



# The Next Generation: Future Nuclear Technologies

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## Energy Industry Report



The Abdullah Bin Hamad Al-Attiyah International Foundation for  
Energy & Sustainable Development





## INTRODUCTION

### THE NEXT GENERATION: FUTURE NUCLEAR TECHNOLOGIES

Nuclear power generation has slowed around the world, despite its promise as a low-carbon, large-scale, dispatchable electricity source. New reactor designs promise to be safer, more efficient, cheaper and easier to build. But will costs come down enough for 'new' nuclear to compete with renewables and decarbonised fossil fuels?

A wide range of reactor types are in varying stages of design and demonstration in the US, China, Russia and elsewhere. Some are incremental improvements on traditional reactors; others are more radical and unlikely to enter service before the 2030s. These new reactors could have a role in the future energy mix, growing nuclear's role much beyond its current market share.



## Energy Industry Report

This research paper is part of a 12-month series published by the Al-Attiyah Foundation every year. Each in-depth research paper focuses on a prevalent energy topic that is of interest to the Foundation's members and partners. The 12 technical papers are distributed in hard copy to members, partners and universities, as well as made available online to all Foundation members.



## EXECUTIVE SUMMARY

- Advanced nuclear power has attracted attention in recent years as a possible source of dispatchable low-carbon electricity that would be safer, faster to build, and cheaper than traditional nuclear reactors.
- Nuclear is a key part of many climate scenarios that keep warming below 1.5°C. The current pace of deployment, however, is likely to lead only to slow growth, not a rapid expansion. That would put more stress on renewables, carbon capture and storage (CCS) and other low-carbon options.
- Generation III/III+ reactors now entering service should be safer, more efficient, and cheaper than traditional Generation II designs. However, skill shortages and project management failings have led to massive delays and budget overruns at new reactors in Europe and the US.
- Large advanced reactor designs (Generation IV) seem unlikely to be deployed commercially until the 2030s, and nuclear fusion not until the 2040s or after.
- Small modular reactors (SMRs), mostly based on larger traditional concepts, appear the most promising because of their inherent safety, lower financial risk, potential for cost reductions, and other advantages. They should enter the market during the 2020s.

### IMPLICATIONS FOR LEADING OIL AND GAS PRODUCERS

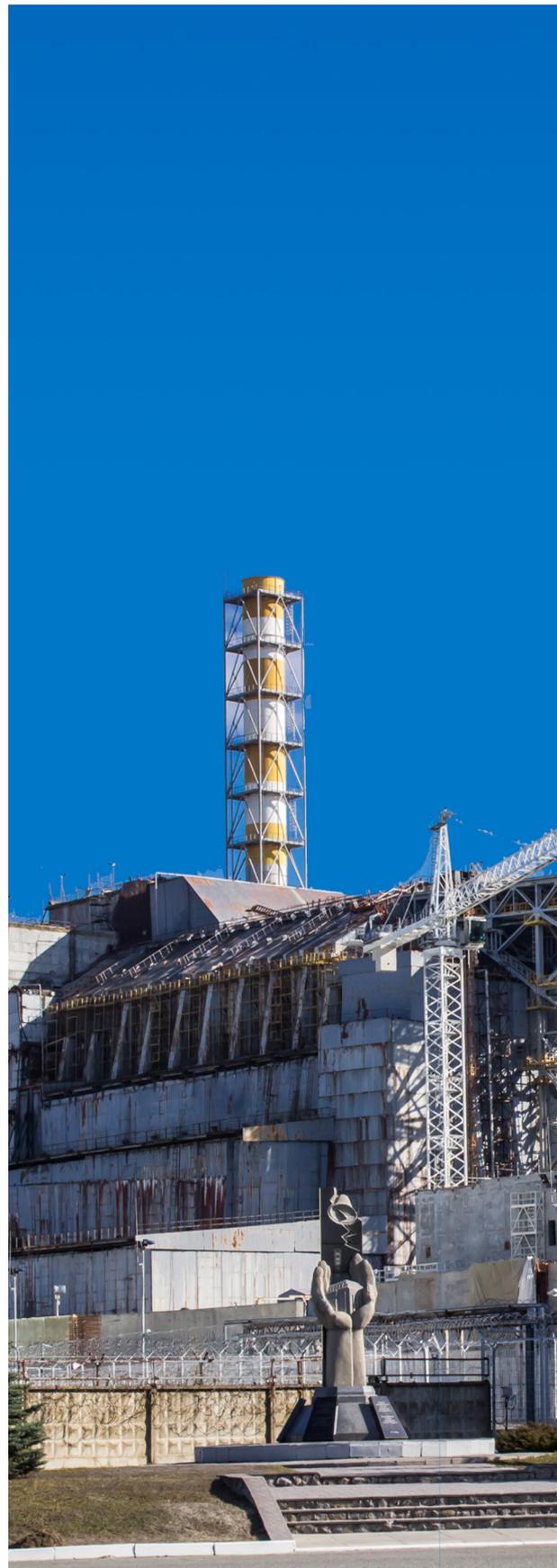
- The costs of energy generation from large Generation IV reactors are higher and flexibility is less than natural gas power, but they could have a role in a nuclear-renewable generation mix.
- High carbon prices or other carbon limits would make advanced nuclear more competitive against gas, unless low-cost CCS for gas power is developed. Given the flexibility and relatively low-carbon nature of gas, new nuclear is more likely to displace coal at present.
- High-temperature advanced reactors could compete against oil and gas to provide industrial process heat for moderate (not very high) temperatures, but probably not until the 2030s. They could also have a role in hydrogen production.
- SMRs could also replace diesel generators in remote locations, or even combustion engines in large ships.
- Oil and gas companies could invest in nuclear power (and several have invested in fusion) as a hedge against a drop in hydrocarbon use. However, this is a technically complex and risky field with many contenders.

