available.

Despite these benefits, one of the biggest challenges with adopting nuclear power is economics. While the economics of nuclear power from today's fleet remains competitive in many markets, financing a new plant has high up-front capital expenses and requires long-term investment.

"The energy market is changing and has become more unpredictable in many countries because they are diversifying their energy sources in order to decarbonize, which has led to more fluctuations in energy prices and supplies," said Wei Huang, Director of the IAEA's Division of Planning, Information and Knowledge Management. "This more volatile market is contributing to the uncertainty of committing to long-lived, capital-intensive technologies with large upfront costs, like nuclear power."

Innovative approaches to financing and market policies in the nuclear industry can help mitigate uncertainty and counteract market fluctuations, said Maria G. Korsnick, President and CEO of the Nuclear Energy Institute. Advances in technology are also helping to make nuclear power a more cost-effective option (see page 14).

"For nuclear to achieve its full potential in a low carbon energy future, nuclear power plants must receive appropriate compensation for the clean energy attributes and other benefits that are inconsistently valued across electricity markets," Korsnick said. "Policymakers should pursue approaches that build upon the growing consensus that including nuclear energy is the most cost-effective way to quickly transition to a clean electricity system. This means prioritizing the preservation of existing nuclear energy assets and creating a pathway for the construction of advanced nuclear energy facilities."

According to the International Renewable Energy Agency, the world's total, direct energy sector subsidies are estimated to have been at least US $634 billion in 2017. These were largely dominated by subsidies to fossil fuels and renewable power generation technologies.

Encouraging nuclear investments

Power purchase agreements (PPAs) have been used for a range of technologies for decades, but they are now gaining ground in nuclear power as the most widely used approach for decreasing uncertainty and securing long-term revenues from a new nuclear power plant project. These agreements are made between the project implementers and the purchasers of the nuclear power plant, with the aim of agreeing on a price for a specific amount of electricity for a specific, usually long period of time, which often covers the full cost of the project plus a margin. PPAs are also generally complemented by other forms of support through governments and vendors as well as innovative nuclear power financing schemes, such as 'contracts for difference' and 'build, own, operate', which are designed to reduce risk and attract investments.

The Akkuyu nuclear power plant project in Turkey, for example, has used PPAs as well as government and vendor financing and loan guarantees.

"The Akkuyu nuclear power plant combines a PPA covering the project cost with vendor financing from 'Rosatom', Russia's State Atomic Energy Corporation, which will build, own and operate the plant. This gives all entities involved the stability and assurance in knowing the price of electricity and various investments are secure," said Anton Dedusenko, Deputy Chairman at Akkuyu Nuclear's Board of Directors. "The security provided by this PPA has opened the way for discussions with potential investors to take up to a 49% equity stake in the project. Such a large investment is usually attractive when there are reassurances and certainty about the plant's future revenues, and that's what the PPA is able to provide."

Carbon pricing

With an eye on a clean energy future, government policies to support low carbon electricity generation have materialized as direct subsidies, feed-in tariffs, quota obligations and energy tax exemptions.

One of the approaches being widely adopted is carbon pricing, which aims to reduce emissions and incentivize the use of low carbon energy sources. This also helps to make these energy sources a more competitive and stable option against the low cost of fossil fuels.

Carbon pricing in its simplest form is a per-tonne levy on carbon dioxide emissions from, for example, electric power stations and industrial boilers. Under a carbon pricing scheme, a factory using fossil fuels and releasing large amounts of carbon dioxide would pay more than a factory using low carbon energy sources and releasing fewer emissions.

"A carbon price is set based on the estimated cost of GHG emissions, such as the cost of damage to people's health and the environment," said Henri Paillere, Head of the IAEA's Planning and Economic Studies Section. "The aim is to shift the burden of damage caused by carbon dioxide emissions back to the source responsible as a way to encourage the use of low carbon energy sources to ultimately reduce GHG emissions."

In the case of nuclear power, a carbon price can also make it more competitive to operate than fossil fuels, especially in the long run, because of the savings on emissions. By stabilizing the price, some of the uncertainties of investing in nuclear power are also reduced.

"Low carbon technologies such as nuclear, but also hydro and variable renewables, require such a carbon price to remain competitive against fossil fuels, especially when the price of fossil fuels falls," said Jan Horst Keppler, Senior Economic Advisor at the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA). "But over the long term, governments have to convince project developers and investors that they are serious about implementing stable or rising carbon prices."

