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The evolution of nuclear technologies and small modular reactors

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Introduction

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In the push for carbon neutrality, nuclear power is making a comeback, reclaiming its place as a crucial player in the global energy mix. Small modular reactors (SMRs), a game-changing innovation with their compact sizes and impressive flexibility, are driving this return to the spotlight. In this article, we take a closer look at nuclear technologies, highlighting their potential to tackle both sustainability and energy security challenges. We delve into the nuclear fuel cycle, covering everything from uranium mining to waste management, and analyse the current investment trends propelling the sector towards achieving net zero emissions. By exploring the upsides and challenges associated with SMRs, we aim to provide a balanced view of their role in shaping the future of nuclear energy and the future of the energy landscape at large.

Overview of nuclear technologies

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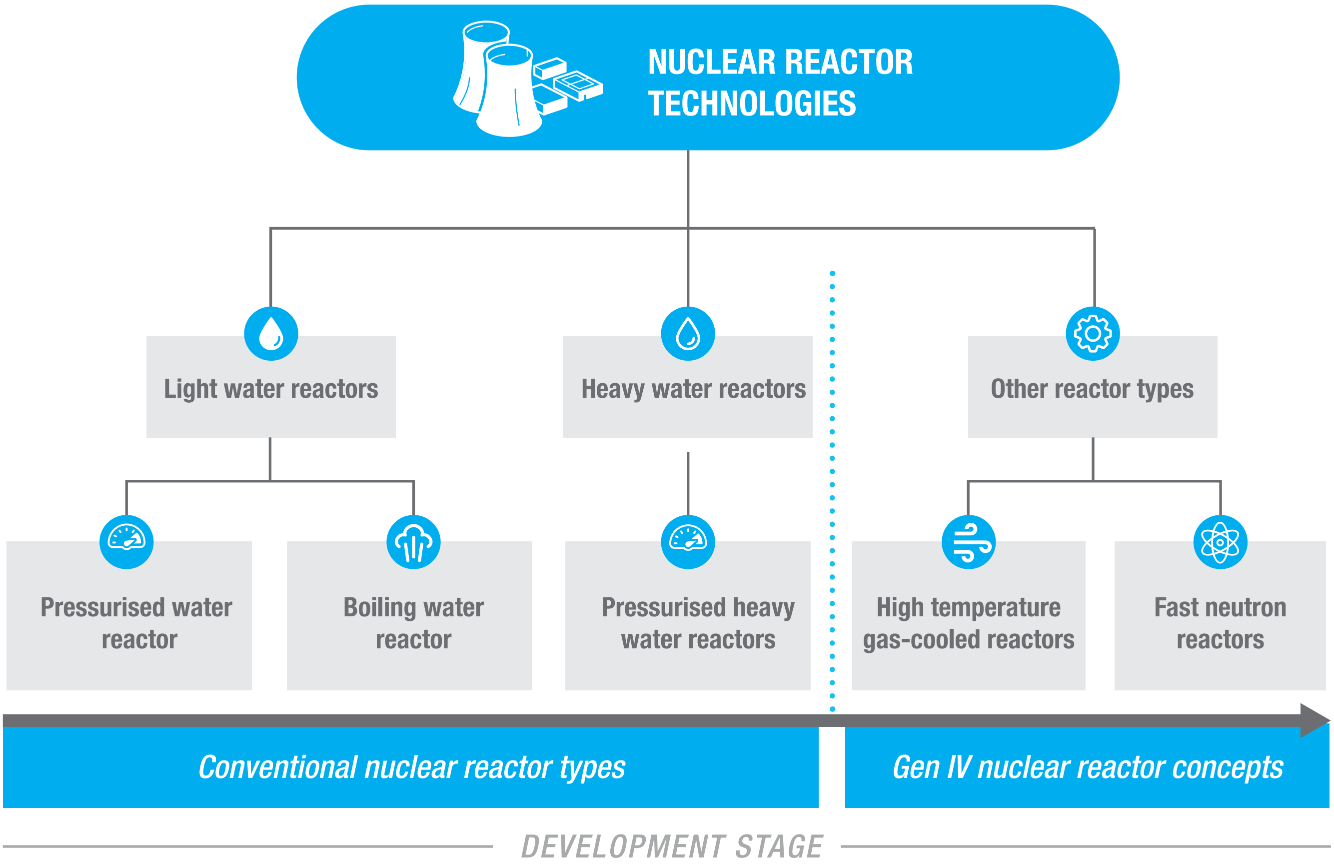
Various technologies exist for nuclear power generation. Some, like the pressurised water reactor, have been in use since the 1950s; others, like the fast neutron reactor, are newer and still under development. Although these reactors share the primary goal of power generation, they differ in how they achieve it. For example, different reactors have different coolant types and use different fission moderators to enhance efficiency. They have different costs due to factors like different construction materials, design complexity, safety measures and fuel availability. We set out below an overview of common reactor types, along with their general advantages and disadvantages.