## TRADITIONAL NUCLEAR POWER DEPLOYMENT HAS SLOWED

The deployment of nuclear power was most rapid during the late 1970s and 1980s (Figure 1) in response to the oil crises. Generation I reactors included early demonstration units during the 1950s and early 1960s. Generation II reactors covered those installed during the 1970s up to the early 1990s. They are usually large units - around 1,000 megawatts (MW) each - with active safety features, still making up the majority of reactors in current operation.

Generation III reactors began to be introduced from 1996, and include passive safety (ie not requiring active controls or operator intervention); load following capability (ie able to operate at low power - as little as 25% of capacity - and to ramp up quickly to full power); smaller physical size for the same output, as well as other improvements in safety, thermal and fuel efficiency, and construction<sup>i</sup>. Generation III+ began development in the 1990s and saw further improvements. The Westinghouse AP1000, certified in 2005, was the first, and the European Pressurised Reactor (EPR), Russia's VVER-1200 and the Korean APR-1400 are other examples<sup>ii</sup>. Finally, Generation IV reactors are under development and are discussed below.

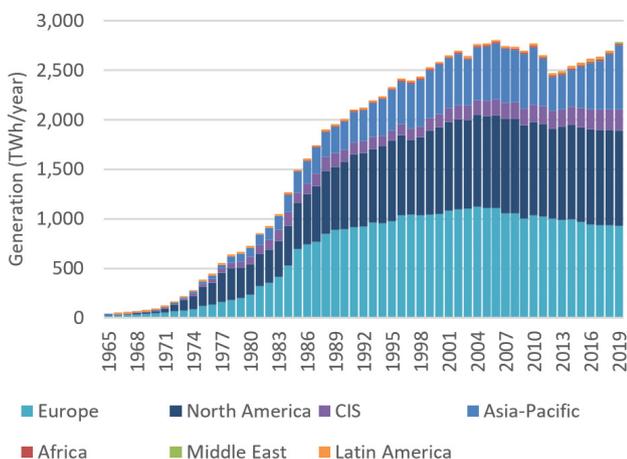
Recently, nuclear generation has slowed. It fell in Europe from 2003 onwards because of the decommissioning of ageing reactors and the lack of new construction; in North America, it has crept up since the early 2000s but because of higher utilisation, not new capacity. Asia-Pacific nuclear generation fell sharply after 2010 because of the shutdown of Japanese reactors following the Fukushima accident and the South Korean government's policy from 2017 of reducing reliance on nuclear.



