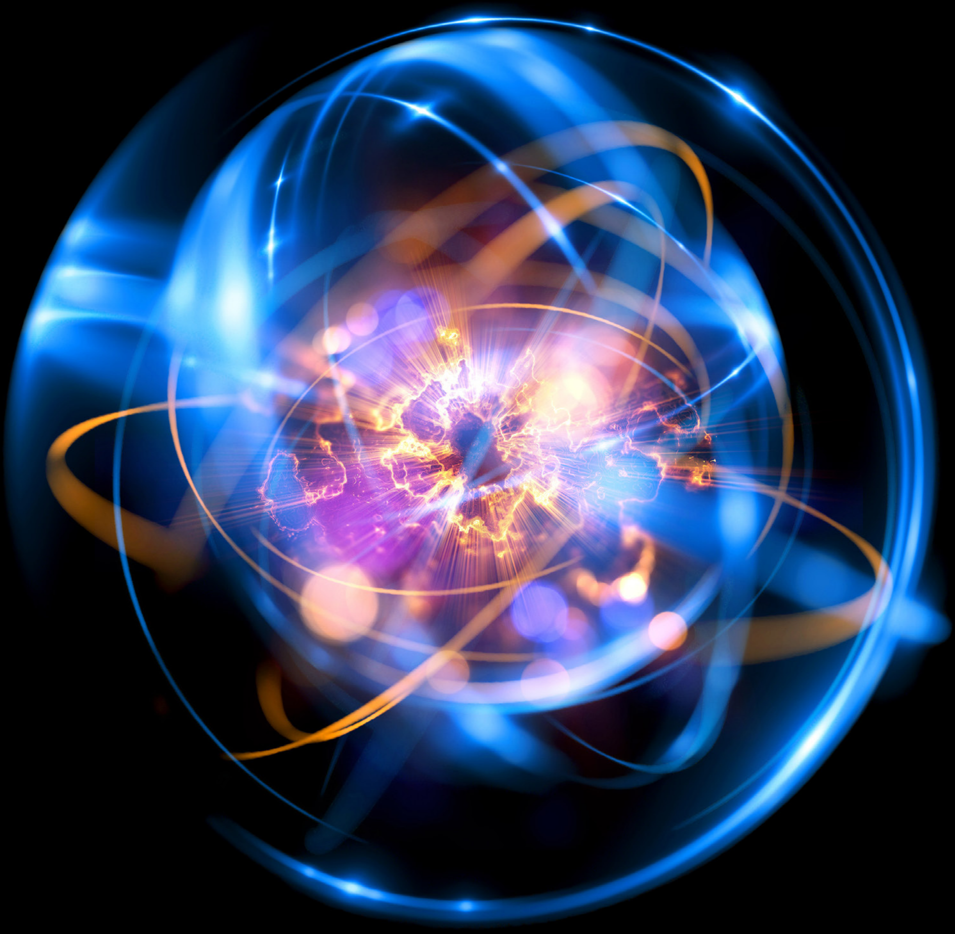
THE GLOBAL NUCLEAR MOMENT



VERSATILE ENERGY SOURCES FOR NET ZERO

EXECUTIVE SUMMARY

Nuclear fission boomed from the 1970s through to the early 2000s. However, in the wake of a series of reactor accidents — culminating in the 2011 Fukushima-Daiichi disaster in Japan — many governments started to rethink its role in the energy mix.

But the joint challenges of the energy crisis and the race to net zero have led to a re-evaluation of nuclear power — equipped with enhanced safety mechanisms — as an alternative source of dispatchable, affordable and CO_2-free energy.

This white paper will explore why nuclear is ideally placed to join renewables and low-carbon fuels to achieve pressing climate targets. It will also look at how existing and new reactors can be made systematically safer, applying learnings from the past, and how emerging technologies will raise the diversity and versatility of nuclear reactors.

INTRODUCTION: THE NUCLEAR REVIVAL

Nuclear energy, historically one of the largest global contributors of carbon-free electricity, has declined over the past couple of decades.

In the wake of the 1973 oil crisis, it boomed, offering energy security and independence as well as dispatchable, low-cost electricity.

The rise of nuclear power continued throughout the 1970s, '80s and '90s, despite setbacks such as Three Mile Island and Chernobyl, and questions over long-term waste storage.

This changed following the Fukushima-Daiichi nuclear accident in Japan in 2011, which led many countries around the world to scale back or even phase out nuclear energy production entirely.

A decade on, the combined pressures of a new energy crisis and the race to net zero have turned the spotlight back onto nuclear as an alternative source of dispatchable, affordable and CO_2-free energy.

Given its chequered past, reverting to nuclear is not straightforward. But policymakers, energy experts and the public's views are changing in favor of nuclear energy — in a new, safer, more agile guise.

THIS WHITE PAPER WILL EXPLORE:

- The benefits nuclear brings as a carbon-neutral energy source.
- The latest technological advances making nuclear more versatile, cheaper and safer.
- The ascent of nuclear fusion as a real-world alternative power source.
- What is required to deliver on the promise of nuclear energy as a safe source of carbon-free electricity that can provide much-needed energy security, and supply the world long into the future?

MHI IN NUCLEAR ENERGY

Mitsubishi Heavy Industries (MHI) Group has built all 24 pressurized water reactor (PWR) plants in Japan since 1970.[1]

In addition to building and maintaining PWR plants, MHI also provides services in almost all areas of nuclear energy, including nuclear fuel fabrication, intermediate storage of spent fuel (in casks) and fuel-cycle facilities.

MHI's commitment to achieving carbon neutrality by 2040 is in its MISSION NET ZERO declaration.[2] It lays out the company's internal decarbonization plans, working with clients and partners on decarbonizing existing infrastructure and implementing solutions ecosystems for both hydrogen and CO_2.

Nuclear energy is core to MISSION NET ZERO.

MHI will first strive to improve the safety of nuclear power plants by supporting the restart and operation of existing nuclear power plants, including the PWRs built by MHI and boiling water reactors (BWRs).

Looking ahead, MHI will be promoting the development and design of advanced light water reactors — set to achieve the world's highest level of safety — to be commercialized in the mid-2030s.

In response to the diversifying energy needs of society and with support from the Japanese government, MHI is developing: small modular reactors and microreactors as distributed power sources; high-temperature gas-cooled reactors for high-volume hydrogen production; and fast reactors for effective use of uranium resources, and to reduce the volume and radiotoxicity of high-level radioactive waste.

MHI is also developing fusion reactor technology as a perpetual energy source with its work on the international experimental reactor International Thermonuclear Experimental Reactor (ITER) project in France.

And MHI will continue to steadily advance efforts to complete the nuclear fuel cycle to ensure the reprocessing of spent fuel and effective use of uranium.