As countries explore financing and policy options, the IAEA's activities in energy planning help them navigate this process. The IAEA carries out surveys of existing financing models, as well as organizes expert meetings and publishes comprehensive reports on the costs and benefits of nuclear power based on successfully completed projects.

"Ensuring the continued operation of existing nuclear power plants and accelerating the deployment of new ones can be challenging in a volatile energy market," Paillere said. "Government institutions need to continue to recognize the role nuclear power plays as key to sustainable development and clean energy generation."

Safety and licensing of small modular reactors

A technology-neutral approach

By Miklos Gaspar

Small modular reactor simulator control room by NuScale Power.
(Photo: Energy Northwest)

Small modular reactors (SMRs) may be smaller and use innovative technologies with many inherent safety features, but the ultimate goal when it comes to regulation remains the same: ensuring the protection of people and the environment and minimizing the risk of accidents and radioactive releases.

The novel approaches in the design and deployment of SMRs can pose challenges to existing regulatory frameworks. In comparison to existing reactors, SMR designs are generally simpler and the safety concept for SMRs relies more on passive systems and inherent safety characteristics of the reactor, such as low power and operating pressure. These increase safety margins and, in some cases, practically eliminate the risk of severe damage to the reactor core and thus the potential for large releases of radioactivity in the event of an accident. Consequently, the reliance on robust containment and emergency response measures is reduced.

“SMRs are in general less dependent on safety systems, operational measures and human intervention than existing reactors. Therefore, the usual regulatory approach, which is based on overlapping safety provisions to compensate for potential mechanical and human failures, may not be appropriate and new ideas should be considered,” said Greg Rzentkowski, Director of the Division of Nuclear Installation Safety at the IAEA. However, the main concepts underpinning the current safety approach — such as, for example, defence in depth, which assures prevention and mitigation of accidents at several engineering and procedural levels — are relevant for SMRs if implemented using risk and performance information, he added.

To demonstrate the safety of the design of a nuclear power plant of any kind, a comprehensive safety assessment of all plant states — normal operation, anticipated operational occurrences and accident conditions — is required. On that basis, the capability of the design to withstand internal and external events can be established and the performance criteria for safety features, including emergency planning, can be defined.

“The proof of concept for SMRs requires the demonstration of the effectiveness of the fundamental safety functions — reactor control, core cooling and confinement of reactivity — based on the optimization of the defence in depth strategies to minimize the risks of accidents and, should an accident occur, practically eliminate its consequences," Rzentkowski said. Given new design and safety concepts, specific consideration should be given to the validation of the safety case, interfaces between units, material properties and human factors. Furthermore, no matter how low the risk of accidents is, scalable arrangements for confinement and emergency response are essential to cover the unexpected, he added.

Technology-neutral framework

As the concepts and designs of innovative technologies, including SMRs, are technologically diverse, the IAEA is working on the establishment of a technology-neutral framework for safety to help harmonize international approaches on the basis of existing IAEA safety standards.

Such a technology-neutral framework consists of a general part — hierarchy of societal and health objectives, risk targets and high-level safety principles and requirements — which can then be elaborated upon in national frameworks to address regulatory and technical elements depending on the specific technology used. This approach allows flexibility and achievement of a balanced combination of innovation and proven techniques, which is required to optimize protective and mitigation measures against general safety objectives and specific risk targets, Rzentkowski added.

Some countries are already actively working in this area. For example, Canada is one of a handful of countries, along with Argentina, China, Russia and the United States, performing regulatory reviews of SMRs.

"The Canadian Nuclear Safety Commission's (CNSC) technology-neutral regulatory framework, which is largely based on IAEA safety standards, enables novelty and innovation in reactor design, construction, operation and decommissioning, without compromising safety," said Hugh Robertson, Director General of the CNSC. "In cases where there are uncertainties in design safety margins and operational experience is limited, additional operational controls may be required. In these cases, the protective measures will be commensurate with the risk."

Collaboration between nuclear regulators and the harmonization of regulatory requirements can benefit all parties involved, he added. "This ultimately makes for a more efficient and effective licensing process. In fact, having multiple sets of eyes looking at the common safety issues can result in an increased level of safety. The same scientific and regulatory information can also be used that respects regulatory sovereignty, as we continue to explore further opportunities for harmonization."

Case studies to demonstrate safety

Although the IAEA safety standards — which serve as a global reference for protecting people and the environment from the harmful effects of ionizing radiation — are generally technology neutral and can be applied to SMRs, the IAEA will further support national regulators by developing specific guidance to provide for their implementation. "Case studies to demonstrate how the design requirements for nuclear power plants can be used to license the two most common SMR technologies, water cooled and high temperature gas cooled reactors, have already been completed," Rzentkowski said.