## CLIMATE POLICY AND TECHNOLOGY COULD MAKE HYDROCARBONS 'STRANDED ASSETS'

Fast-rising Chinese and Indian nuclear generation has led to a rebound, but the overall Asia-Pacific level of 2010 was only surpassed in 2019. Commonwealth of Independent States (CIS) generation - nearly all in Russia - has continued to gain slowly. The start-up of reactors in Iran (2011) and the UAE (2020) will lead to Middle East growth, but use there, in Africa, and Latin America, remains minor.

FIGURE 1 NUCLEAR GENERATION BY REGION <sup>iii</sup>



This stagnation is problematic because of nuclear's role as a large, dispatchable, low-carbon power source with very low operating costs (though high capital costs). The reasons are largely the interconnected issues of cost and public acceptability. Following the Three Mile Island (1979), Chernobyl (1986) and Fukushima (2011) accidents, and 'Green' campaigners in countries such as Germany from the 1970s, nuclear power has become tainted in public eyes as dangerous. Introduction into new countries is often opposed because of concerns of weapons proliferation. Nuclear plant life extensions and new construction thus faces legal challenges, public opposition, demands for re-designs and very stringent (possibly over-engineered) safety standards.

A lack of recent experience in nuclear construction in Europe and North America leads to project management and construction failings and cost overruns. For instance:

- The Finnish government's decision to build a third reactor at Olkiluoto in 2005 was the first order in Western Europe since 1990. The European Pressurised Reactor (EPR) at Olkiluoto, the first of a new Generation III design, was intended to enter service in 2010, but is now expected in March 2021, with costs rising from an initial estimate of €6.4 billion to now around €11 billion;
- Flamanville, another EPR in France, intended to cost €3.3 billion and enter service in 2012, is now looking at loading fuel at the end of 2022, and costing €12.4 billion <sup>iv</sup>; and
- Two reactors at Vogtle in Georgia, US, would be the first new units in the US since 2007, but costs have risen from \$14 billion to \$25 billion, and start-up has fallen behind the original 2016-17 timeframe given at approval in 2009. The problems were due to redesign related to the Fukushima accident, then to the bankruptcy of Westinghouse, the lead contractor. They have now been further delayed from the now planned start-up in 2021-22 by the Covid-19 pandemic.



The very large capital cost and risks mean that only large contractors and utilities, nearly always state-owned or at least state-backed, can afford to take on the challenge of financing and building a new nuclear plant. Only a few countries, mainly Russia (Rosatom), Korea (KEPCO), US (Westinghouse, sold by Toshiba in 2018, and GE Hitachi), France (Areva/EDF), Japan (Mitsubishi), China (CNNC, CGN and SNPTC) and arguably Canada (SNC-Lavalin) offer international construction of nuclear plants. Of these, the expertise and designs from the US and Japan are doubtful. In turn, this limits the room for innovation, learning and cost-control. The size of reactors, around 1,000 MW, with some Generation III designs of 1,400-1,600 MW, was chosen to maximise economies of scale, but makes them unsuitable for countries with small grids.

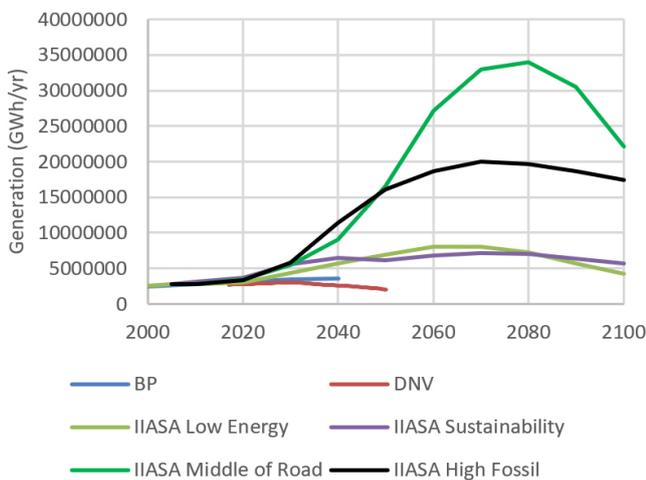
The greatly delayed construction times raise costs directly but also increase financing costs and investor risks. Overall, these factors contribute to a high levelised cost of electricity (LCOE), which makes nuclear uncompetitive against cheap natural gas and modern renewables.