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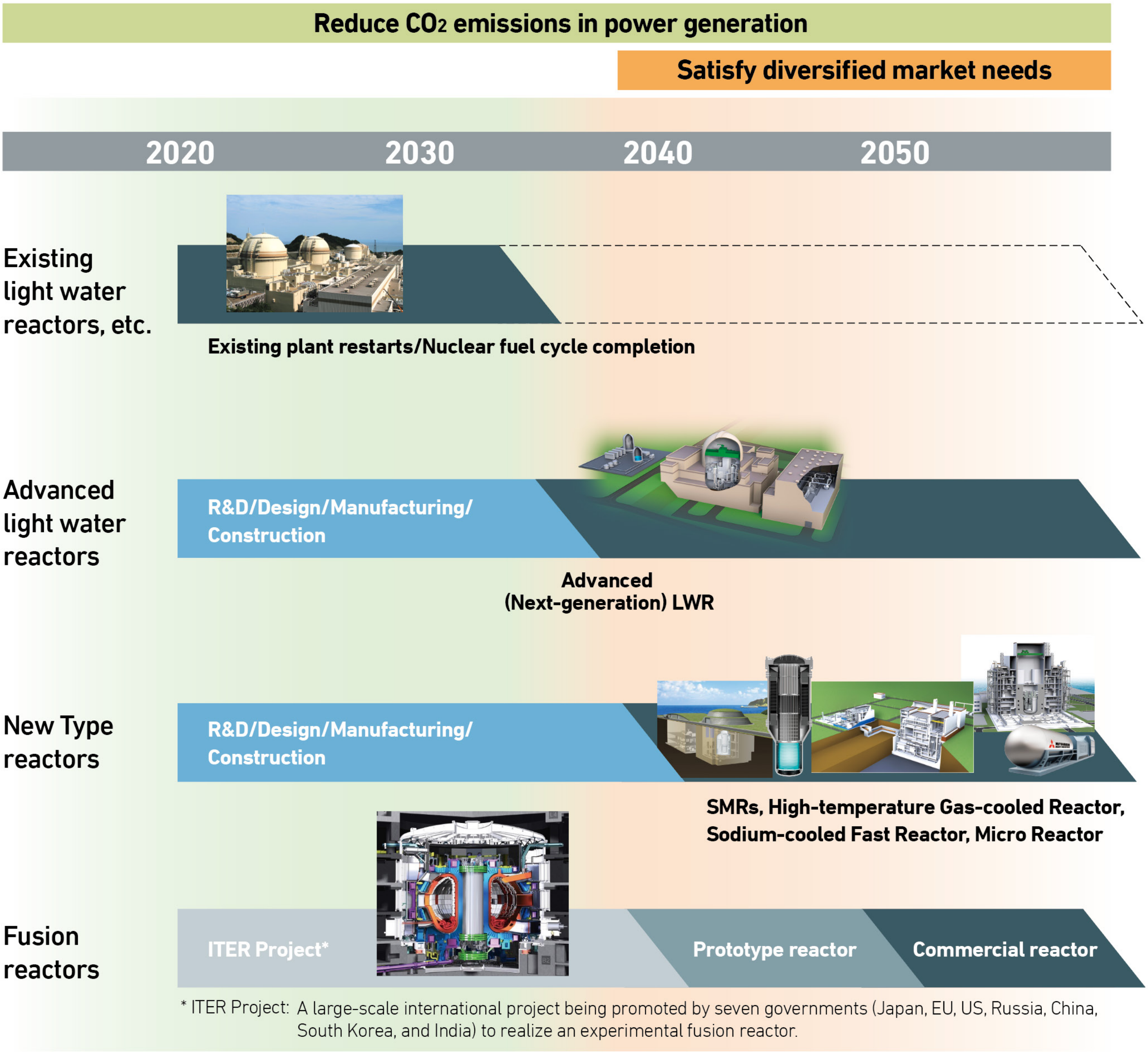
[1] Mitsubishi Heavy Industries (MHI)
[2] MHI

MHI'S NUCLEAR ENERGY ROADMAP



Reduce CO_2 emissions in power generation

Satisfy diversified market needs

2020 | 2030 | 2040 | 2050

Existing light water reactors, etc.

Existing plant restarts/Nuclear fuel cycle completion

Advanced light water reactors

R&D/Design/Manufacturing/Construction

Advanced (Next-generation) LWR

New Type reactors

R&D/Design/Manufacturing/Construction

SMRs, High-temperature Gas-cooled Reactor, Sodium-cooled Fast Reactor, Micro Reactor

Fusion reactors

ITER Project* → Prototype reactor → Commercial reactor

* ITER Project: A large-scale international project being promoted by seven governments (Japan, EU, US, Russia, China, South Korea, and India) to realize an experimental fusion reactor.

SECTION 1:
WHY NUCLEAR?

SECTION 1.1:
MEETING MULTIPLE ENERGY CHALLENGES

Much like the oil crisis propelled the rise of nuclear power in the 1970s, the ongoing energy crisis has been a major driver of revisiting nuclear as a power source for the future.

Unlike oil and gas, which depend on where deposits are located and mined, nuclear reactors can be rolled out virtually anywhere, without creating the same strong geopolitical dependencies. For example, there are widespread uranium supplies among a politically diverse range of countries, helping reduce the risk of supply disruptions.[3]

Other than the capital investment in construction — which can be up to 60% of the levelized cost of electricity (LCOE)[4] — nuclear energy offers low and stable costs over time.[5]

The other catalyst is the race to net zero by 2050 — or earlier in some regions — which a shift to renewable energy sources and energy efficiency measures alone cannot achieve.

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[3] World Nuclear Association

[4] The total cost to build and operate a power plant over its lifetime divided by the total electricity output dispatched from the plant over that period (cost per megawatt hour)

[5] World Nuclear Association

Even today, after a decade of declining use, nuclear power is the world's second-largest zero-emission power source after hydropower.[6] It provides carbon-free electricity, helping avoid 1.5 gigatonnes (Gt) of global emissions and 180 billion cubic meters of global gas demand annually.[7]

To this end, the International Energy Agency (IEA) has recently highlighted its "significant potential to contribute to power sector decarbonization".[8]

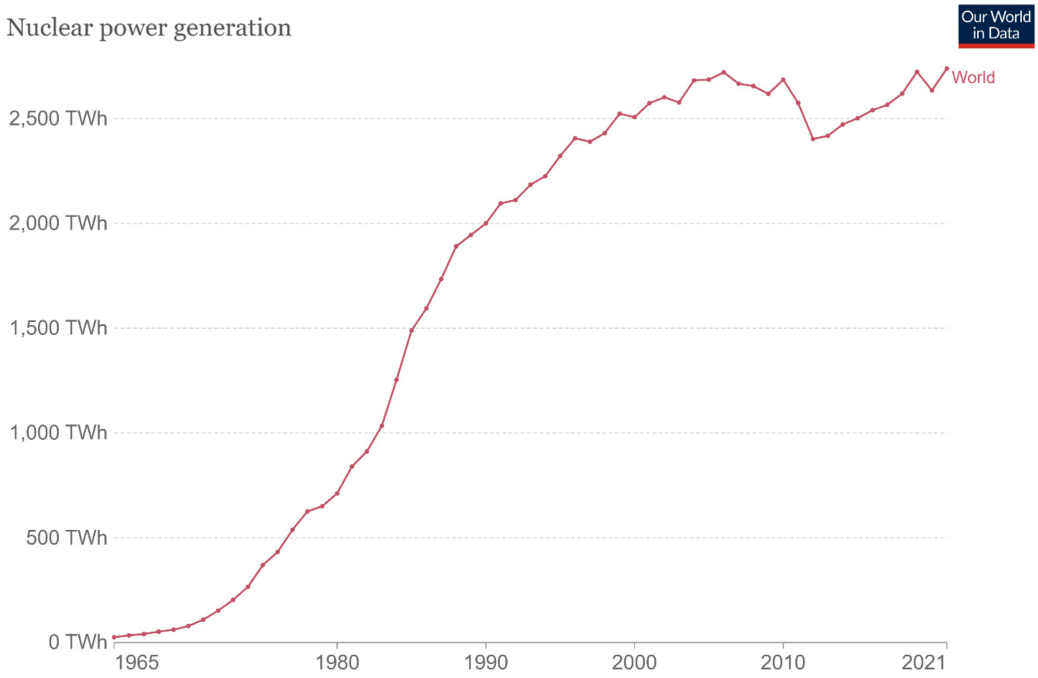
Nuclear offers dispatchable baseload power to step in at times of peak demand and cover for the intermittency of renewable energy sources. It can also supply electricity and heat to produce "pink" carbon-free hydrogen, which can then be used as an alternative to fossil fuels in industry and transportation.[9]

In essence, nuclear meets the tall order of providing energy independence and energy security that is carbon-neutral, affordable and dispatchable.

