2025

January

Small and Modular is Beautiful: Shaping the Future of Clean Nuclear Energy

The Al-Attiyah Foundation

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Building on the success of COP28 in Dubai and the first Nuclear Energy Summit in Brussels, global momentum for nuclear energy is accelerating. The latest International Atomic Energy Agency (IAEA) projections highlight growing recognition of nuclear power as a clean and secure energy source. There is rising interest in Small Modular Reactors (SMRs) for both power and non-power generation applications, aiming to meet climate goals and promote sustainable development.

How are ongoing advances in small modular reactors (SMRs) impacting their current and planned applications? What are the economic considerations associated with SMRs' deployment? What investment and development activities are taking place in the United States, Europe, and Asia? What is the role of SMRs in the energy mix of emerging energy consumers?

ENERGY RESEARCH PAPER

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 current energy topic that is of interest to the Foundation's members and partners. The 12 technical papers are distributed to members, partners, and universities, as well as made available on the Foundation's website.

- The 2023 United Nations Climate Change Conference (COP28), held in the UAE during November 2023, launched a declaration to triple nuclear power capacity by 2050, recognising nuclear power as part of the solution to climate change due to its large-scale, low-carbon, and reliable power generation.
- Current global nuclear capacity is 404 GW. Projected global capacity by 2030 based on current plans is only 468 GW, a construction rate far short of the 1200 GW target by 2050.
- Nearly half of new nuclear construction is in China, indicating even more limited progress elsewhere.
- Many reactors in industrialised countries are old and expensive to upgrade. Long construction timelines and financial risks make conventional nuclear power less competitive than renewables and fossil fuels, even accounting for intermittency and carbon costs.
- There is a new perception that growth in artificial intelligence (AI) and data centres, along with other demand sources such as electric vehicles, electrified heating and industry, will increase electricity demand beyond previous projections, particularly in the US. Renewables, even with battery backup, may struggle to supply nearby power with the required reliability.
- Small Modular Reactors (SMRs), with sizes typically of 0.5-300 MW, offer a potential solution with shorter build times and lower risks.
- SMRs are intended to have a simplified, standardised design, with factory fabrication and on-site assembly to reduce costs and risks.

- SMRs are suitable for more locations due to smaller footprint and lower cooling needs.
- Their smaller size results in lower financial risk and quicker development, a more diverse investor base and business models, and so lower cost of capital.
- They typically have enhanced safety features and lower fuel requirements.
- However, SMRs also have disadvantages. Their smaller size results in less economies of scale. They suffer from similar design and approval requirements as large reactors. And there is limited technical experience with civilian SMRs, with only China and Russia operating a few units today.
- A wide variety of SMR designs has been proposed, with some already in operation in Russia and China. Generation III+ and Generation IV reactors offer different technological approaches, advantages and risks.
- There is potential for significant global SMR capacity by 2050 with tailored policies and cost reductions. A base case of 40 GW could increase to 190-375 GW, which would be a substantial fraction of the 1200 GW tripling target.
- SMRs could become economically attractive compared to renewables with battery backup. However, learning rates and cost reductions depend on large-scale deployment and standardization. Current cost estimates are probably still optimistic.
- Large-scale deployment of SMRs requires consistent long-term political support and public acceptability. Careful management and planning will be required to avoid potential bottlenecks in supply chain and cost squeezes.
- Various countries are advancing SMR technologies. The US has the most innovation, Russia the most historic experience, and China probably the most manufacturing skills and ability to construct and export. But domestically, China and South Korea are likely to concentrate on traditional large reactors given their successful deployment and initial cost advantages.
- Countries will not want to depend on a single supplier, and different reactor types have different niches and applications. However, it would be better not to have too many competing SMR designs, as that reduces the gains from standardisation and learning.
- SMRs offer hope for reviving the nuclear power industry, particularly in the West. They are likely to play a supporting role in global nuclear expansion, bringing nuclear power to new settings, and supporting large reactor advances.
- Middle East interest in SMRs, mostly by the UAE and Saudi Arabia, is due to interest in leading new technologies, their growing domestic electricity demand and the UAE's successful large-scale reactor programme.