## NUCLEAR STILL REMAINS AN IMPORTANT SOURCE OF LOW-CARBON ENERGY IN FUTURE SCENARIOS

Scenarios of future energy use have a very wide spread of opinions for nuclear (Figure 2). The four International Institute for Applied Systems Analysis (IIASA) scenarios are all compatible with limiting global warming to 1.5°C by 2100. They have high nuclear use, particularly in the 'High Fossil' and 'Middle of the Road' scenarios, where peak nuclear generation around 2070-80 is 7-12 times the size of the current nuclear industry. BP and DNV, though with shorter time horizons, have much less nuclear use: a slow rise to 2031 followed by gradual decline, in DNV's case; and a slight rise averaging 2% annually to 2040 in BP's case. In BP's scenario, nuclear gradually loses as a share of world primary energy demand to renewables and gas, though gaining relative to coal and oil.

**FIGURE 2 SCENARIOS FOR FUTURE NUCLEAR GENERATION <sup>v</sup>**



Nevertheless, the rapid gain in nuclear in the higher scenarios from about 2030 onwards appears challenging given the slow pace of nuclear construction.

### NUMEROUS ADVANCED REACTOR DESIGNS ARE AT VARIOUS STAGES OF DEVELOPMENT

New nuclear reactor designs include small reactors, often modular (SMRs) and Generation IV. There can be overlap between these groups.

Small reactors are those of 300 MW or less. Very small reactors (vSMRs), of less than 15 MW, are being proposed for applications such as powering remote communities. Small reactors are not new – for instance, the first nuclear submarine was launched by the US in 1954, and submarines and aircraft carriers have reactors of some 36-125 MW. But interest in deploying them more widely for power generation is a more recent phenomenon.



SMRs have potentially numerous advantages (Table 1). The question is whether these are sufficient to overcome the inherent cost disadvantage of a smaller-scale reactor.

TABLE 1 ADVANTAGES AND DISADVANTAGES OF SMRS

Advantages	Disadvantages
Lower capital cost per unit giving more benefits of learning	Lower economies of scale per unit, leading to higher electricity costs
Smaller total capital cost reduces utility's financial exposure	High licensing costs per unit for new designs
Simpler design	
Shorter construction times	
Modular, factory-based construction	
Larger plants can be developed from multiple units	
Can power smaller grids, and less risk for grid stability	
Can replace coal-fired plants of similar size with existing grid connections	
Lower safety risk per unit	
Simpler safety requirements and easier cooling	
Can be located underground for protection	
Lower cooling water requirement	
Can be removed whole for decommissioning	

Key developers of SMRs include NuScale Power and Oklo in the US and Rolls Royce in the UK<sup>vi</sup>. Russia and China are working on floating reactors, with Russia aiming for deployment in the Arctic.

Fluor, the engineering firm, has invested in NuScale, which expects its design to be certified by the end of 2020. It has agreed to install up to twelve 60 MW units for a utility in Idaho, to be operational by 2027. Rolls Royce's design, of 440 MW, is larger than the typical size for an SMR, but the company considers it a reasonable trade-off for economies of scale.

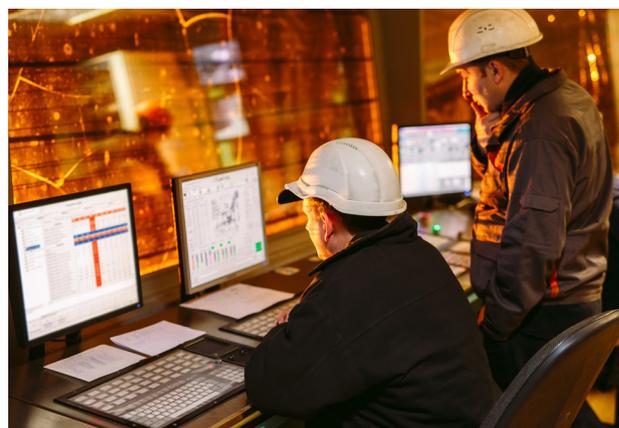
However, this design is at least a decade away. Oklo's advanced design is very small (1.5 MW), designed for remote off-grid sites, and targeting a first demonstration in 2022-24.