In parallel, work is under way at the SMR Regulators' Forum to share regulatory knowledge and experience and identify good practices. Hosted by the IAEA, the Forum is made up of an international group working on the challenges of regulating the novel designs of SMRs, in order to define new safety recommendations for SMRs. These recommendations are now available on the IAEA's website, following a meeting on the development of national standards specific to SMRs. The Forum's work concentrates on the multi-modular nature of SMRs and on the safety aspects of the interdependency between the modules to verify that if something were to go wrong in one module, its impact on the other modules would be minimal.

"Recognizing that safety will always remain the number one priority, the regulatory approach for SMRs requires a shift in focus from one reactor at a time to the global safety assessment of the robustness of design, the completeness of the safety case, and the adequacy of the processes undertaken to ensure safety throughout the reactor lifetime to avoid building first and fixing safety issues later," Rzentkowski said.

Evolving for the future
Safeguards and nuclear power

By Adem Mutluer

As nuclear power technology continues to evolve, the number of nuclear facilities increases and the amount of nuclear material grows around the world, safeguards technology needs to keep pace to stay effective. Safeguards are a set of technical measures to verify that nuclear material and technology are used for peaceful purposes only and are not diverted to make nuclear bombs.

"Artificial intelligence, additive manufacturing and distributed ledger technology are some of the changes on the horizon that may impact the implementation of international safeguards," said Chad Haddal, Safeguards Outreach Coordination Officer at the IAEA. "With the development of advanced means of nuclear power production, it is also a requirement that safeguards continue to be adapted to ensure continuous and effective safeguards verification."

Advances in technology are helping to make nuclear power production more sustainable, cost-effective, safe and secure. Reliable low carbon energy sources such as nuclear power have become increasingly important for many countries as they look for ways to decarbonize energy production and build a clean energy future.

"While nuclear power technology continues to develop, it is a requirement that safeguards are part of the plans," said Menekse Basturk Tatlisu, Safeguards Analyst at the IAEA. "States' safeguards agreements require that the IAEA can verify all nuclear material in their respective countries. To meet this obligation, States are required to provide design information for all nuclear facilities for which the IAEA can verify the use and amount of the nuclear material."

New and emerging tech

IAEA safeguards experts closely follow new and emerging technologies to stay abreast of developments and how they may influence their work. Part of this effort includes Emerging Technologies Workshops organized by the IAEA's Department of Safeguards, where international experts discuss and profile these technologies together with IAEA staff.

"Having experts profile new technologies with potential implications for nuclear power generation, and nuclear more generally, helps us understand how this could affect the safeguards mission and the environment in which we will be conducting the mission in the future," said Haddal. "We look to both the advantages offered and challenges posed by new technologies. We are required to be aware of and adaptable to relevant technological developments in our external environment, and we do that by taking a proactive and forward-looking approach."

Applying and refining technology

One of the latest examples of new technology being developed by the IAEA is a set of learning-based algorithms known as neural networks. These computer-operated networks are loosely based on the associative memory of the human brain and are designed to progressively learn, analyze, and identify patterns to help understand data.

In safeguards, analysts review large quantities of data collected through video surveillance. In 2019, 1,425 surveillance cameras were maintained by the IAEA at nuclear facilities around the world. These cameras operate around the clock. They provide continuity of knowledge of nuclear material and allow safeguards inspectors to make sure that there is no undetected access to the material and no undeclared operation of the facility. With some facilities using multiple surveillance cameras, this can produce a vast amount of data.

Using neural networks that could be developed through artificial intelligence and machine learning could help safeguards inspectors identify nuclear material movements and other safeguards-relevant activities at a facility. These technologies could also identify the most relevant indicators to assess and track objects and identify unexpected objects and behavior. This would allow analysts to use their time more effectively and efficiently when reviewing surveillance data.

Built-in safeguards

As technology opens new doors for effectively using nuclear power, experience has shown that it is best to design new facilities with safeguards in mind from early on.

"Building in safeguards considerations from the ground up is a win-win for a country, the operators and IAEA safeguards," said Basturk Tatlisu. "By including safeguards considerations early in the designs of new nuclear power facilities and processes, it can further ease the safeguards verification process for operators, as well as IAEA safeguards inspectors."

For example, by designing the fresh fuel storage, reactor core and spent fuel storage at a new nuclear facility with safeguards in mind, it can make safeguards implementation more cost-effective and efficient while minimizing the impact on nuclear facility operations.