- ***Pressurised water reactors*** (PWRs) are the most common type of reactor, accounting for approximately 70% of nuclear power plants worldwide. Water is pressurised and circulated through the reactor core, where it absorbs heat from the nuclear fission reactions. This heated water then passes through a steam generator, driving a turbine to generate electricity. PWRs use a closed-loop system, minimising the risk of radioactive contamination.

  - Advantages: PWRs are stable and feature a closed-loop system, reducing the risk of contamination.
  - Disadvantages: PWR construction is costly, and reactors cannot be refuelled during operation.

- ***Boiling water reactors*** (BWRs) are the second most common type of reactor after PWRs. In BWRs, water in the primary cooling loop boils directly from the heat of nuclear fission reactions. The resulting steam drives a turbine for electricity generation.

  - Advantages: BWRs use less water and have simpler designs, leading to lower costs and higher efficiency.
  - Disadvantages: BWRs have a higher risk of radioactive contamination due to their turbine not being in a closed-loop system.

- ***Pressurised heavy water reactors*** (PHWRs) use heavy water as a moderator to facilitate nuclear fission. Heavy water slows down neutrons, enhancing the efficiency of the fission process. PHWRs can use natural uranium, reducing the need for enrichment plants.

  - Advantages: PHWRs use natural uranium, lowering fuel costs, and operate at lower temperatures for increased efficiency.
  - Disadvantages: Heavy water is expensive and requires refilling, and concerns exist about tritium, a by-product of the process.

- ***High-temperature gas-cooled reactors*** (HTGRs) and very high-temperature gas-cooled reactors (VHTGRs) use helium as a coolant and graphite as a moderator. They offer high efficiency and safety due to helium's inert nature.

  - Advantages: HTGRs are among the safest reactors, with minimal risk of contamination or explosions.
  - Disadvantages: Helium's heat transfer characteristics require further research for optimal efficiency.

- ***Fast neutron reactors*** (FNRs) use fast neutrons to sustain fission reactions, offering sustainability and potential for multiple fuel sources.