To realise the full economies of mass production, the industry will have to standardise on one or a few SMR designs, though currently many are under development.

Numerous large-scale Generation IV reactors are also under development. Key features of these are that they should be simpler, standardised, cost-effective, safe, clean and proliferation resistant. Sizes range from 150-1,500 MW.

The Generation IV International Forum (GIF) selected six designs for further development, with commercial deployment around 2030-40. These designs included:

- Gas-cooled Fast Reactor
- Lead-cooled Fast Reactor
- Molten Salt Reactor (MSR)
- Supercritical Water-cooled Reactor
- Sodium-cooled Fast Reactor
- Very High Temperature Reactor



## NUMEROUS ADVANCED REACTOR DESIGNS ARE AT VARIOUS STAGES OF DEVELOPMENT

The key differences between these designs are whether they use moderated neutrons as in a traditional reactor or 'fast' neutrons, and the coolant (gas, lead, sodium, supercritical water, or molten salt with the fuel dissolved in it). These choices have various advantages. MSRs operate at atmospheric pressure, rather than the 75–150 atmospheres of conventional light-water reactors, therefore not requiring large and expensive containment systems, and reducing leakage risk. In the event of a breach, the molten salt will solidify, trapping the fuel and waste products. Higher operating temperatures give increased efficiency.

GE Hitachi's PRISM reactor is a fast sodium-cooled design. Moltex (a UK/Canadian firm), Elysium Industries, Terrestrial Energy and ThorCon Power are all working on MSRs. Transatomic Power, another designer of an MSR, halted its work in 2018. X-Energy is developing a high-temperature gas-cooled pebble-bed reactor. Oklo's small design (mentioned above) is a fast reactor.

Both China and Russia are investing in Generation IV development. China's State Nuclear Power Technology Corp (SNPTC)'s designs include a 250 MW high-temperature gas-cooled reactor <sup>vii</sup>. Tests on a demonstration unit are set to be completed in 2020.

All traditional designs, and all the Generation IV designs other than ThorCon's, are fuelled by uranium. The possibility of using thorium as a fuel has been a long-running interest. Thorium is more abundant than uranium, less prone to nuclear weapons proliferation, has some favourable nuclear and physical properties, and yields less long-lived waste.

## Fast reactors

- Use 'fast' neutrons for fission.
- Do not require a moderator, so the reactor size is greatly reduced.
- Burn up most of the long-lived waste, and 'breed' new fissionable fuel from depleted uranium and thorium.
- Ease concerns about the availability of nuclear fuel in the case of a very large fission programme worldwide.

India historically has been interested in thorium, because of its large reserves of the element.

Some 'Generation V' designs have been proposed, including ones that avoid a heat cycle entirely, or hybrids with fusion reactors, but none are attracting serious research at present.

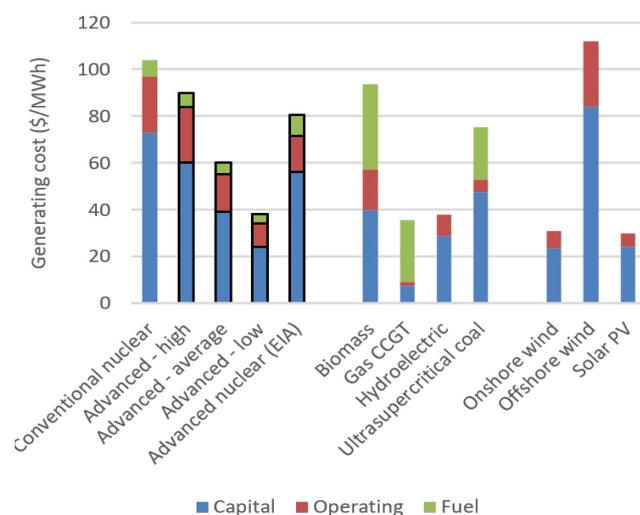
Advances in computing, simulation, and material science may make it feasible to bring some of these concepts to practicality. However, all these reactors face significant challenges. Licensing novel designs in the US is a long and costly process. Fast reactors have historically proved expensive to build and operate, and uneconomic unless the price of uranium rises significantly. They require more highly enriched fuel, which is expensive and raises proliferation worries. The various alternative coolants, such as sodium, molten salt and lead, raise technical issues in each case.