Countries can turn to the IAEA's safeguards by design series of documents to find guidance and advice on which safeguards factors to consider when, for example, designing a new nuclear reactor, upgrading or constructing a nuclear facility, and setting up a long-term spent fuel management facility. The series provides advice for authorities, designers, equipment providers and prospective purchasers to make informed choices, while also building in the economic, operational, safety and security factors related to designing a nuclear facility.

"The safeguards by design series aims to help countries strike the optimal balance of cost, legal requirements and operational efficiency," said Basturk Tatlisu. "When developing all aspects of the nuclear fuel cycle, from initial planning to decommissioning, safeguards by design should be considered."

Safeguards inspectors setting up a surveillance camera.

(Photo: D. Calma/IAEA)

Driving deeper decarbonization with nuclear energy

By Kirsty Gogan and Eric Ingersoll

Kirsty Gogan is co-founder and Executive Director of Energy for Humanity, an environmental NGO focused on large scale deep decarbonization and energy access.

Eric Ingersoll is Chief Technology Officer at Energy for Humanity and a strategic advisor and entrepreneur with deep experience in the commercialization of new energy technologies.

The world is far off track when it comes to meeting the Paris Agreement climate goals of limiting the global temperature increase by 1.5°C to 2°C by 2050. Current projections show that fossil fuels will still make up the majority of world energy use by 2050.

If we miss the 1.5°C target, this could mean accepting climate impacts, such as millions of people being displaced by sea level rise and millions more being exposed to extreme heatwaves, as well as major biodiversity-related impacts, including species loss, the elimination of sea ice in the Arctic Ocean, and the loss of virtually all coral reefs.

If we miss the 2°C target, half the world's population could be exposed to summertime 'deadly heat,' Antarctic ice sheets could collapse, droughts could increase massively, and the Sahara Desert could begin to expand into southern Europe. World food supplies could be imperilled, driving mass human migration and leading to a growing risk of civilizational collapse.

Current energy pathways, even those that include a vast expansion of renewables generation, are pushing the world towards catastrophic climate outcomes, with a high risk of a 4°C outcome. This could mean substantial areas of the planet becoming uninhabitable.

The Clean Energy Ministerial Flexible Nuclear Campaign we co-founded explores the expanded role that nuclear energy can play in de-risking the energy transition. Here, we describe two opportunities to drive deeper decarbonization with nuclear energy.

The first is to expand the role of nuclear energy in electricity production through a combination of advanced reactors and thermal energy storage. This is intended to complement renewables in future energy grids.

The second is to address the use of oil and gas, which currently accounts for three quarters of energy consumption, by providing large-scale, low-cost hydrogen produced with nuclear power.

To achieve the necessary cost, scale and rates of nuclear energy deployment, a new paradigm is needed. The nuclear industry must apply commitment and creativity, combined with technical and business innovation, just as the renewables industries learned to do.

How could a high-volume, low-cost, rapidly deployable and commercially attractive manufacturing model enable nuclear technologies to contribute to zero emissions and sustainable energy for all by 2050?

Flexible nuclear in future electricity grids

Our recent study on cost and performance requirements for advanced nuclear plants, as part of ARPA-E's MEITNER Program in the United States, defines market requirements for advanced reactor developers seeking to design useful and cost-competitive products for commercialization in the early 2030s.

Our study identifies price and performance characteristics that will be required for nuclear plant owners and investors, as well as for society at large, to achieve affordable, reliable, resilient, flexible and — above all — clean future electricity systems. Our findings show that there will be large markets for advanced reactors that cost less than US $3,000/kW. Combining nuclear plants with thermal energy storage enables nuclear to be a peaking resource — creating additional valuable energy storage — and added value for the energy system. For grid operators, energy system modellers and policymakers this shows the value of flexible nuclear technologies, not only in lowering emissions, but also in lowering total costs across the whole energy system.

Hydrogen-enabled synthetic fuels

To achieve the scale and pace of emissions reduction required, alongside increased global energy access and economic growth, zero- and carbon-neutral fuel substitutes need to achieve price and performance parity with fossil fuels.

Emissions-free nuclear hydrogen production can be cost-competitive with other zero-carbon dioxide (CO2) production methods and has the potential to be cost competitive with steam methane reforming of low-cost natural gas (Allen et al. 1986; BloombergNEF 2020; Boardman et al. 2019; Gogan and Ingersoll 2018; Hydrogen Council 2020; IEA 2019b; NREL 2019b; M. Ruth et al. 2017; Yan 2017). Even expensive first-of-a-kind conventional nuclear plants in the European Union and the United States can produce clean hydrogen at costs comparable to today's wind and solar resources, with good capacity factors.