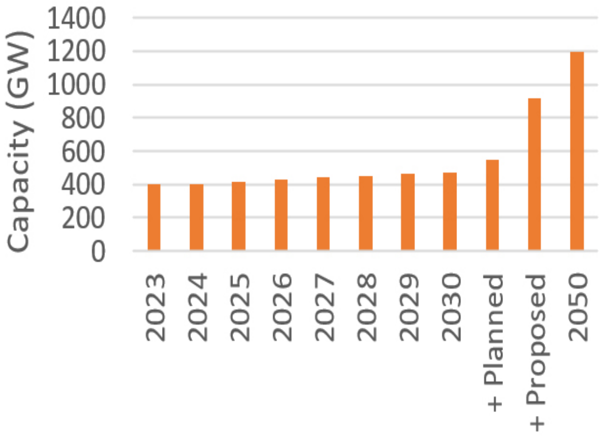
The 2023 United Nations Climate Change Conference (COP28), held in the UAE during November 2023, saw the launch of a declaration to triple nuclear power capacity by 2050, and the formal recognition of nuclear power as one of the solutions to climate change[i]. Nuclear power generates on a very large scale, has a very low carbon footprint, and produces reliable, dispatchable power. Modern reactors are generally very safe, and the small amounts of nuclear waste they produce can be stored indefinitely, until deep disposal repositories are ready.

However, there is widespread recognition that the goal of tripling capacity will not be achieved on nuclear's current track. For most countries, the timeline for construction of conventional nuclear power is too long, the financial risk is too high, and the cost of the final delivered electricity is expensive compared to that of modern renewable options, solar and wind, and fossil-fuelled generation with coal or natural gas.

Current global nuclear capacity is 404 gigawatts (GW). Reactors in industrialised countries are typically old – more than half of those in the US and Sweden, and more than a third in France, are older than 40 years[ii], and many of these are likely to be shut down as too expensive to upgrade. On current construction timelines (which are often delayed), and ignoring retirements, global capacity would reach 468 GW by 2030 (Figure 1). At this rate of additions, the goal of tripling would not be reached until after the year 2100. Adding all currently planned reactors takes the total to 550 GW, and currently proposed reactors increases this to 915 GW, still well short of the

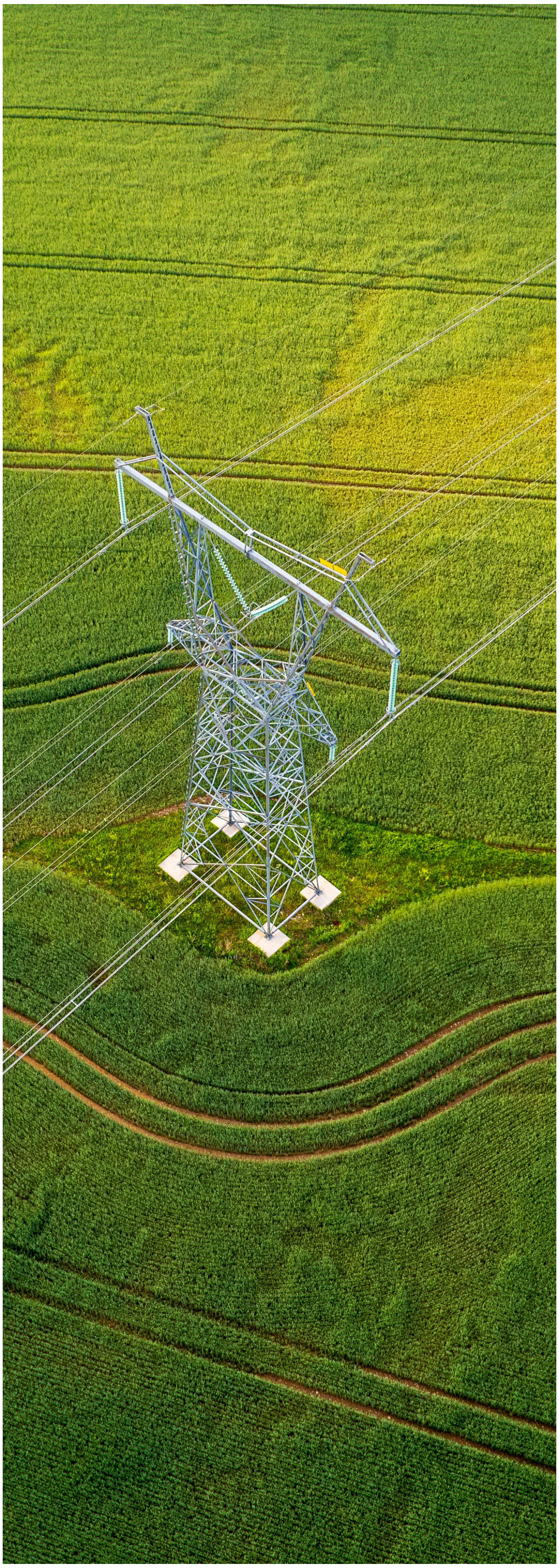
1200 GW implied by the tripling target. Many proposals have not resulted in a finished reactor.