## ADVANCED REACTORS COULD BE COST-COMPETITIVE

Figure 3 compares costs for new generation reactors in the US. Note that the costs are location-dependent (particularly for renewables) and that the Energy Innovation Reform Product estimates for advanced nuclear may not be exactly comparable with the US Energy Information Administration figures for other generations, because of different methodologies.

The generating methods are grouped into nuclear; other dispatchable; and non-dispatchable (variable) renewables. Carbon costs for coal and gas are not included.

**FIGURE 3 COST FOR NEW ELECTRICITY GENERATION, US**<sup>viii</sup>



It can be seen that the advanced nuclear reactors have the potential for substantial cost reductions on conventional designs, in capital, operating and fuel costs. Advanced reactors also have the chance to be more competitive than coal, especially if pollution and carbon costs are included. Gas combined-cycle turbines (CCGT) are very cheap, given expected continuing low gas prices, but they still emit carbon dioxide and will eventually have to be decarbonised with CCS or hydrogen as fuel. Biomass and hydroelectric are limited by land-use issues.

The variable renewables have much lower costs (and their costs, particularly for offshore wind, are likely to drop significantly). But as renewable penetration levels increase, they need more back-up, seasonal storage and interconnections.



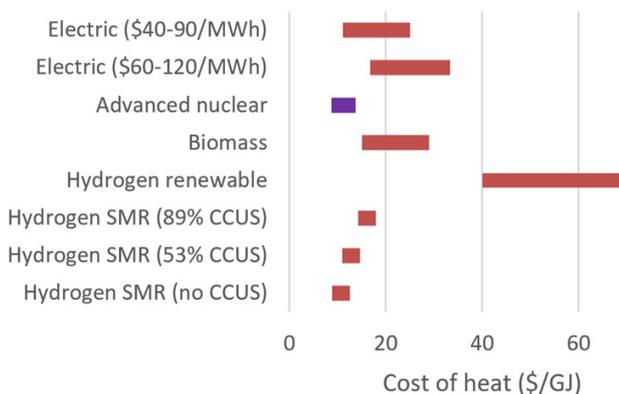
## ADVANCED REACTORS OFFER ADDITIONAL SERVICES BEYOND POWER GENERATION

Generation II and III reactors produce low-temperature heat. This could be sufficient, for example: for district heating (common in the former Soviet Union), or district cooling (via an absorption chiller), or desalination (possible applications in the Middle East).

Some advanced designs operate at high temperatures of between 510-1,000°C (compared to less than 330°C for a typical light-water reactor). At these high temperatures, they could be used for thermochemical hydrogen production ('purple' hydrogen), or for ammonia, petrochemicals, and industrial process heat. However, no current designs reach sufficient temperatures to manufacture steel, glass or cement.

Costs of advanced nuclear heat appear very competitive with other options (Figure 4) – in fact, the cheapest of the low-carbon options. Of course, this relies on advanced nuclear reactors being delivered within a reasonable timescale and to acceptable costs. Electric and hydrogen heating options will probably fall in cost over time with technical developments and upscaling.

**FIGURE 4 COST OF HIGH-TEMPERATURE HEAT FOR INDUSTRIAL USE**<sup>ix</sup>



## NUCLEAR FUSION

Nuclear fission, the basis of current nuclear reactors, relies on splitting heavy nuclei (uranium or thorium). Nuclear fusion, the process that powers the sun, instead fuses light nuclei (usually hydrogen isotopes deuterium and tritium, but could also be helium, lithium or boron) to release energy.