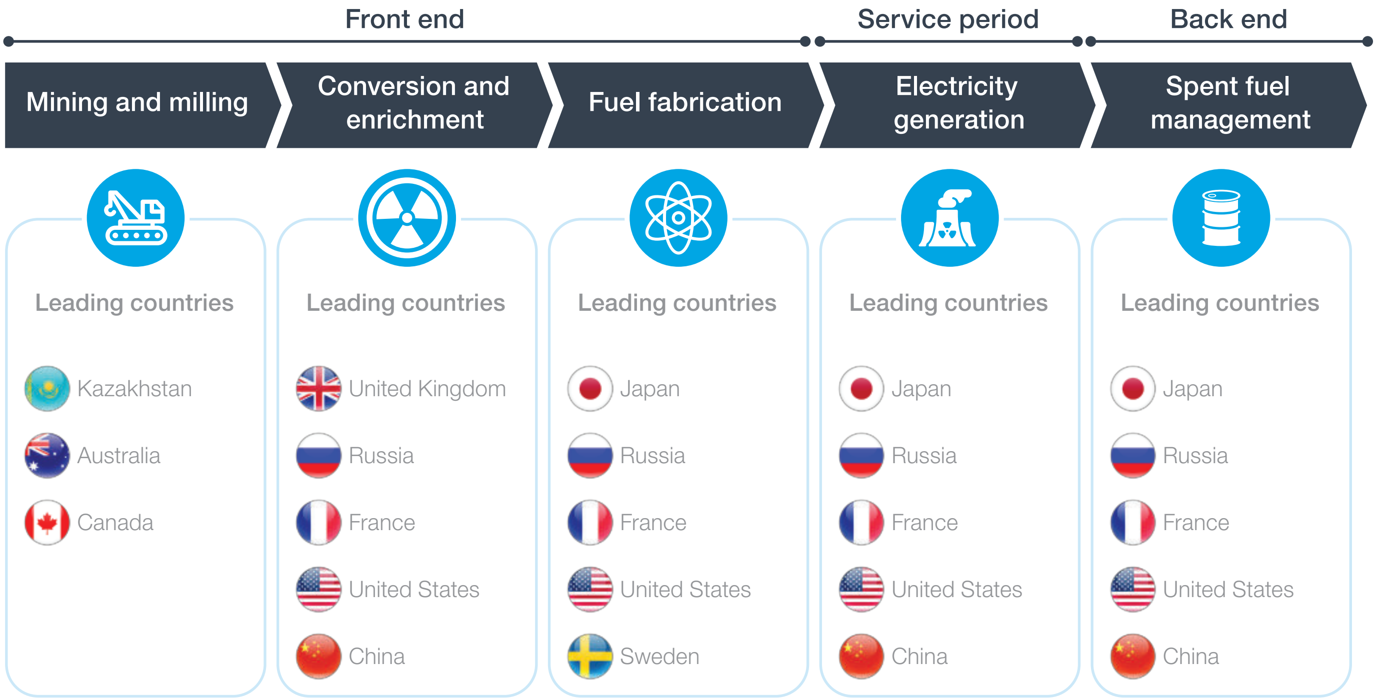
  - Advantages: FNRs can use various types of fuel. In addition, they are classified as 'breeder' reactors as they generate more fissile material than they consume, effectively 'breeding' fuel and thus, extending the world's uranium resources.
  - Disadvantages: There is currently limited safety knowledge for these reactors due to their ongoing development.

- ***Small modular reactors*** (SMRs) are a compact and scalable evolution of traditional nuclear reactors, offering flexibility and prefabrication advantages. Their modular design allows for streamlined construction, potentially reducing costs and time compared with larger reactors. SMRs blend established nuclear technology with modular flexibility, catering to diverse energy needs.

The nuclear fuel cycle

The nuclear fuel cycle encompasses the entire process of generating electricity from nuclear reactors, starting with uranium mining and concluding with the management of nuclear waste. Uranium undergoes various transformations to become an efficient fuel source for electricity production, with spent fuel requiring careful handling for either recycling or disposal. This cycle includes three main stages: the ‘front end’ for fuel preparation; the ‘service period’ when the fuel powers the reactor; and the ‘back end’ focusing on the safe management of spent fuel, including reprocessing, recycling and disposal. The cycle can be ‘open’ (without spent fuel reprocessing) or ‘closed’ (involving reprocessing and recycling).

Nuclear fuel cycle



Source: IEA

- *Front end* – The nuclear fuel cycle begins with uranium mining, using methods like open-pit, underground or in-situ leach mining to extract uranium ore. The ore is then milled, converting it into uranium oxide or ‘yellowcake’. To make it suitable for nuclear reactors, this material is converted into a gaseous form for enrichment, increasing the concentration of U-235 – the fissile isotope needed for fission – from its natural level of 0.7% to between 3% and 5%. Enriched uranium is then fabricated into pellets, loaded into metal tubes called fuel rods and bundled together, ready for use in a nuclear reactor.

- *Service period* – During this phase, prepared nuclear fuel is inserted into a reactor, where it undergoes fission to generate heat. This heat is used to produce electricity via a turbine-generator system. Typically, nuclear fuel remains in the reactor for 3–6 years, with partial refuelling occurring approximately once a year. Over time, fission products accumulate, including recyclable elements like plutonium, alongside waste material.

- *Back end* – The concluding phase involves managing the spent fuel that is removed from the reactor after use. Initially hot and highly radioactive, spent fuel is stored in pools at the reactor site, with water providing cooling and radiation shielding. Over time, the fuel may be transferred to interim storage facilities, using either wet or dry storage methods. As years pass, the radioactivity of spent fuel significantly diminishes. Some countries choose to reprocess spent fuel to recover valuable materials like plutonium and unused uranium, which can be reused in new fuel assemblies. Ultimately, spent fuel and highly irradiated waste are destined for disposal in deep geological repositories.