Figure 1 Global Reactor Capacity (GW)[iii]



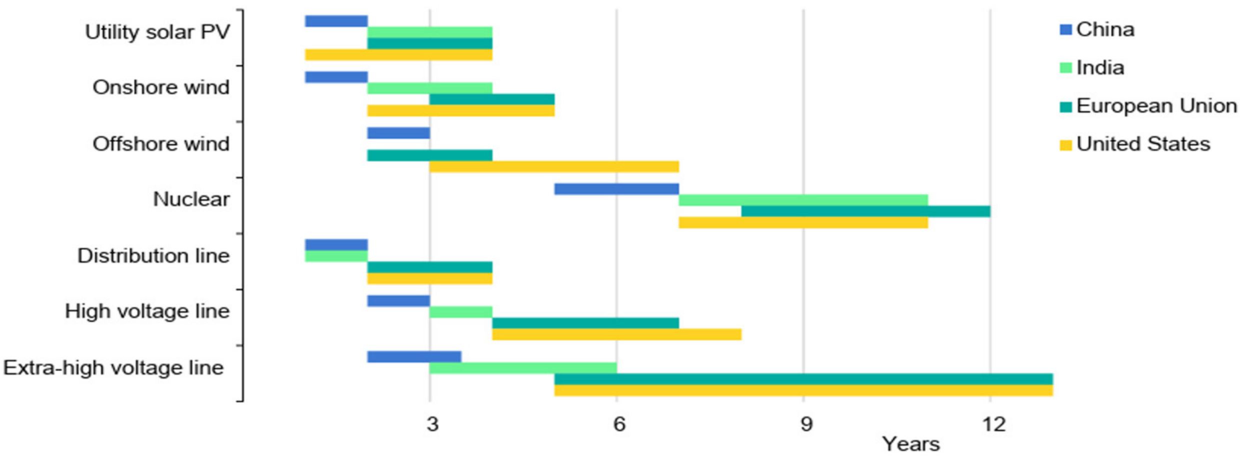
Furthermore, this construction is highly concentrated. Nearly half, 33 GW out of 70 GW, is in China. China also accounts for nearly half of the planned new capacity and more than half of the proposed new capacity. Other countries will have to contribute more if the potential of nuclear power is to be realised.

Nuclear power has also received recent higher attention because of the realisation that electricity demand growth in developed countries, notably the US, will likely be considerably higher than previously forecast. This is because of the growth of artificial intelligence and the requirement for electricity-intensive data centres. As these have large demand, several hundred megawatts or even gigawatts in a single location, and continuous operation and cooling is required, there are concerns that solar and wind will not be sufficient and suitable as their sole power source.



However, traditional nuclear power, with its long construction timelines (Figure 2) and frequent delays and cost overruns, is also problematic for serving the fast-evolving data centre industry. Even in China, build times are from five to seven years, and this stretches to seven to twelve years in the US, Europe and India. This contrasts to a solar or wind plus battery system that can be installed in one to four years.