Large-scale, low-cost clean hydrogen could enable decarbonization of aviation, shipping, cement production and industry, if it's competitive with cheap oil. We estimate this target price to be US $0.90/kg.

Current projections for renewables-generated hydrogen are estimated to be as low as US $2 by 2030, and even less by 2050. Price reductions are constrained by low capacity factors even though we expect capital costs for renewables to continue to fall.

Nuclear plants today could deliver clean hydrogen for below US $2/kg and a new generation of advanced modular reactors could achieve US $0.90/kg, potentially by 2030.

To drive a massive increase in clean hydrogen production, the nuclear industry will need to transform project delivery and deployment models in order to scale up and deliver clean heat, fuels and power. This will require the same intensity of focus on cost reduction, performance improvements and deployment rates that have enabled renewables to begin transforming the global energy system.

Steep, near-term cost reduction is achievable by shifting from traditional construction projects to high-productivity manufacturing environments, such as shipyards, or 'hydrogen gigafactories', which are next generation refineries located on brownfield sites, such as large coastal oil and gas refineries.

Moving from traditional construction to high-productivity manufacturing of advanced reactors will dramatically lower the cost of clean hydrogen and synthetic fuel production. Leading shipyards already have extensive manufacturing capacity, which can produce designed-for-purpose hydrogen production facilities.

Gigafactories and shipyard-manufactured offshore nuclear power plants could put the world back on track to meet 1.5/2°C Paris Agreement goals. This massive decarbonization effort can be achieved with very little land take, allowing large areas of land to be spared for rewilding and regeneration of natural ecosystems, unlike the 'energy sprawl' associated with country-sized renewables industrial developments.

Using these delivery models, the three-decade transition from 100million barrels of oil consumed per day today to an equivalent flow of clean substitute fuels can be achieved at a much lower cost: instead of US $25 trillion required to maintain oil flows until 2050, the clean energy substitute fuels would cost US $17 trillion. This contrasts further with the US $70 trillion for a renewables-only strategy.

Nuclear energy, through these transformed delivery models, can decarbonize the economy at a cost lower than that required to maintain fossil fuels. However, this transition will not begin without urgent action by governments and other actors to bring down costs and accelerate innovation and deployment. Nuclear energy needs to be brought fully into the world's decarbonization efforts.

Streamlining storage
IAEA conducts training in radioactive waste management in Africa

Trainees watch as an IAEA expert removes a disused source — previously deployed in an industrial context — during the hands-on exercise.
(Photo: O. Yusuf/IAEA)

The appropriate processing, conditioning and storage of disused sealed radioactive sources (DSRSs) is essential to ensuring the safety and security of people and the environment. These activities, however, can be challenging, particularly for countries that do not yet have domestic know-how in this area. Therefore, the IAEA has supported the development of an approach to DSRS management that is simpler and more cost-effective for countries with relatively few DSRSs. An IAEA training course held in Kampala, Uganda, in 2020 used this new approach for the first time.

The approach involves a facility that provides all the necessary elements for the processing, conditioning and storage of low activity, neutron- and gamma-emitting sources, of the type typically used in industry and medicine. Called the '2 ISO Container' concept, the facility comprises two standard shipping containers — placed in close proximity to one another — equipped with the appropriate ventilation, contamination control, safety and security infrastructure. One container serves as a processing and conditioning facility, while the other provides for the receipt and interim storage of low activity DSRSs and then of the conditioned sources.

The facility and its procedures have benefitted from an international peer review. A panel of international radioactive waste management experts — from Germany, Ghana, Morocco and the United States — was convened to observe the functioning of the 2 ISO Container facility as well as the IAEA training course itself. The experts also reviewed the facility and the technical procedures of waste management — from initial receipt to eventual storage — in order to assess the approach against all relevant international standards and best practices. These efforts, financially supported by the European Union, are part of a broader IAEA initiative under the African Regional Cooperative Agreement for Research, Development and Training Related to Nuclear Science and Technology (AFRA), which is focused on providing support to African countries in strengthening their legal and regulatory infrastructures for nuclear safety and security. Use of the facility with active radioactive sources will need to be licensed by the national regulatory body in each country. In Uganda, this had been done prior to the training course. "This approach was implemented in line with the IAEA safety standards," said Deogratias Sekyanzi, CEO of Uganda's Atomic Energy Council, the country's regulator.