4 The potential of small nuclear reactors (SMRs)

Small modular reactors are emerging as a promising addition to the global nuclear fleet. With a power capacity of up to 300 MW(e) per unit – roughly one-third of traditional nuclear plants – SMRs offer cost-effectiveness and adaptability for various energy needs. Over 50 different designs are currently in development worldwide, suggesting a notable shift towards modular, scalable nuclear solutions.

These advanced reactors have diverse applications, from electricity generation to process heat provision, desalination and industrial uses. That their capacities range from tens to hundreds of megawatts means SMRs can employ different cooling methods, including light water, gas, liquid metal or molten salts.

SMRs offer several construction and operational benefits:

- *Flexibility and scalability* – Additional energy cores can be incrementally deployed to match increasing demand for power, addressing energy scaling challenges practically.

- *Enhanced safety* – Lower power and operating pressures, simpler designs, and passive safety systems contribute to improved safety margins.

- *Economic efficiency* – Standardised, simpler designs alongside expected mass production promise reduced costs.

- *Reduced construction time* – Factory-built modules assembled on site shorten construction timelines considerably.

- *Smaller footprint* – Compact sizes enable installation in various locations, including remote areas and off-grid settings.

- *Complementary to renewables* – SMRs provide consistent electricity supply, balancing the intermittent nature of renewable energy sources like wind and solar power.

The development and deployment of SMRs are supported by innovation, regulatory progress and international partnerships, all aiming to achieve a clean, reliable and diversified energy future.

However, despite the powerful advantages of SMRs, challenges remain. They can be grouped into three main categories:

- *Economic* – SMRs face significant cost challenges, including high capital requirements and uncertainty regarding economies of scale. Mass manufacturing of modular components has not yet proved cost-effective, making the financial case for SMR investment less compelling. Further, the limited number of examples of cost competitiveness against other energy sources adds risk for potential investors.

- *Technological* – SMRs face technical challenges, including demonstrating operational reliability and safety at a commercial scale. Integration into existing energy infrastructure, grid compatibility and the establishment of supply chains for new designs represent significant hurdles. In addition, achieving flexibility, such as adjusting power output in response to energy demand fluctuations, presents further technological barriers.

- *Political/Regulatory* – SMRs face complex licensing processes and require public acceptance. Adapting regulatory frameworks designed for large reactors takes time and political support. The public perception of nuclear energy varies, influenced by safety concerns, waste management and proliferation risks. Building trust needs transparent communication on the benefits and risks of the technology, together with a commitment to high safety standards.

Addressing SMR challenges requires a comprehensive approach: the investment case must be strengthened; technological advances for safety must be validated; and a regulatory environment that balances rigor with adaptability must be fostered. Building public trust is essential. Overcoming these obstacles is crucial for SMRs to contribute to a diverse, reliable and low-carbon energy future.