Figure 2 Construction Times for Electricity Infrastructure[iv]



Small modular reactors (or small and medium reactors), SMRs, promise to solve these problems. They range from micro-reactors of 10 MW or less, to medium-sized reactors of 470 MW (Rolls-Royce's design), though the International Atomic Energy Agency defines an SMR as being up to 300 MW. Not all small or medium reactors are modular (for example, India operates Bharat Small Reactors, 220 MW pressurised heavy water reactors, which are not modular), so this discussion concentrates on small and medium modular reactors.

The overall aim for SMRs is to reduce the time and risk associated with constructing large nuclear reactors. Although the per-megawatt cost of SMRs will probably initially be higher than for conventional plants, this should also fall. This recognises that the erosion of nuclear skills and supply chain in Europe and the US, and an unfavourable outlook from regulations and public perception, mean that just trying to do conventional large nuclear power "better" will not be enough.

SMRs have a number of potential advantages over large conventional reactors[v]:

- Their design is simplified and standardised.
- They would be fabricated in factories and assembled on-site, so reducing costs, construction time and on-site risks.
- Construction of multiple units in a factory allows for "learning by doing", so reducing costs. The ambition is that manufacturing SMRs should be more like the assembly line for large commercial aircraft, than the one-off megaprojects for conventional nuclear reactors.
- Their smaller footprint makes them suitable for more locations than large conventional reactors. Their lower cooling needs and use of passive cooling means they do not need to be located next to bodies of water.
- Multiple modules can be installed at a single site, so matching increasing demand, and sharing some common facilities such as control rooms and substations.
- Some designs are intended to be buried, for enhanced safety.
- They have a lower individual financial risk for the fabricator and developer. A quicker and more predictable cost should in turn lower the cost of capital, further reducing the delivered cost of electricity from the SMR.
- They open up a more diverse range of investors and business models, because the lower capital exposure and financial risk means they are not limited only to use by large utilities, usually requiring state backing or regulatory guarantees of cost recovery from customers. They could, for instance, be financed based on an offtake agreement from a financially strong data centre user such as Alphabet (Google) or Microsoft.

- They can be developed and installed more quickly, so meeting urgent power needs.
- They offer a lower risk to the grid, since a single generating unit ideally should not represent more than 10% of total grid capacity. They also offer more geographic diversification of sites, so reducing the impact of extreme weather, natural disasters and so on. They also would require less grid build-out, since they can be located relatively close to demand centres.
- They can be installed sequentially to meet growing electricity needs, reducing the risk of under- or over-estimation of demand.
- The micro-reactors can be located in remote communities, mines, military sites and suchlike, or to meet specific needs, such as heat provision or desalination. They could even be located on ships to provide motive power or plug-in mobile power for coastal sites (nuclear reactors for military submarines and aircraft carriers are, of course, widely used and typically range from 4-165 MW of electrical output).
- They often have more passive safety systems than large conventional reactors. Their smaller size means they may not require active cooling, reducing or eliminating the risk of 'meltdown', and lowering the consequences of an accident, as well as reducing the potential amount of radioactive material that could be released.
- They have lower fuel requirements than large conventional reactors and can operate for three to seven years without refuelling, or even up to 30 years in the case of some designs, as compared to conventional reactors which require refuelling every one to two years. This can lower operating costs, raise uptime, and reduce proliferation and accident risks. It would also give less concern about interruptions to fuel supply, an issue with Russia's dominance of parts of the fuel supply chain as discussed below.

Overall, the main case for SMRs is that they will be delivered quicker, and at lower and more predictable costs, than large conventional reactors. Achieving this requires a significant number of orders of one design, to allow manufacturing experience to be gained, and design and procurement costs to be spread over multiple units.

However, SMRs have disadvantages too. In particular, their smaller size gives them less economies of scale than a large plant. They face many of the same design and approval requirements as a large reactor but spread over a smaller output.

Despite their better proliferation resistance, they may also be considered as a proliferation or security risk, given that more would be built, and they would be located in more diverse locations than large conventional reactors, and with less individually tailored security at each site.