Some countries, such as Cameroon, have well advanced plans for using shipping containers for the storage of DSRSs, but in other countries, the safety of this method has not yet been demonstrated. Under a new technical cooperation project, launched in 2020, the IAEA is working to increase the capabilities of national organizations to demonstrate the safety of storage, explained David Bennett, a waste safety specialist at the IAEA.

The container and capsule approach

Once the facility has been constructed, the next step is to retrieve the radioactive sources from their devices in line with the requirements and guidance outlined in the Code of Conduct on the Safety and Security of Radioactive Sources and the IAEA safety standards. At the heart of the proposed approach are technical procedures that local personnel must follow to recover the disused sources and condition them into a form suitable for storage. The procedures involve the use of a special capsule made from stainless steel into which the disused sources are sealed. The design of this capsule enables proper sealing without the use of specialized equipment, making it easy to handle in any country. Once sealed, the capsule containing the sources is placed inside a lead shield, which, in turn, is put in a concrete-lined barrel that serves as a package for DSRS storage and transport.

"A new facility of the type demonstrated in Uganda can be built on an area of less than 1,000 square metres and at an affordable cost," said Mohamed Al-Mughrabi, a senior IAEA expert.

Training Africa's radioactive waste managers

As part of its ongoing efforts to support the control of DSRSs around the world, the IAEA is organizing a series of hands-on training courses, delivered through the IAEA technical cooperation programme, including the construction, licensing and use of 2 ISO Container facilities. These training courses are expected to be conducted throughout Africa, particularly in countries where waste processing, conditioning and storage facilities do not yet exist.

Following demonstrations of the 2 ISO Container approach in Uganda, as well as in Cameroon, Senegal and Zimbabwe, and benefiting from the conclusions of an international technical peer review, plans exist to introduce the concept to more countries, including Cameroon, Ethiopia, Madagascar and Nigeria.

Project RAF9062, entitled "Strengthening Radioactive Waste Management (AFRA)", was conducted by the IAEA, with co-funding from the European Commission, Spain and the United States.

— By Omar Yusuf

Tastier and more nutritious vegetables
Bulgaria improves food quality with IAEA support

Nasya Tomlekova, professor at the MCVRI, and Iliya Valchanov, a grower of the newly developed varieties.
(Photo: MCVRI)

Bulgaria, one of the most biodiverse countries in Europe, has long been a major exporter of various food products. With gradually warming temperatures over the past decades, farmers have seen the yield and quality of key crops fall. To adapt to the changing environment and continue to provide healthy and sustainable vegetables, nuclear techniques are now being used.

"We are known for high-quality crops in Bulgaria, based on longstanding traditions in vegetable production throughout the country," said Nasya Tomlekova, Head of the Molecular Biology Laboratory at the Maritsa Vegetable Crops Research Institute (MVCRI) located in Bulgaria's second largest city, Plovdiv. "We now have more complex issues related to low production and the quality of the local varieties. We need to develop within this area and promote these products — using nuclear techniques, this is possible."

Current plant breeding programmes, supported by the IAEA in partnership with the Food and Agriculture Organization of the United Nations (FAO), are focusing on developing new pepper, tomato and potato varieties.

As of 2020, three pepper varieties will be made available to farmers over the next three years. One of them, Zlatna shipka, released in 2020, has a 7% higher yield than traditional varieties. In 2021, a Desislava pepper variety with higher yields and increased beta-carotene concentrations, the same amount found in a carrot, will be released. This is important, because high beta-carotene intake, which our body converts into vitamin A, is crucial for healthy skin and eyes as well as a strong immune system. A Toniko pepper variety to be released in 2022 will also have increased beta-carotene concentrations.

"Like every farmer, I have invested a lot of care and work in providing a healthy and high-quality harvest," said Yancho Valchev, one of the farmers involved in the pilot trials of the plant breeding programme. "We face many difficulties — climate change, vegetable diseases, insects and pests — but through these programmes we have been able to record higher yields and better quality in our crops."

"As a young person in my late 20s, I am interested in healthy food and healthy living, and as a farmer I am able to provide this through the new varieties," said Iliya Valchanov, another farmer involved in the programme. "Right now, such products are preferred in the local markets, especially by young people, who share an interest in healthy eating."

This is only the latest effort by the IAEA and the FAO to support agriculture in Bulgaria. Over the past 50 years, 76 crop varieties have been developed by Bulgarian specialists following their participation in IAEA training courses and research in the use of nuclear techniques for sustainable food production and food security (see The Science box).