A CHANGING LANDSCAPE FOR POLICY

Nuclear's advantages for energy security and carbon-free electricity must be balanced against the perceived risk of nuclear reactors following a series of disasters in the preceding decades, as well as public concern over the safe storage of nuclear waste.

THE ASCENT OF NUCLEAR POWER GENERATION



Source: Our World in Data based on BP Statistical Review of World Energy & Ember

OurWorldInData.org/energy • CC BY

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[6] International Energy Agency (IEA)
[7] IEA
[8] IEA
[9] MHI

This is why, to this day, policymakers' and public attitudes vary greatly.[10]

Following the Fukushima-Daiichi accident in 2011, Japan scaled back on nuclear and shut down many reactors, but it reversed this decision in late 2022.[11] The nuclear closures led the world's third-largest economy to depend on fossil fuels (coal, oil and natural gas) for more than three-quarters of its power needs. In 2020, renewables covered around a fifth of electricity and nuclear 4% — down from 30% before 2011.[12]

But nuclear is now a key part of the country's energy strategy. Japan is extending the lifespan of existing reactors beyond 60 years and restarting reactors it had shut down in the wake of the Fukushima incident.[13] In 2022, nuclear's share bounced back to 8%.[14] By 2030, at least 20% of energy is to be supplied by nuclear reactors, in line with Japan's 6th Strategic Energy Plan.[15]

The Biden administration's Infrastructure Bill and Inflation Reduction Act include renewed support for nuclear energy, for example, keeping plants online for longer and subsidizing smaller, more flexible reactors.[16] Measures such as the $6 billion Civil Nuclear Credit Program support the continued operation of safe and reliable nuclear energy facilities,[17] underlining the vital role of nuclear in achieving 100% clean electricity by 2035 and a net zero emissions economy by 2050.

In the UK, "new nuclear" is considered vital to energy security and economic growth. There are plans for a total of eight large reactors to be built by 2050, two of which are underway. The UK is also investing in developing small modular reactors.[18]

France's support for nuclear energy never faltered but now it needs to upgrade its fleet.[19] Europe's biggest nuclear power generator plans to extend the lives of all reactors where it is safe to do so and build six new ones from 2028, with the potential for eight more by 2050.[20]

The European Commission eventually decided to include "advanced" nuclear technologies in its Net Zero Industry Act,[21] following deep divisions between both member states and commissioners.[22] Pro-nuclear France stood against Luxembourg and Austria, which opposed the law on principle.

China has been the biggest contributor to new global nuclear capacity since 2010.[23] It is expected to have the world's largest nuclear fleet by the end of the decade.

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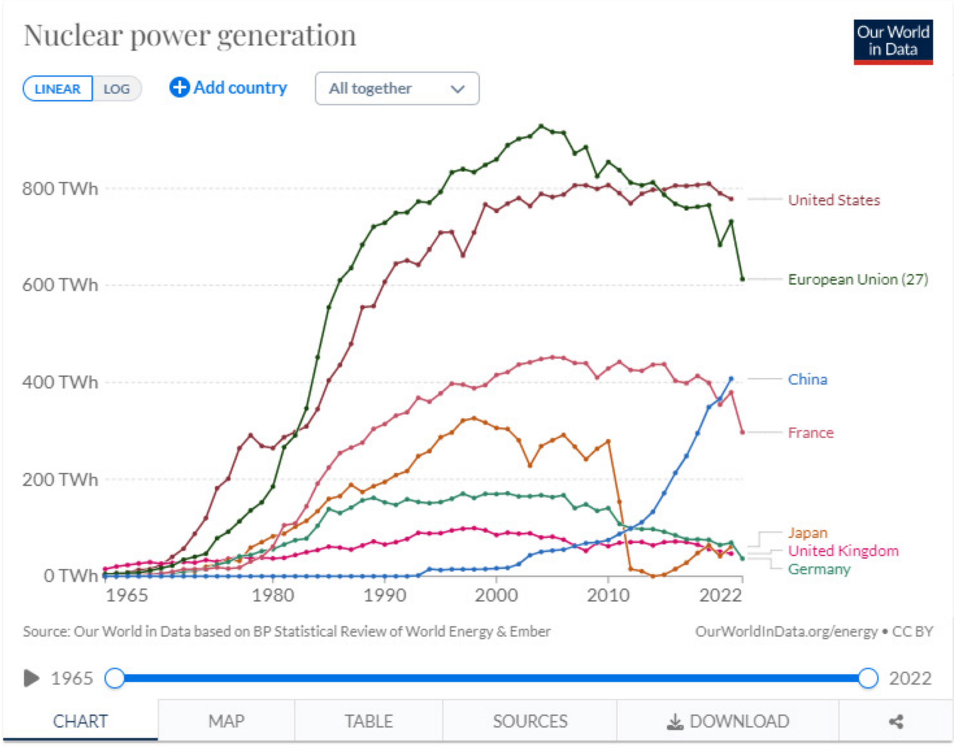
[10] Nucnet
[11] Financial Times
[12] Ministry of Energy, Trade and Industry (Japan)
[13] World Nuclear News
[14] Australia-Japan Research Centre
[15] Ministry of Energy, Trade and Industry (Japan)
[16] MHI
[17] US Department of Energy
[18] Department for Business, Energy & Industrial Strategy (United Kingdom)
[19] CNBC.com
[20] IEA
[21] Euractiv.com
[22] Financial Times
[23] The Oxford Institute for Energy Studies

In the ASEAN bloc, the Philippines, Indonesia and Vietnam have plans to move to nuclear power.[24] The ASEAN Centre for Energy has identified these countries, along with Malaysia and Thailand, as the region's nuclear power "front runners". And, in Singapore, a report commissioned by the Energy Market Authority anticipated that nuclear power could make up about 10% of its 2050 energy mix. ASEAN is one of the fastest-growing energy markets, and its member states need to balance growing energy needs and energy security with meeting net zero carbon pledges.

At the other end of the spectrum, Germany has stood firm on its decision to phase nuclear out completely. The country announced plans to decommission its nuclear plants in 2011 and put these into action. In 2022, some of the remaining reactors were kept online longer to tide Germany over during the energy crisis. However, as of April 2023, it no longer produces any electricity from nuclear power plants, a decision that has caused much controversy.[25]

At the same time, public attitudes are veering toward nuclear again, research shows.[26] Support for keeping reactors online for longer in Germany stood at close to 80% before their final shutdown, with over 40% advocating the construction of new nuclear power plants.[27] And, even in Japan, nuclear support is experiencing a steep rise.[28]

THE EVOLUTION OF NUCLEAR POWER GENERATION IN KEY MARKETS



Source: Our World in Data based on BP Statistical Review of World Energy & Ember

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[24] The Straits Times
[25] CNBC.com
[26] World Nuclear News
[27] Der Spiegel
[28] WNN

INNOVATION CHANGES THE PLAYING FIELD AND ADDS TO SAFETY

Another contributing factor to nuclear’s revival is advances in reactor technology.

To start with, there is a much greater breadth of technology choices and associated applications.

We most typically associate nuclear power generation with large-scale light water reactors (LWRs), which come with high upfront capital investments and are more suited to large-scale electricity grids.

Advanced options now include smaller, more versatile types of reactors such as small modular reactors (SMRs) and microreactors.

Alongside versatility, the economics for reactors are changing, with less costly options available for a wider range of end-users — beyond power generation — for example in industry and transportation.

Nuclear reactors are also discovering a new lease of life in alternative fuels, by stepping in to drive the production of electrolytic hydrogen (often referred to as pink, purple or red hydrogen). This comes at a time when there is not enough renewable electricity available to produce sufficient amounts to meet current and future demand.

Reactor safety has also improved substantially — tighter regulation has raised the bar on design criteria in terms of plant safety.