Fusion has the attractions of producing only small amounts of short-lived nuclear waste, being inherently safe (it cannot melt down or cause an explosion), having no weapons proliferation risk, and using essentially limitless fuels.

However, nuclear fusion only takes place under extreme conditions of temperature and pressure. The most practical reactions produce an intense flux of neutrons, which cause damage to the reactor's chamber. Containing the plasma requires very precise control of strong magnetic fields generated by superconducting magnets. A large energy input is required to generate the plasma, so creating a net energy output and a self-sustaining fusion reaction has been challenging.

The international collaboration ITER, based in France and backed by the EU, UK, China, India, Japan, South Korea, Russia and the US, has so far spent \$22 billion since 1985. It plans to begin plasma tests in 2025. But a number of start-ups and private companies have invested in alternative, hopefully less technically challenging and lower-cost approaches.

General Fusion, a Canadian company, is trying to develop a demonstration unit by 2024. Commonwealth Fusion Systems (CFS) aims for a commercial reactor in the early 2030s<sup>x</sup>. Defence firm Lockheed Martin has constructed five experimental reactors to date<sup>xi</sup>, and hopes

for a design the size of a shipping container that could power an aircraft or aircraft carrier (suggesting at least 100 MW).

Nuclear fusion start-ups have received some surprising interest from oil companies: Chevron invested in Zap Energy<sup>xii</sup>, and Equinor and ENI in CFS<sup>xiii</sup>.

General Fusion eventually hopes to produce electricity for \$50-60/MWh (similar to the average costs for advanced fission reactors in Figure 3). Beyond conventional electricity generation, fusion would also have long-term applications such as powering space flight and orbiting stations.