"The fruitful collaboration between the IAEA, the FAO and the MVCRI will continue in the development of improved varieties of pepper, tomato and potato with high yields, improved nutritional quality and the ability to adapt to climate change, enhancing food security throughout the country," said Fatma Sarsu, a plant breeder and geneticist at the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture.

THE SCIENCE

What is mutation breeding?

Mutation breeding works through using nuclear technologies like X-rays or gamma rays to induce changes in plants for crop improvement. The seeds or cells of a plant are exposed to radiation, and scientists retrieve these new mutated plantlets or seeds and place them in a sterile medium to grow. As the plants grow, they are monitored and selected depending on characteristics such as growth, colour, nutritional value and heat tolerance. These selections continue to be monitored over a few generations, after which new lines and new varieties of plants are developed.

Nuclear techniques are used to speed up the natural process of evolution, and crop varieties with improved characteristics emerge.

There are now 18 gamma irradiation facilities in Bulgaria, allowing the country to continue working towards providing sustainable food for domestic consumption and maintaining strong exports. In the national irradiation facilities, mutant lines and varieties that have been developed and show desired characteristics are stored in the national gene bank, which holds 60 000 seed samples, or research institutions across the country for future use. Through the IAEA technical cooperation programme and coordinated research projects implemented in Bulgaria over the past 50 years, 76 crop varieties have been released. These are recorded in the FAO/IAEA Mutant Variety Database.

— By Carley Willis

With IAEA support, China's electron beam industry opens world's largest wastewater treatment facility

With a capacity to treat 30 million litres of industrial wastewater per day, the world's largest wastewater treatment facility using electron beam technology was inaugurated in China in June 2020. Built using technology transferred by the IAEA since 2010, the treatment process will save 4.5 billion litres of fresh water annually — enough to quench the thirst of 100 000 people each year.

Operating at the world's largest combed yarn importer, Guanhua Knitting Factory, in southern China, the plant uses electron beam technology to treat water polluted with industrial dye residues, whose molecules cannot be broken down using bacteria or chemicals. By using electron beam technology, these long and complex molecules in the wastewater can be decomposed and the treated water can be reused.

The textile industry in China, the world's largest textile producer, has traditionally used chemicals to treat wastewater. But with strengthened policies on environmental protection, the industry is turning to electron beam technology, which offers a highly efficient and environmentally friendly wastewater treatment method.

"Normally such wastewater would be treated through chemical processes which generate secondary waste," said Bum Soo Han, a radiation chemist at the IAEA. "Electron beam treatment is an eco-friendly and cost-effective method of wastewater treatment, as it saves treatment time and cost of chemicals, and there is no secondary waste generated."

It all started as an IAEA technical cooperation project in 2012, through which Chinese scientists developed a programme to treat wastewater with electron beams. The IAEA support included fellowships at existing facilities in other countries, a national training course and advice from visiting experts, who provided guidance on project development.

Seven electron accelerators treat printing and dyeing wastewater at Guanhua Knitting Factory.
(Photo: Nuclear and Energy Technology Institute, Tsinghua University)

"I pursued a fellowship in Hungary in 2013 through IAEA support," said Shijun He, Professor at the Institute of Nuclear and New Energy Technology (INET) at Tsinghua University. "Working in an international laboratory and taking part in training courses directly reflects on the current work we are doing."

In 2017, a pilot facility was built in Jinhua, a city 300 kilometres south-west of Shanghai, with a capacity to treat 1.5 million litres of wastewater per day from a nearby textile factory. Two years after the launch of this demonstration project, construction of a commercial wastewater treatment plant at the Guanhua Knitting Factory began. Constructed by CGN Nuclear Technology Development Company (CGNNT), a subsidiary of China General Nuclear Power Corporation (CGN), the new wastewater plant treats more than 30 million litres of wastewater per day through the operation of seven electron accelerators. "Over 70% of the wastewater that runs through this operation can be reused in the factory, up from the previous reuse rate of 50%. This means less water directly from the nearby river is needed for the operation of the factory, saving 4.5 billion litres of water every year," said Dongming Hu, general manager at CGNNT.

The success of this project has been widely shared with other industries in China, with a view to implementing the technology to treat increasing amounts of wastewater resulting from population growth and industrial and agricultural development. "We have a high amount of wastewater discharged in China and it is difficult to treat it with conventional technologies. But with electron beams, we can greatly improve the discharge water recycling rate," said He. Other demonstration projects are underway in Xinjiang, Hubei and Guangxi provinces. "We are working on implementing electron beam technology in a variety of different industries in China," said He.