And, with a series of advanced development initiatives underway, nuclear fusion is now closer than ever to being within reach, after nearly a century of experimentation.

SECTION 2: SCALING NUCLEAR TECHNOLOGY

Extending the life of existing nuclear power stations will be critical to dealing with the global energy crisis by way of cost-effective, accessible electricity.

Restarting or continuing to run old LWRs will require particular care and adaptation to ensure they are operated safely and remain stable.

At the same time, the underlying technologies need to be developed and modernized. This will begin with advanced LWRs and then branch out into a more diversified range of nuclear reactor technologies over the coming decades.

The ultimate target for the power industry will be nuclear fusion, which is expected to become commercially available this century.

Here we look at some of these technologies.

SECTION 2.1:

KEEPING THE GRID IN BALANCE — ADVANCED LWRs

Alongside extending the life of existing reactors, a new generation of advanced LWRs will emerge over the next decade or so to provide baseload electricity alongside varying degrees of renewable energies.

Since the Fukushima-Daiichi accident, significant improvements have been made to improve the safety of LWRs. Next-generation reactor designs reflect the goal that, however unlikely a major incident may be, effective systems are in place that reduce the probability of radioactivity being released. In this way, the impact of a potential accident on the plant site, its surroundings and the public can be limited substantially.

Advanced LWRs are envisioned as medium- or large-scale reactors for electricity generation that will, like their predecessors, primarily operate within large-scale electricity grids. Their output typically starts around 1000MWe.

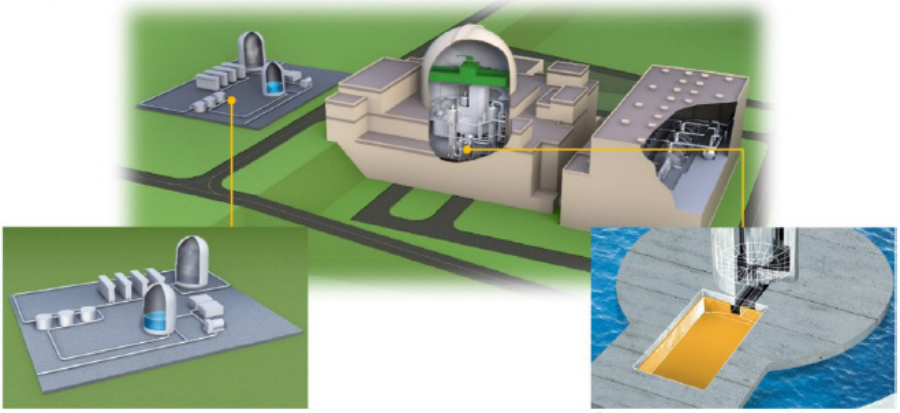
They will provide baseload power as centralized grid resources, contributing to carbon neutrality, affordability and a stable energy supply as demand continues to grow.

Unlike their predecessors, advanced LWR systems will also be more agile in terms of adjusting power output alongside variable electric power sources such as renewables or to cover peaks in electricity demand. They will also provide grid inertia, stabilizing the grid in the event of disturbances.

THE MHI SOLUTION: ADVANCED LWR “SRZ-1200”

Advanced light water reactor “SRZ-1200”

Carbon-free, large-scale, and stable power source that realizes world's highest level of safety and reliability



Radioactive material release prevention system

Confines radioactive materials and limits the impact of an accident to the premises

Core catcher

Protects the containment vessel, which is the final barrier, with measures against molten core

MHI’s Advanced LWR SRZ-1200 was designed in collaboration with four Japanese utility companies as a power source for existing grids.[29]

The SRZ-1200 will have a capacity of 1,200MWe and is set to achieve the highest levels of safety — and meet Japan’s new regulatory requirements — based on the lessons learned from the past, especially the Fukushima-Daiichi accident.

Its key design features[30] include:

1. RESISTANCE TO EXTERNAL THREATS

Seismic conditions in Japan meant designers gave particular consideration to seismic resistance. The reactor’s ability to withstand earthquakes is strengthened by embedding it in the chosen site’s bedrock. And, by raising the level of the site to an appropriate elevation, the potential effects of tsunamis can be mitigated.

Resistance to other natural disasters such as typhoons or volcano eruptions is significantly enhanced by making the building itself more robust and adding measures to prevent risks such as volcanic ash intrusion.

The design of the reactor containment vessel and shielding shells feature a double containment structure and toughened external shielding walls. This also strengthens their resistance to potential acts of terrorism such as a large airplane crash.

Cybersecurity is also enhanced to prevent electronic intrusion and protect equipment essential to the operation of the plant from external threats.

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[29] MHI

[30] MHI

2. CORE COOLING AND CONFINEMENT

MHI adopted new safety designs to enhance the resilience of core cooling and confinement.

A mix of active safety systems (which require electricity and human intervention), and passive safety systems (which operate automatically), enable both a rapid response and a quick recovery following an incident.

Safety redundancy has been improved by increasing the number of safety systems — from two, conventionally, to three — and through complete physical separation of safety-related areas.

A “core catcher” ensures that in the unlikely case of a core meltdown, the molten core is cooled and securely held within the containment vessel.

A radioactive-material release prevention system confines radioactive materials and limits the impact of a potential accident on the power plant itself.

3. WORKING IN CONJUNCTION WITH RENEWABLE ENERGY

The SRZ-1200 can adjust its output dynamically to changes in supply and demand thanks to improved load-following and frequency-control capabilities. This enhances the reactor’s ability to mitigate typical issues such as output fluctuations during night hours and stormy weather.

The unit achieves a stable supply of dispatchable electricity to stabilize the grid as the share of intermittent renewable energy sources expands. This makes it a reliable source of baseload energy but also an adjustable power source in a diversified, decentralized grid. In addition, any surplus energy generated can be used to produce pink hydrogen.

MHI is aiming to commercialize the SRZ-1200 in the mid-2030s.

SECTION 2.2:

GENERATING ENERGY WHERE IT'S NEEDED — SMR

In recent years, SMRs have been attracting attention as a distributed power source for decarbonization. Unlike their larger counterparts, they are aimed at small-scale grids and industrial applications.

While SMRs draw on the same technology as LWRs, they are scaled down in size and the main components within the reactor vessel are integrated. The power output is expected to be up to 300MWe. This is about a third of the capacity of a conventional reactor.[31]

Their small footprint means SMRs can be deployed in locations that would not be suitable for traditional nuclear power plants. They could be used to improve grid coverage in rural areas cost-effectively, for example, or provide electricity for industry, including industrial heat.

SMRs could also be used to generate pink hydrogen on-site or close to where end-users are based.

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[31] International Atomic Energy Agency

Given their compact size, SMRs could also be installed onboard ships to provide floating power generation to support local power grids and shortages.

In the future, SMRs will be standardized and can hence be prefabricated, shipped and installed easily, compared to the custom designs for conventional reactors. This also makes them more affordable and quicker to roll out.

They can also be deployed incrementally to match increasing energy demand, such as in remote areas.