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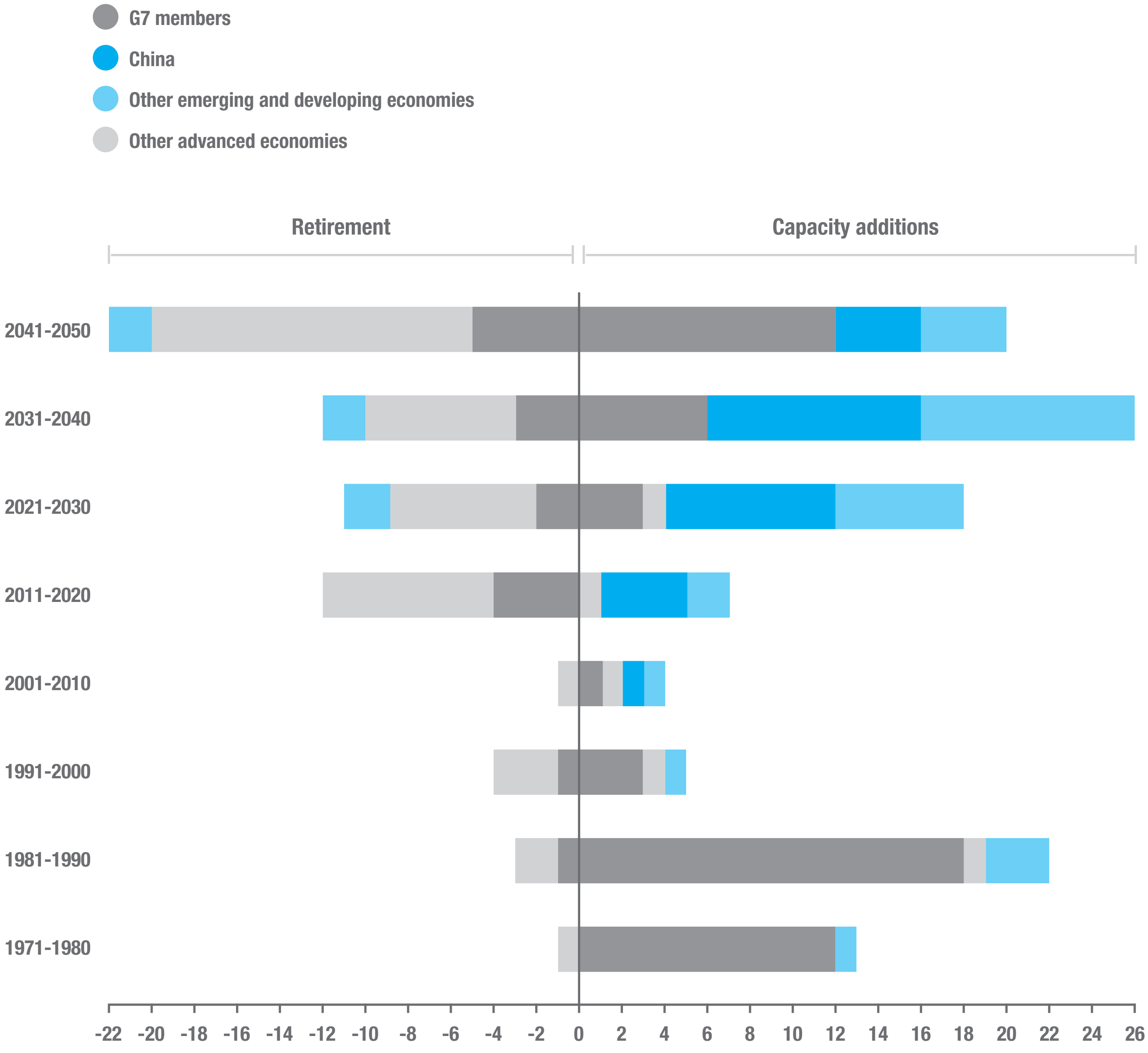
Investment trends and the path to net zero

Investment in nuclear energy is crucial to achieve the International Energy Agency's Net Zero Scenario by 2050. This involves extending the life of current plants and building new ones to bolster energy security and address climate objectives. Yet, the dilemma of retiring ageing facilities without ample new capacity jeopardises the role of nuclear power in the global electricity supply.