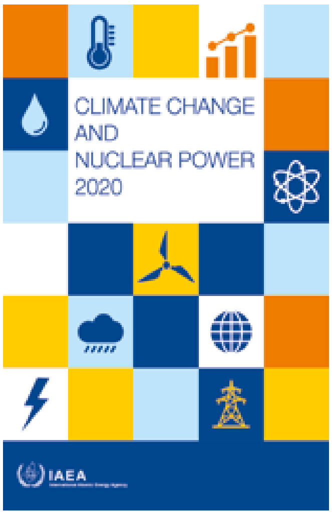
How it works

The textile industry consumes huge amounts of water and chemicals, such as dyes, starches, acids, salts and detergents, which are all discharged during the production process.

"Radiation techniques using electron beam technology can decompose the large amount of contaminants in the wastewater and remove these complex pollutants," said Han. In this process, an electron accelerator generates an electron beam capable of ionizing water molecules, thereby generating active radicals that react with the harmful organic contaminants found in the wastewater. These contaminants then degrade and become simpler chemical forms and are easier to treat through traditional methods.

"This project is a notable example of how a small amount of seed support from the IAEA technical cooperation programme and coordinated research projects can contribute to stimulating the emergence of a sustainable industry in a country," said Gashaw Wolde, who manages the IAEA's technical cooperation projects in China. "The result is cleaner, more efficient industrial processes that clearly have a socio-economic impact on a national scale."

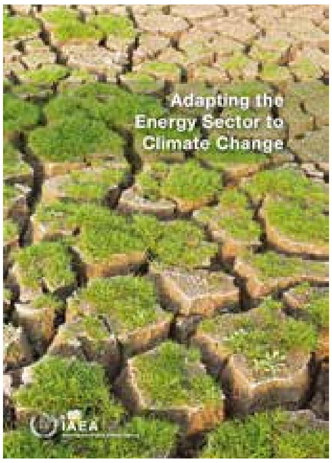
— By Carley Willis



Climate Change and Nuclear Power 2020

provides an update on the current status of nuclear power and prospects for its contribution, together with other low carbon energy sources, to ambitious mitigation strategies that will help the world limit global warming to 1.5°C in line with the 2016 Paris Agreement. Since 2000, the IAEA has issued such information and analysis regularly, in order to support those Member States that choose to include nuclear power in their energy system as well as those considering other strategies. The focus of the 2020 publication is on the significant potential of nuclear energy, integrated in a low carbon energy system, to contribute to the 1.5°C climate change mitigation target, and the challenges of realizing this potential. Energy system and market related factors affecting the transition to a low carbon energy system are reviewed. This edition also outlines developments needed to realize the large scale capacity increase required to rapidly decarbonize the global energy system in line with limiting global warming to 1.5°C.

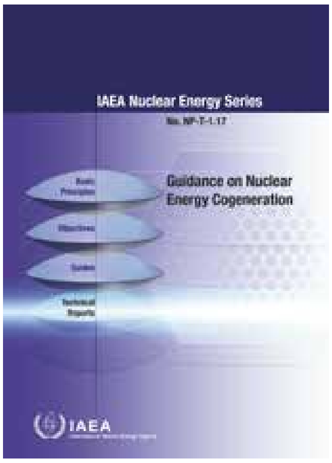
Non-serial Publications; ISBN 978-92-0-115020-2; English Edition; 28.00 euro; 2020



Adapting the Energy Sector to Climate Change

explores the diverse range of impacts on the energy sector resulting from gradual climate change and extreme weather events, and the potential ways to counter them. All elements of the supply chain are explored: resource base, extraction and transport of depletable energy sources, power generation, transmission and distribution. The publication includes three case studies which assess the energy sector vulnerability of Argentina, Pakistan and Slovenia.

Non-serial Publications; ISBN: 978-92-0-100919-7; English Edition; 40.00 euro; 2019



Guidance on Nuclear Energy Cogeneration

provides a quick introduction to the advantages, experience, and future planning for implementation of nuclear cogeneration. It also highlights some demonstration projects that were developed in the past in connection with industries, describing technical concepts for combined nuclear-industrial complexes. The publication is intended to be of interest to users in academia and industry as well as government agencies and public institutions requiring basic information on various aspects of using nuclear power for cogeneration.

IAEA Nuclear Energy Series NP-T-1.17; ISBN: 978-92-0-104119-7; English Edition; 32.00 euro; 2019

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