Safety features typically focus on passive systems that require no human intervention as they rely on physical phenomena like natural circulation, convection, gravity and self-pressurization. Along with inherent safety characteristics, such as low power and operating pressure, this means the potential for radioactive leakage is significantly lower or even eliminated.[32]

More than 70 commercial SMR designs being developed around the world target varied outputs and different applications, with a small floating nuclear power plant already in operation. They are expected to become commercially available within this decade.[33]

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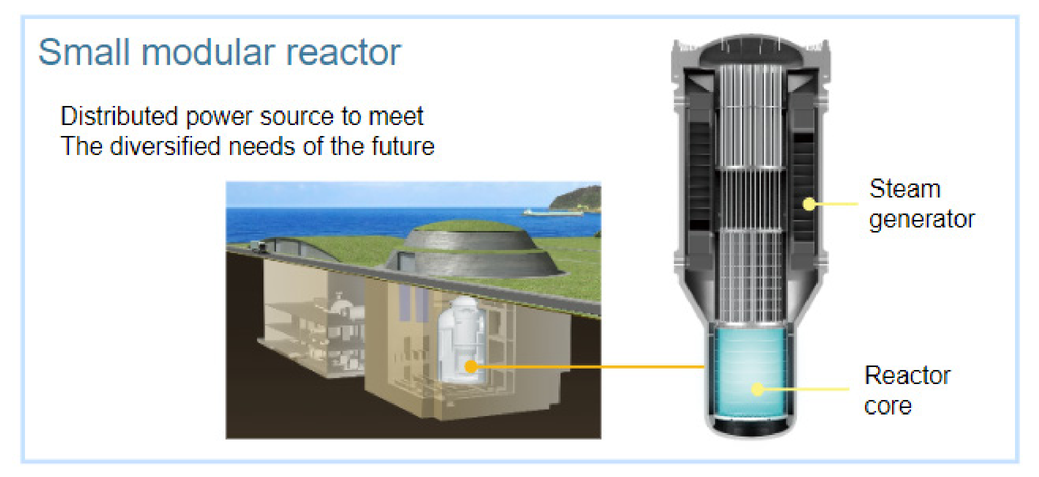
[32] International Atomic Energy Agency

[33] International Atomic Energy Agency

THE MHI SOLUTION: SMALL MODULAR REACTOR



MHI has been developing the core technologies for SMRs since the 2000s. This was initially through its work on an integrated modular water reactor (IMR) and then as part of the NEXIP nuclear innovation initiative by the Ministry of Economy, Trade and Industry (METI), which started in 2019.[34]

MHI's SMR model adopts an integrated reactor structure where the main components, including the steam generator, are built into the reactor vessel itself. This eliminates the need for primary coolant piping to link the main components.

The primary coolant can circulate naturally thanks to the density difference between coolant heated in the reactor core and coolant cooled by the steam generator. This means no primary coolant pump is required and, in principle, the risk of loss-of-coolant accidents can be eliminated.

Alongside, MHI's design adopts a passive safety system that requires no external power source and no human intervention during a potential accident.

The reactor and buildings will be located underground to strengthen resistance to external risks such as airplane crashes and natural catastrophes. Furthermore, a double containment structure enhances the confinement of radioactive materials in the unlikely case of an accident.

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[34] MHI

SECTION 3: NUCLEAR INTO THE FUTURE

Nuclear technology advances will not only enable reactors to be scaled but will also lead to a proliferation of applications that go far beyond their role in centralized energy grids.

SECTION 3.1:

MOBILE POWER ON LAND AT SEA AND IN SPACE — MICRO REACTORS

The growing versatility and footprint reduction of nuclear reactor technology will not stop at SMRs.

In the future, we will see nuclear reactor technology further reduced to the size of microreactors with output levels of up to around 10MWe.[35]

Like SMRs, they will be based on a simplified, integrated design, with the reactor core and power generation system designed to fit inside something the size of a shipping container.

These reactors will be small enough to transport on the back of a lorry and quick to install — only taking weeks instead of months or years compared to a large-scale traditional reactor.[36]

They are designed as portable, multi-purpose reactors that can greatly impact energy provision in challenging scenarios. These include powering microgrids in remote areas that cannot be linked easily to the

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[35] International Atomic Energy Agency

[36] US Department of Energy

national grid infrastructure. Isolated islands with no connectivity to the mainland grid could equally benefit from a microreactor, and they will also have a role to play when it comes to providing emergency power.

Their portability also means they could be used as a propulsion technique, not only in traditional shipping but also for space rockets. It's also conceivable a microreactor could be deployed to supply power for space stations.

THE MHI SOLUTION: MICRO REACTOR

MHI is developing a multi-purpose modular-type microreactor for use as a power source in remote islands and areas where power grids are less-developed or don't exist.

Its proprietary all-solid-state reactor employs an innovative safety concept that prevents coolant leakage into the environment and the associated factors that can cause accidents.

The reactor's compact size is achieved by using graphite-based materials, which have a lower density than metallic materials to reduce the reactor weight and downsize the core.[37]

The goal is for the reactor to be maintenance-free and with a long operating lifecycle. It should be operable remotely or run autonomously, without frequent refueling.

MHI expects the first microreactors to ship in 2040.

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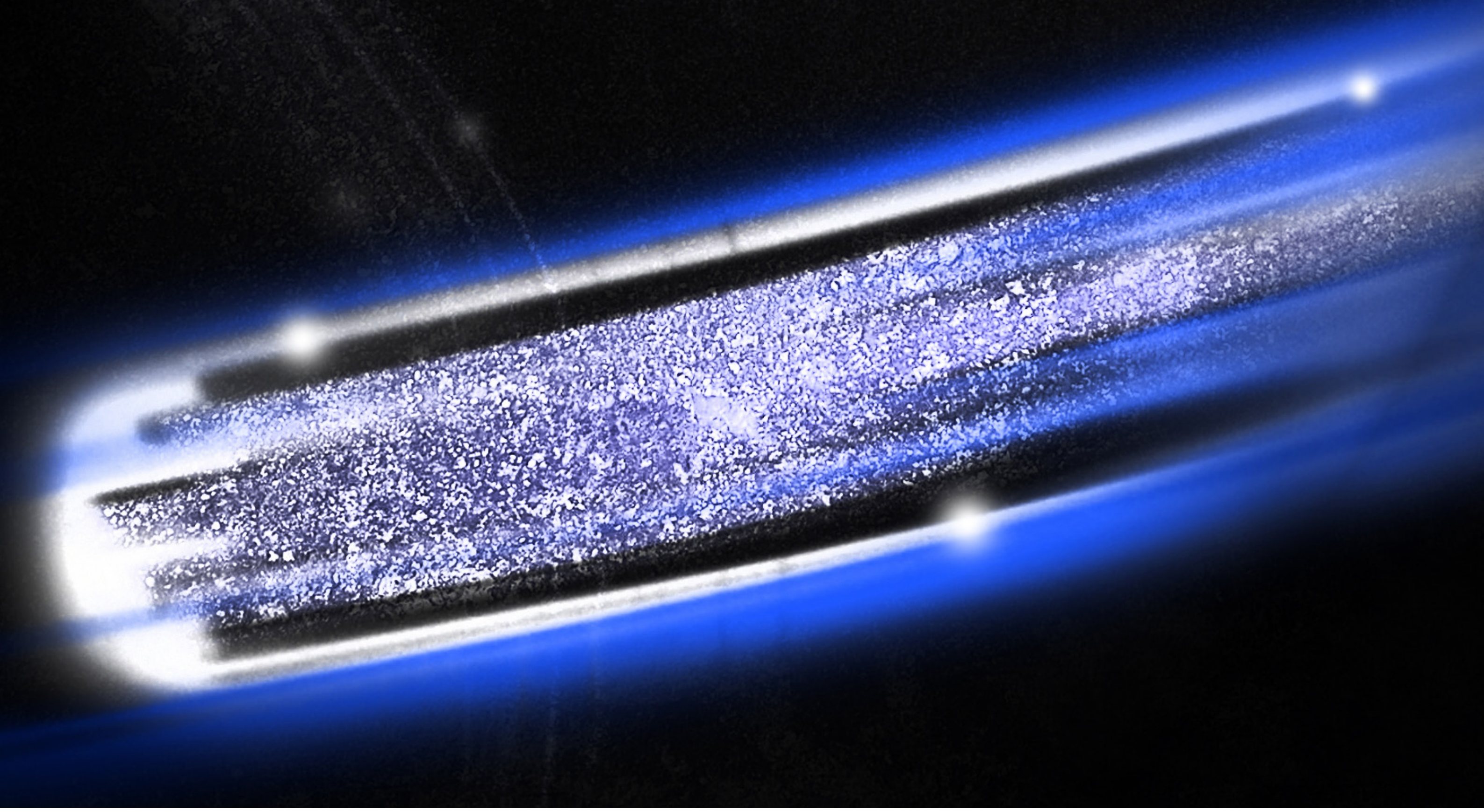
[37] MHI



SECTION 3.2:
FAST REACTORS

Closing the fuel cycle for radioactive materials to reduce their impact on humanity and the environment is an ambition in many countries. The idea is that spent nuclear fuel is reprocessed and the plutonium recovered from it is then recycled.[38]

In this way, uranium resources are not only used efficiently, but the volume and hazards of radioactive waste are also reduced. Fast reactors are one of the reactor types that can use MOX (mixed-oxide) fuel.