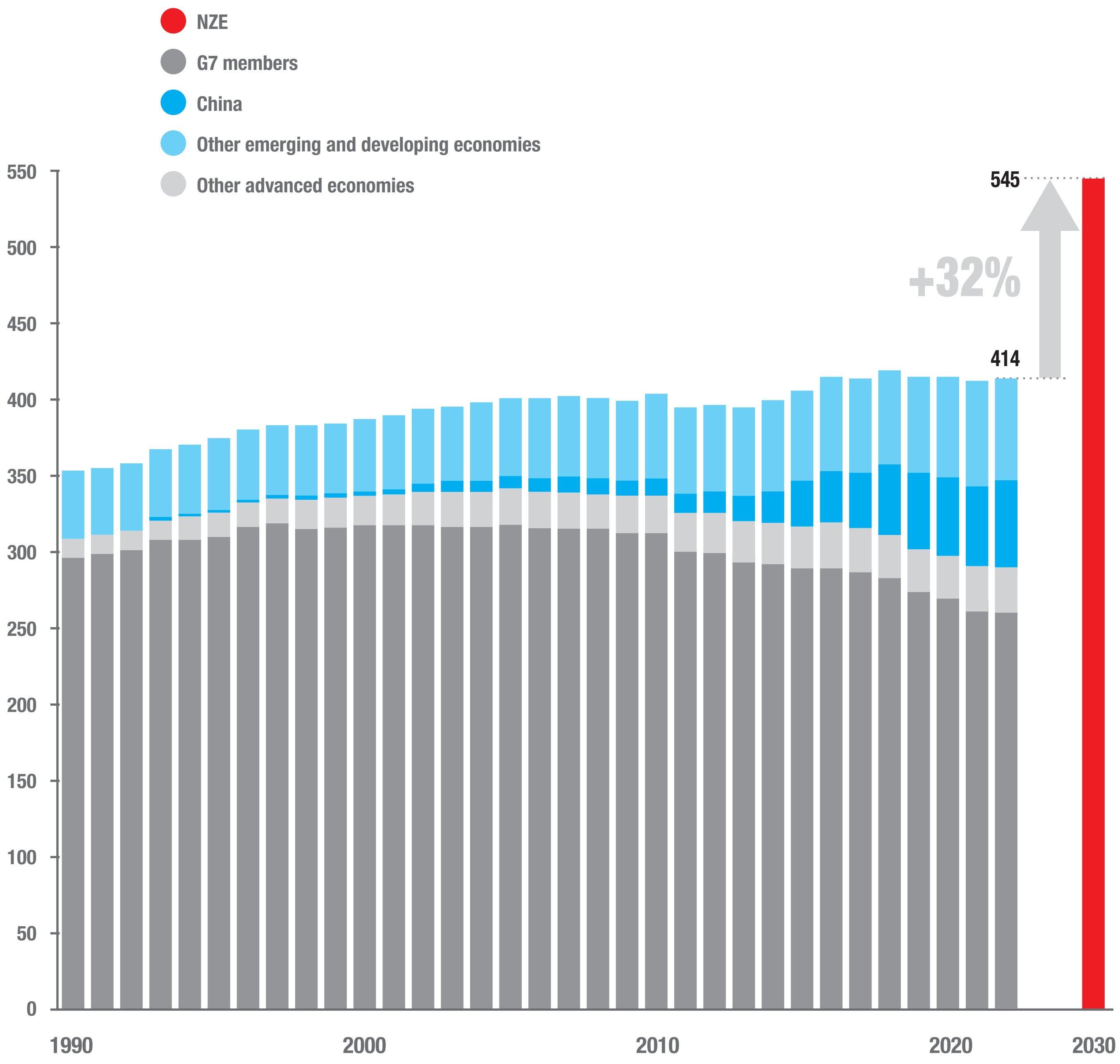
Nuclear power capacity additions and retirements by region (GW)



Source: IEA

The International Energy Agency (IEA) has estimated the potential cost of not replacing retiring nuclear capacity at an additional $1.6 trillion in alternative clean energy investments over the next two decades in advanced economies. This highlights the significance of expanding nuclear capacity for a cost-effective and sustainable transition to net-zero energy. With 63% of the current nuclear fleet aged over 30 years, extending plant lifespans is essential to meet future capacity targets. The IEA projects that achieving its Net Zero Scenario will require a 32% rise in global nuclear power capacity to reach 545 GW by 2030.

Nuclear power capacity by region in the Net Zero Scenario (GW), 1990–2030



Source: IEA

The IEA has upgraded nuclear power growth forecasts due to energy security concerns and climate action urgency. This revision, triggered by geopolitical factors, has prompted countries like Belgium, South Korea and the UK to rethink nuclear phase-outs or hasten new reactor plans. The global trend towards nuclear expansion, particularly in emerging markets and developing economies – which contributed 60% of new additions in 2022 – underlines nuclear energy's crucial role in achieving net-zero goals. This involves embracing innovative technologies like small modular reactors to overcome the limitations of traditional plants.

In short, nuclear energy's contribution to a sustainable, low-carbon future is critical. Addressing challenges such as ageing nuclear infrastructure and the need for significant new capacity, alongside leveraging new technologies, is essential to realise net-zero goals.

7 Conclusion

Exploring nuclear technologies, particularly small modular reactors, provides a forward-thinking view of the nuclear energy sector's investment landscape. Trends indicate a strategic focus on sustaining and advancing nuclear power for energy sustainability and climate goals. The commitment to expanding nuclear capability demonstrates its pivotal role in a low-carbon future. SMRs offer promising prospects for enhanced safety, flexibility and cost-effectiveness, but they also face challenges related to economic viability, technological readiness and regulatory adaptation. Navigating these obstacles is critical to leverage nuclear energy for a sustainable and secure future, emphasising the need for public acceptance, continued investment and innovation in the nuclear sector.

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