There is little technical experience today in constructing and operating civilian SMRs. Only two countries are currently operating non-military SMRs: Russia (the water-cooled RITM-200 and KLT-40S) and China (the gas-cooled HTR-PM). The RITM-200, with 40 MW output, has been installed in icebreakers. This makes it hard to be sure how the reactors will perform in practice, and whether ordering and building numerous units will indeed drive down costs as proponents suggest.

An enormous variety of types and sizes of SMRs have been proposed, numbering almost 100 worldwide as of 2024.

Modern reactors can be divided into Generation III+ and Generation IV. Generation III+ are essentially traditional, usually pressurised water-cooled reactors, operating at output temperatures of <350°C, and using light or heavy water. They have additional safety features which distinguish them from Generation III and earlier reactors. They use either traditional low-enriched uranium fuel (LEU) with <5% uranium-235, or mixed oxide of uranium and plutonium (MOX), which can be derived from waste reprocessing or nuclear weapons decommissioning. LEU has the advantage of being familiar and widely commercially available. SMRs of this type would essentially be scaled-down versions of current commercial reactor types.

The exception is Canada's CANDU, an SMR version of a familiar large design, which uses natural (non-enriched) uranium with a heavy water moderator.

Generation IV, by contrast, may use novel coolants, allowing them to operate at much higher temperatures, in some designs up to 950°C. This raises their thermal efficiency, above the 30-34% achieved by water-cooled reactors. Coolants under investigation include sodium, lead, and a mix of lithium and beryllium fluoride salts[vi]. The waste heat could be used for purposes such as heavy industry, water desalination or thermal production of hydrogen. However, hydrogen production would require temperatures >900°C, which only a few designs achieve, and which would need novel, high-performance materials.

There is not as much experience with these coolants as with water, they are not so readily available, and they may be corrosive and present issues of material design. Sodium, for example, is combustible in contact with water or air. However, they operate at atmospheric pressure, unlike pressurised water reactors, which improves safety and lowers the requirements for the containment vessel. The boiling point of the coolant is usually well above the operating temperature of the reactor, reducing the risk of boiling and loss of cooling. Molten salts have a negative temperature coefficient of reactivity; that is, as their temperature increases, the rate of the nuclear reactor slows, preventing runaway reactions of the sort seen in the 1986 Chernobyl accident (a water-cooled reactor). Molten salt models can be capable of storing thermal energy to provide steady output or to follow load.

The Generation IV reactors would mostly use high-assay low-enriched uranium (HALEU) as fuel, which is enriched up to 5-20% uranium-235, as this allows longer times between refuelling, smaller sizes and higher efficiency. TRISO (tri-structural isotropic fuel) is enriched up to 20%. However, Russia and China are the only countries producing HALEU commercially, while the US has just begun to produce its own[vii]. A few proposed designs employ thorium, which has lower proliferation risk and widens the resource availability (India has large thorium resources but little uranium). However, thorium-based fuels are not widely developed.

Generation IV reactors can be developed in SMR size ranges or larger. Most SMR designs today would be considered Generation IV, though some would be Generation III+, being essentially derivatives of existing large designs. Generation IV SMRs may also be known as Advanced Modular Reactors (AMRs)[viii].

Table 1 Typology of Some Key Features of SMR designs[ix]

Generation	Generation III+		Generation IV			
Operating temperature	<350°C		400-950°C			
Coolant	Pressurised water Boiling water		High-temperature gas (helium, others)	Liquid metal (sodium, lead, bismuth, others)	Micro-reactor[1]	Molten salt (lithium beryllium fluoride, others)
Fuel	LEU	MOX	HALEU			LEU HALEU Thorium
Size	10 MW to 350 MW				<10 MW	1-350 MW

1. A variety of cooling strategies are proposed; cooling is easier in a micro-reactor

A non-exhaustive typology is shown in Table 1; note that this does not include all SMR designs or necessarily imply that some combinations of characteristics are non-viable.

A wide variety of SMRs are in various stages of design and development worldwide. Examples of some of the most prominent SMR designs include the following.