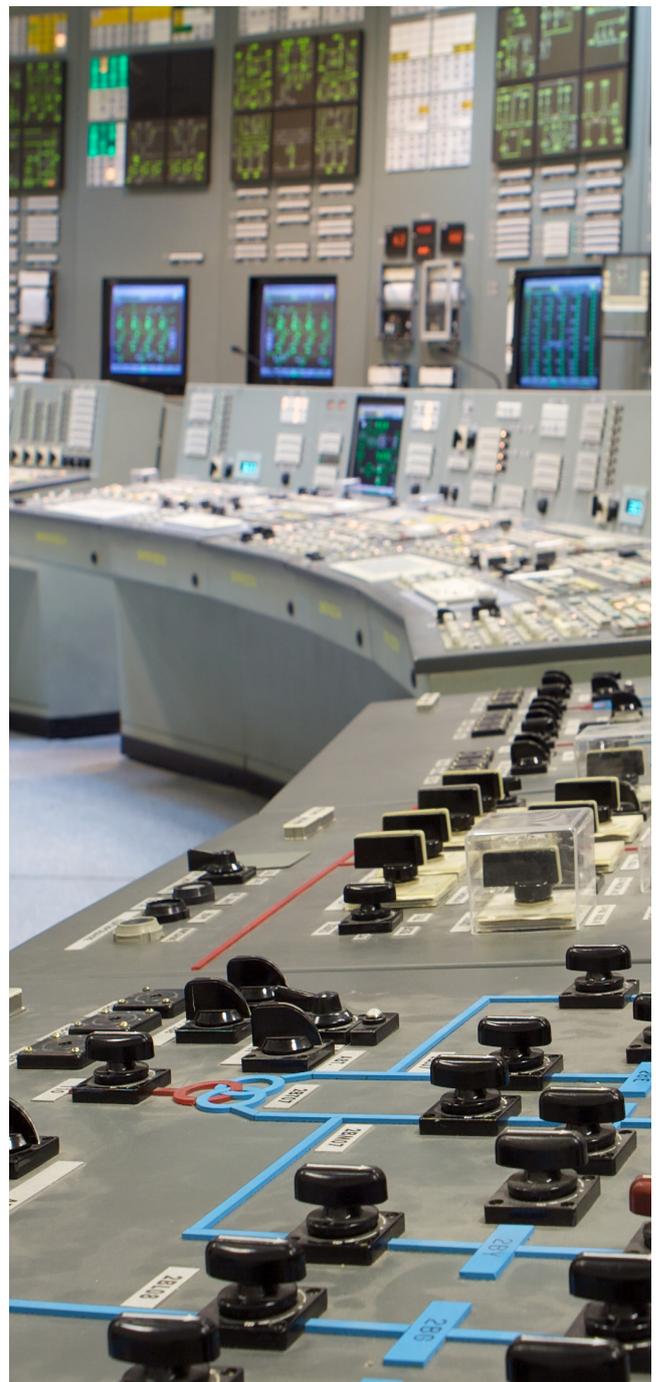
## CONCLUSIONS

Given the technical challenges to large Generation IV reactors, it seems unlikely that any will enter commercial service before the 2030s. They could be cost-competitive with other low-carbon dispatchable generation options but will face a major economic challenge from low-cost renewables combined with storage. High-temperature heat generation is also a promising application, but again electrical and hydrogen heating are more advanced for now. 'Purple' hydrogen generation is a further option, but has to compete with a recent major effort, mostly in Europe, to commercialise 'green' hydrogen from renewable electrolysis.

Fusion reactors are likely even further away, although a breakthrough from one of the numerous companies researching new designs is possible and might produce a commercial reactor in the 2030s.

So continuing expansion of nuclear power will likely have to be based on Generation III/III+ designs, but with improved construction practices and standardisation, and better public acceptability, to reduce costs, build repeatable expertise, and avoid the very long timelines and budget overruns that have plagued new reactors in the US and Europe. Countries in the former Soviet Union, Middle East and parts of developing Asia-Pacific may be more promising locations for deployment. Due to high costs, new nuclear will still struggle to compete with renewables and cheap natural gas, so the very large expansion of the nuclear industry seen in some climate scenarios is improbable.

Small modular reactors seem to offer the best hope for more rapid nuclear build-up. If they can achieve safety, standardisation and cost reduction through factory assembly, they have a wide range of applications. The NuScale plant in Idaho is particularly interesting and important for testing this concept in the near future.



## APPENDIX

- i. <https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/advanced-nuclear-power-reactors.aspx>
- ii. <http://www.amacad.org/sites/default/files/academy/pdfs/nuclearReactors.pdf>
- iii. Data from BP Statistical Review of World Energy 2020
- iv. <https://www.ft.com/content/fc6a8610-ea5e-11e9-a240-3b065ef5fc55>
- v. BP Energy Outlook 2019; DNV Energy Transition Outlook 2019; International Institute for Applied Systems Analysis <https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/#/workspaces/2>
- vi. <https://www.bbc.com/future/article/20200309-are-small-nuclear-power-plants-safe-and-efficient>
- vii. <https://energycentral.com/c/ec/forecast-future-gen-iv-reactors-5050-chance-success-three-types>
- viii. Advanced nuclear costs from [https://www.innovationreform.org/wp-content/uploads/2018/01/Advanced-Nuclear-Re-](https://www.innovationreform.org/wp-content/uploads/2018/01/Advanced-Nuclear-Reactors-Cost-Study.pdf)  
[actors-Cost-Study.pdf](https://www.innovationreform.org/wp-content/uploads/2018/01/Advanced-Nuclear-Reactors-Cost-Study.pdf); other generation from [https://www.eia.gov/outlooks/aeo/pdf/electricity\\_generation.pdf](https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf)
- ix. [https://energypolicy.columbia.edu/sites/default/files/file-uploads/LowCarbonHeat-CGEP\\_Report\\_100219-2\\_0.pdf](https://energypolicy.columbia.edu/sites/default/files/file-uploads/LowCarbonHeat-CGEP_Report_100219-2_0.pdf)
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- xi. <https://www.thedrive.com/the-war-zone/29074/skunk-works-exotic-fusion-reactor-program-moves-forward-with-larger-more-powerful-design>
- xii. <https://uk.mobile.reuters.com/article/amp/idUKKC-N25831E>
- xiii. <https://www.eni.com/en-IT/media/press-release/2018/03/eni-joins-mit-and-cfs-to-advanced-fusion-energy.html>





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