A fast reactor is a nuclear reactor that uses fast neutrons. It is therefore also referred to as a "fast neutron reactor". In traditional fission reactors, fast neutrons are slowed to ensure effective fission. In fast reactors, they help convert uranium isotopes into plutonium, increasing the efficiency of the resources used. By doing so, they also turn isotopes with very long half-lives into atoms with short half-lives, reducing high-level radioactive waste hazards.[39]

Instead of water, most fast reactors use liquid metals like sodium as coolants because they are less efficient at slowing fast neutrons.

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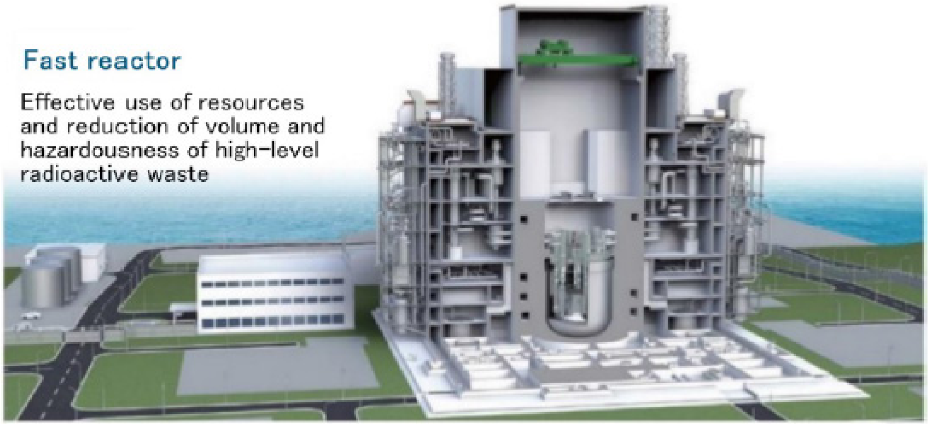
[38] MHI
[39] MHI

There are currently about 20 fast reactors, some operating since as far back as the 1950s, and only a proportion of them deliver energy commercially. However, the concept is expected to become more mainstream, with over 20 fast reactor projects on the starting lines worldwide and demonstration projects underway.[40] Among those is TerraPower's Natrium (sodium) fast reactor with a molten-salt energy storage system.[41]

In addition to electricity generation, fast reactors can be an option for process industries with high energy consumption.

THE MHI SOLUTION: FAST REACTORS



This figure includes the results of "Technical Development for International Cooperation on Fast Reactors, etc.", a project commissioned by METI.

MHI has a 50-year track record in developing and building fast reactors, going back to national research initiatives such as the "Joyo" and "Monju" reactors in the 1970s.

Since 2007, MHI has been leading the development of fast reactors in Japan. As part of a government project, it has been advancing the development of MOX-fueled, sodium-cooled fast reactors.

And, since January 2022, MHI has been working with TerraPower on the development of its sodium-cooled fast reactor as part of an international program — a joint project with the Japan Atomic Energy Agency (JAEA).[42]

MHI will also develop a demonstration fast reactor concept for a facility expected to start operating in Japan by 2050.

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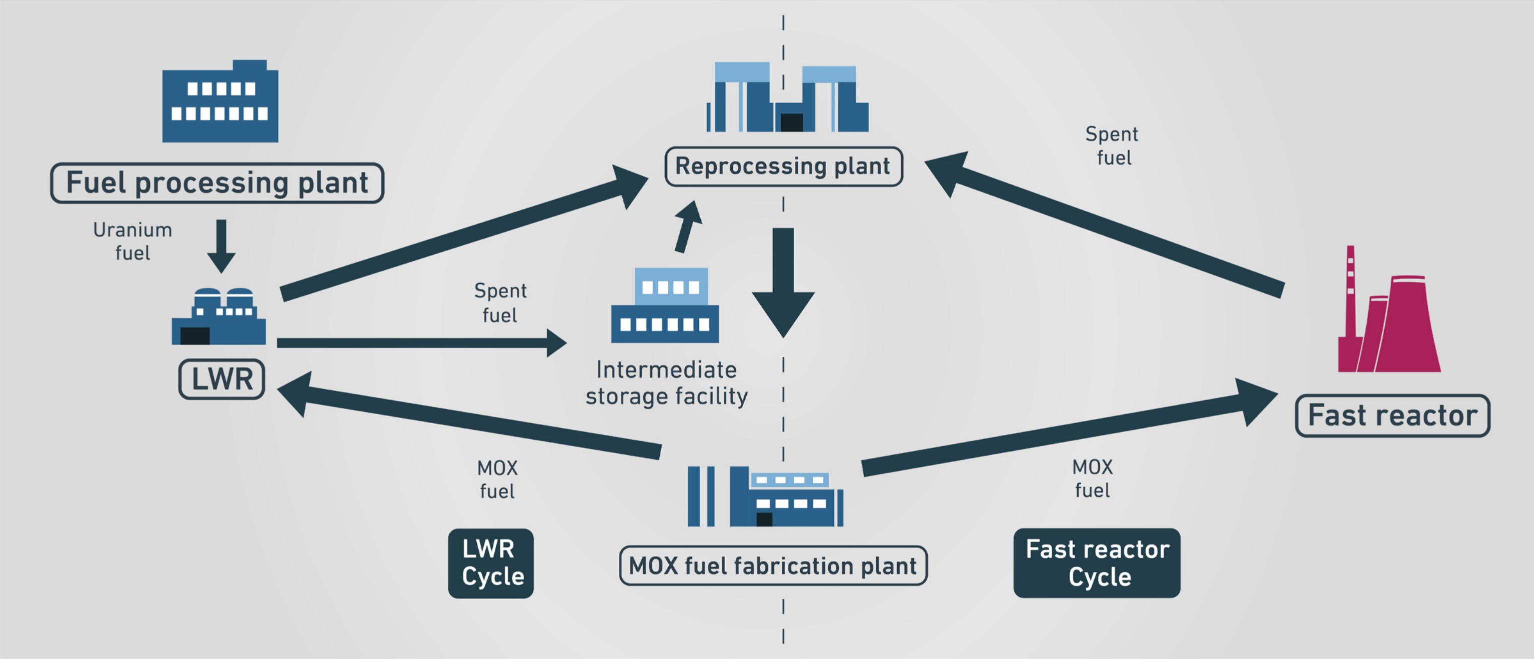
[40] World Nuclear Association
[41] TerraPower
[42] Nuclear Engineering International

CLOSING THE FUEL CYCLE

This is how a nuclear fuel cycle ensures the volume and risks of high-level radioactive waste are minimized



THE NUCLEAR FUEL CYCLE

An important factor to enhance nuclear energy sustainability is establishing a nuclear fuel cycle. This aims to ensure that spent fuel is continuously reprocessed, transported and stored safely at all stages of its lifecycle.