Table 2 Selected SMR designs (iPWR = integral pressurised water reactor, PHWR = pressurised heavy water reactor, BWR = boiling water reactor, MSR = molten salt reactor, LFR = lead-cooled fast reactor, SFR = sodium-cooled fast reactor, HTGR = high-temperature gas-cooled reactor, LEU = low-enriched uranium, HALEU = high-assay low-enriched uranium, TRISO = tri-structural isotropic fuel, MNUP = nitride uranium-plutonium)

Reactor	Company	Country	Size (MWe)	Fuel	Reactor Type	Temperature (°C)	Year available
Conventional							
VOYGR	NuScale	US	77	LEU	iPWR	343[x]	2029
Westinghouse SMR	Westinghouse	US	300	LEU	iPWR	325	2029
Rolls-Royce SMR	Rolls-Royce	UK	470	LEU	iPWR	325	Early 2030s
ACP100	CNNC	China	125	LEU	iPWR	303[xi]	2026
CAREM	CNEA	Argentina	32	LEU	iPWR	320	2028
RITM-200N	Rosatom	Russia	55	LEU	iPWR	316	2028
BWRX-300	GE-Hitachi	US / Japan	300	LEU	BWR	288	2028
SMART	KAERI	South Korea	330	LEU	iPWR	310[xii]	NA
Nuward	EDF	France	170 (x2)	LEU	iPWR	320	2030
CANDU SMR	SNC Lavalin	Canada	300	Natural U	PHWR	310	2028
Advanced							
Aurora	Oklo	US	0.5	HALEU	SFR	500	2029
BREST-OD-300	Rosatom	Russia	300	MNUP	LFR	540	2026
Natrium	TerraPower	US	345	HALEU	SFR	500-600[xiii]	2028
ARC-100	ARC Clean Energy	Canada	100	HALEU	SFR	510[xiv]	2029
Xe-100	X-Energy	US	80	TRISO	HTGR	>750	2029
CMSR	Seaborg Tech	Denmark	100	LEU[2]	MSR	600-700	2028

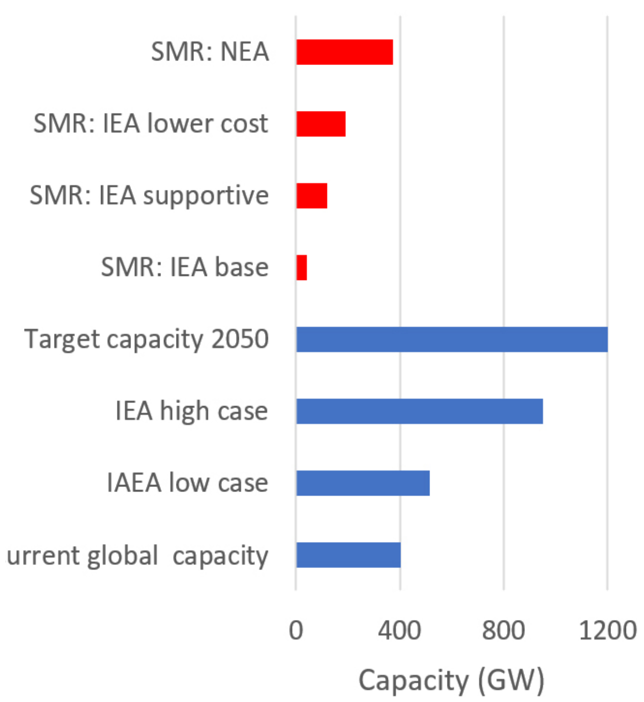
2. Could switch to HALEU later

THE OUTLOOK FOR SMRS

The International Energy Agency (IEA) has found that current plans total about 25 GW of SMR capacity. With today's policies, installed SMR capacity would reach 40 GW by 2050. This would be about 10% of current nuclear capacity of all types, and an insignificant part of the overall electricity generation picture.

With tailored policies to support nuclear power, SMR installations could add up to 120 GW by 2050, from more than one thousand reactors. Cumulative investment would be $670 billion . If construction costs could be reduced to parity with large, on-budget reactors by 2040, then cumulative installations by 2050 would reach 190 GW, with $900 billion invested.

Figure 3 Global overall nuclear and SMR capacity projections[xvi]



Average unit capital cost would be $5.6 million per megawatt in the 120 GW case, and $4.7 million per megawatt in the 190 GW case. The OECD's Nuclear Energy Agency has a high case of 375 GW by 2050.

To compare this to projections of total nuclear capacity, the IEA's 190 GW case would amount to 20% of total installed nuclear capacity by 2050 in its high case. The NEA's high case by 2050 would be about equal to the current installed base of (conventional) nuclear capacity, and more than 30% of the amount required to triple global capacity by 2050.

The levelised cost of nuclear power depends primarily on the capital cost, the construction period, the cost of capital and the capacity factor (the ratio of average to maximum generation, i.e. allowing for outages, refuelling and periods of lower demand when output is deliberately reduced). Fuel costs, other operating costs, decommissioning and waste disposal are typically a small fraction of the overall cost.

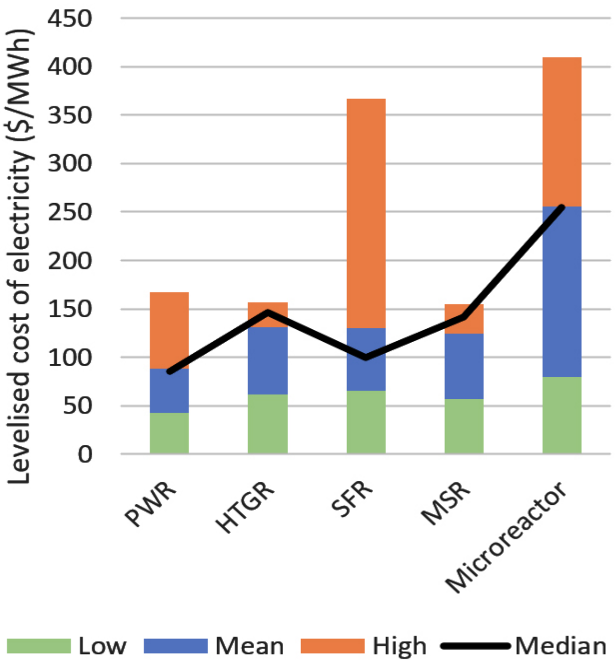
The economic attractiveness of SMRs could be further boosted by making use of their waste heat for district cooling, desalination or industrial use.

Estimated levelised cost of electricity (LCOE) includes capital and operating costs and return on capital over plant life. LCOEs for SMRs have increased in recent years, partly because of general inflation in materials and other inputs, partly because of higher interest rates, and partly because of some delays and disappointments in delivering new SMR designs.

Notably, the target cost for NuScale's SMR rose from $55 per megawatt hour (MWh) in 2016 to $58 in 2021, then to $89 in January 2023. As noted, excluding government tax credits, the cost may be as much as $120 per MWh.

Cost estimates for different types of advanced reactor have been compiled and standardised (Figure 4). Note that this includes both SMRs and large reactors. The non-PWR designs do not appear to have any clear cost advantage; in fact, their minimum, average and median costs are all higher than for the set of PWRs considered. Microreactors are significantly more costly, not surprisingly given the lack of economies of scale. Excluding the microreactors, minimum costs are in the range $43-57 per MWh and averages from $89-131. Depending on the location, it's likely that levelised electricity costs of $80 or below would make SMRs a viable option versus renewables with battery backup.

Figure 4 Cost Estimates for Different Advanced Reactor Types[xvii]



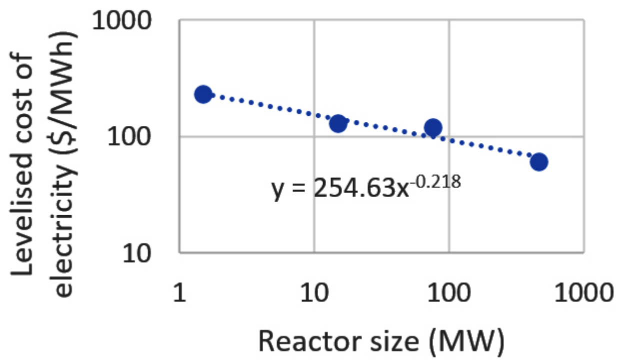
Rolls-Royce suggests the fifth unit delivered of its 470 MW design would cost £1.8 billion ($2.27 billion at current exchange rates), and it targets the ultimate levelised cost of generated electricity as £40-60 per MWh ($50-70 / MWh). Oklo suggests $80-130 per MWh for its 15 MW design and $230 per MWh for its 1.5 MW design. As noted, NuScale's costs for its 77 MW design have appear to be around $120 per MWh.