This ensures uranium resources are used efficiently and the volume and risks of high-level radioactive waste are minimized. In Japan, closing the nuclear fuel cycle is also considered vital to improving the country's energy security.[43]

MHI is involved in the construction of the Rokkasho Reprocessing Plant, the key facility for Japan's nuclear fuel cycle, and the Rokkasho MOX Fuel Fabrication Plant. It also provides related products, such as intermediate storage casks.

MOX (or mixed oxide) fuel is made by mixing plutonium recovered from used reactor fuel with depleted uranium.[44] Commercially available since the 1980s, MOX is currently used by about 30 reactors in Europe. In Japan, several reactors use MOX fuel and 10 facilities in total are licensed to use it.[45]

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[43] MHI
[44] World Nuclear Association
[45] World Nuclear Association

SECTION 3.3:

HIGH-TEMPERATURE GAS-COOLED REACTORS

While the power sector saw the biggest increase in CO_2 emissions in 2022,[46] decarbonizing power generation itself is only one strand on the road to net zero.

In sectors such as steel and chemicals, as well as transportation and heating, a major focus is on replacing fossil fuels such as coal and natural gas with hydrogen. For this transition to succeed, a large, stable supply of low-carbon and fully decarbonized hydrogen is required.

Policymakers around the world are keen to boost the amount of hydrogen produced, either through the electrolysis of water — driven by renewable energy — or traditional methods using carbon capture to sequester CO_2. However, as it stands, renewable or low-carbon hydrogen still only makes up 1% of global hydrogen production.[47]

Nuclear energy can step in here to provide carbon-free electricity to fuel electrolyzers. High-temperature gas-cooled reactors (HTGR) are particularly suited to this task, although other types of reactors could also be used (see Section 2).

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[46] IEA

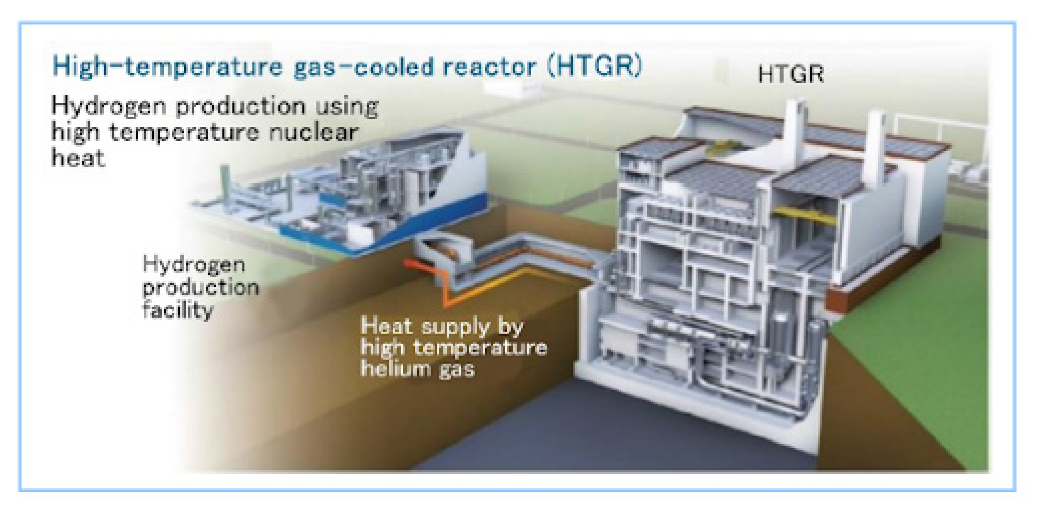
[47] IEA

HTGRs generate heat at 900°C or higher that can be used for carbon-free hydrogen production. They are expected to be widely used to make steel or cement, or power vehicles, as well as be infused into the gas grid for home heating.

HTGRs use a highly heat-resistant graphite moderator, SiC ceramics and helium gas as a coolant, which offers great resistance to the temperatures generated.

Another advantage is the core heat can be vented naturally and released into the atmosphere without the risk of a core meltdown.[48]

THE MHI SOLUTION: HTGR



MHI has been involved in the development of HTGRs since the 1970s and participated in the construction of an HTTR (High-Temperature Engineering Test Reactor) owned by the Japan Atomic Energy Agency (JAEA) — the only HTGR in Japan.

Since 2019, as part of the NEXIP initiative of METI, MHI has been developing a plant system that can produce several hundred thousand tonnes of hydrogen per year by using an HTGR as a heat source. With an output of 600MWt, the reactor is set for commercialization around 2040.[49]

In 2022, MHI and the JAEA started a demonstration project for hydrogen production technology using a HTGR. The plan is to connect a hydrogen production facility to the HTGR to use the high temperatures generated in the production process.

And while this facility will be based on steam methane reduction, MHI will see the HTGR provide heat for the electrolytic — carbon-free — production of hydrogen.[50]

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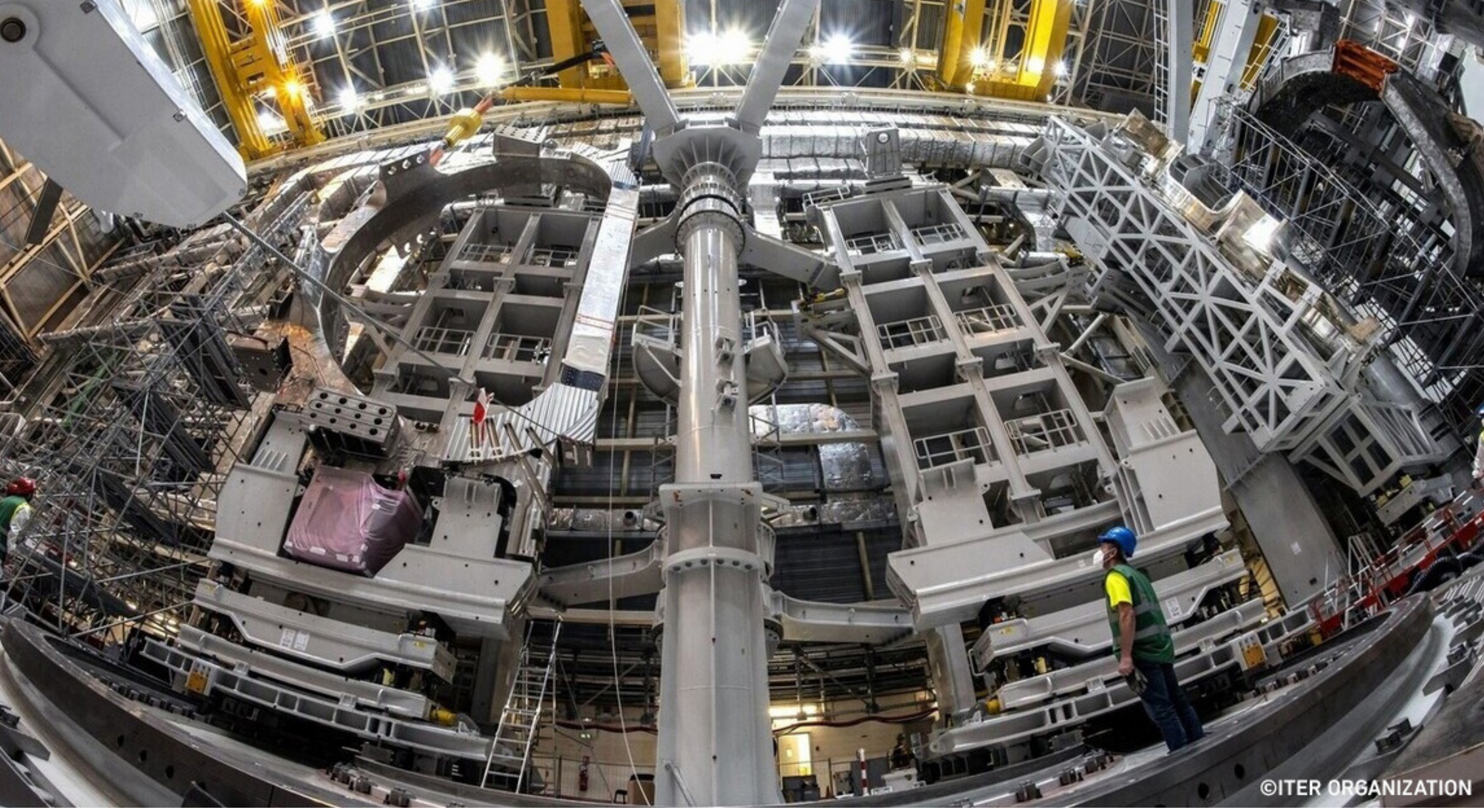
[48] MHI
[49] MHI
[50] MHI



SECTION 3.4:

NUCLEAR FUSION'S COMING OF AGE

Nuclear fusion has long been held up as the future of energy. The same process that powers the sun promises a continuous supply without the greenhouse gas emissions of fossil fuels and is safer than nuclear fission.

However, what could be a trump card in the world's quest for emission-free energy has eluded scientists for the better part of a century. The first scientific suggestion that fusion was the reaction that powered the stars goes back to the 1920s and the first proposals for actual fusion reactors started in the 1950s.[51]

The immense energies needed to bring about fusion on Earth have been a challenge to its success ever since. However, multiple projects are now entering critical phases that could see fusion become a reality.

The most promising technology is the so-called tokamaks, a doughnut-shaped (toroidal) vacuum chamber that uses strong electromagnetic fields to maintain and confine super-heated plasma at temperatures of between 150 and 300 million degrees Celsius.[52]

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[51] ITER
[52] MHI

Fusion does not bear some of the inherent risks of fission's chain reactions, as heavy atoms are split into ever smaller ones. Fusion merges very light atoms, like hydrogen isotopes deuterium and tritium, to form heavier elements with no chain reaction involved.[53]

Fusion "fuel" can be extracted from seawater in virtually unlimited quantities.[54]

Following numerous national and international initiatives over the past few decades, a new tokamak-based fusion reactor, ITER, is currently being built in the South of France.[55]

In the US, MIT and Commonwealth Fusion Systems are working on the Sparc project with similar targets — supported by investors including Bill Gates[56] — as is China with its "Artificial Sun" reactor.[57]

And, in Germany, the Max Planck Institute for Plasma Physics is pursuing an alternative approach using its stellarator fusion device.[58]

ITER's successor in Europe will be a demonstration power plant called DEMO and the next step toward the commercialization of fusion.[59]

Meanwhile, private enterprise initiatives have also emerged, trialing different fusion technologies.[60]

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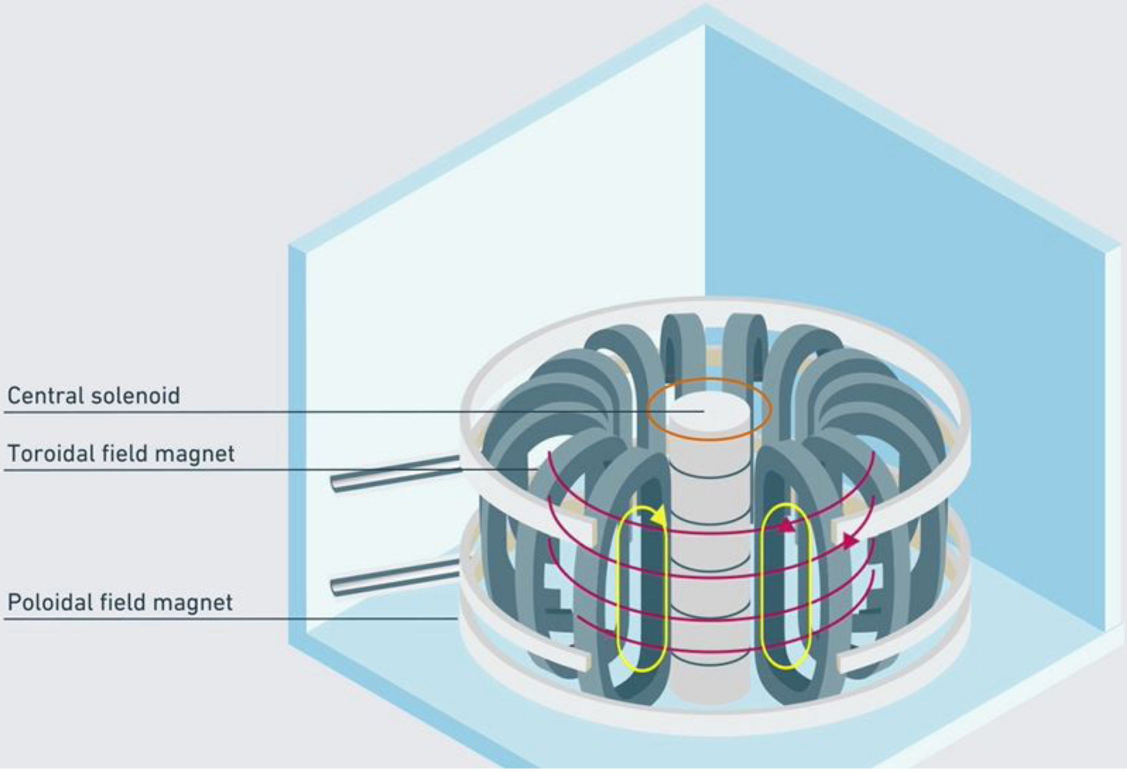
[53] MHI
[54] MHI
[55] ITER
[56] Massachusetts Institute of Technology News
[57] Newsweek
[58] Nuclear Engineering International
[59] Eurofusion
[60] Energy Intelligence



THE MHI SOLUTION: NUCLEAR FUSION

MHI is involved in the construction of the International Thermonuclear Experimental Reactor (ITER) project in the South of France.[61]

ITER aims to prove the feasibility of fusion as a large-scale and carbon-free source of energy. Its fusion reactor will contain 10 times the plasma volume of the largest fusion devices that exist today. The goal is for it to produce a ten-fold return on input heating power. To date, fusion reactors have only achieved outputs significantly less than the total input heating power.[62]

For the ITER project, in which a total of 35 countries are participating, MHI is in charge of manufacturing toroidal field coils and diverters, which are the main components of a tokamak-based fusion reactor.[63]

Toroidal field coils must meet strict manufacturing tolerance requirements. By applying technological capabilities cultivated through the design and manufacture of nuclear power equipment over many decades, MHI was the first company in the world to manufacture and ship them.[64]

MHI is also involved in developing a prototype fusion reactor in Japan, again based on tokamak technology, to provide commercial fusion reactors from the 2050s onwards.

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[61] MHI
[62] ITER
[63] ITER
[64] MHI

CONCLUSION

Looking at the latest advances in nuclear energy and the challenges global energy systems face, it is clear why experts such as the IEA and policymakers around the world are revisiting nuclear's role in the energy transition.

With improved safety features, greater versatility and lower cost barriers, nuclear is reinventing itself and emerging from the shadow of its history. But nuclear still needs more support to play its designated part in the energy transition.

Policymakers' commitment and public acceptance have been growing, but debates in Europe have shown that doubts about the inclusion of nuclear in a decarbonized energy mix prevail. Political commitment will be vital, not least to stimulate investment — another critical factor for the future development of nuclear energy.

The roadmap of nuclear reactors expected to come online between now and the middle of the century also highlights the great amount of work required in technology development. This not only refers to reactor designs, but also to closing the fuel cycle to raise efficiency, create a circular economy and minimize nuclear waste.

The multitude of international projects in the nuclear arena underscores that only collaborative approaches will get us to a place where nuclear energy becomes a safe source of carbon-free electricity, providing much-needed energy security and supplying the world long into the future.

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