There are some important caveats:

- These estimates are probably still over-optimistic
- The estimates are not necessarily on the same basis (date of the estimate, given recent cost inflation, and assumptions on cost of capital, fuel price, operating rate, etc)
- They include two Generation IV designs (the two Oklo versions) and two Generation III+ (NuScale and Rolls-Royce)

Nevertheless, they line up reasonably on a logarithmic plot (Figure 4). This suggests that doubling the size of the reactor reduces the unit cost of electricity generated by about 20%.

Figure 5 Levelised Cost of Electricity from SMRs Versus Size

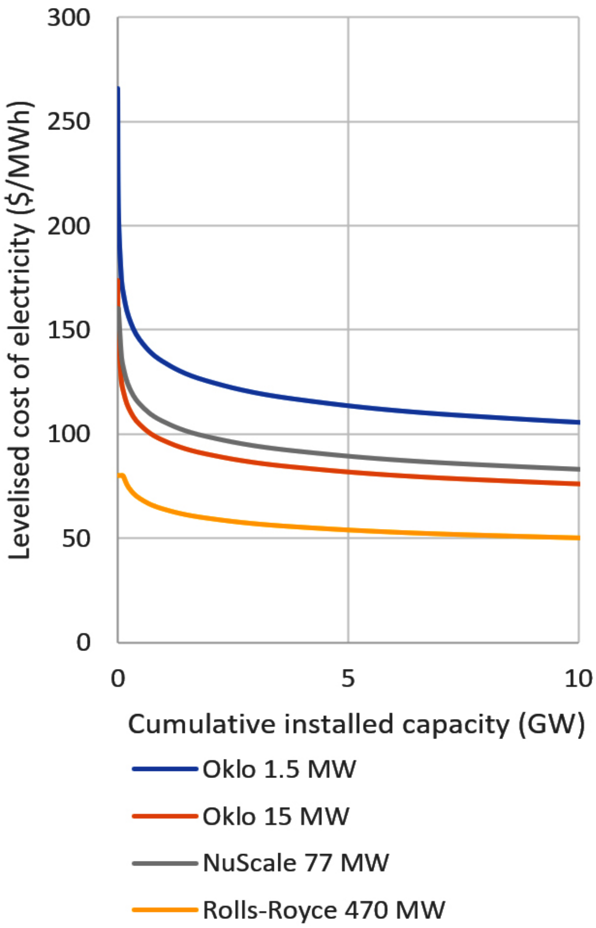


SMRs are expected to show higher learning rates than traditional large reactors, because of the greater repeatability and standardisation of factory construction. The US Department of Energy suggests a learning rate of 7% - i.e. a cost reduction of 7% for every doubling of cumulative installed capacity. A UK government study suggests learning rates of 7-10%[xviii]. Achieving these learning rates depends on deploying reactors quickly so lessons are not forgotten, minimising re-designs, and standardising on one or a few models.

Considering a range of SMR sizes from the smallest (Oklo's 1.5 MW design) to the largest (Rolls-Royce's 470 MW), the smaller designs are more expensive, but they should also learn quicker as more are build for the same cumulative GW capacity. Figure 5 illustrates some important conclusions from this. If the scaling relationship derived above is reasonable, and applying a learning factor of 0.93, the learning does not outweigh the cost disadvantage of the smaller reactor.

This may partly explain why NuScale has several times redesigned its plant to larger versions. Most of the learning is achieved in the first 10 GW of deployment.

Figure 6 Potential Costs with Learning for Four Sample SMR designs



In the case of the Rolls-Royce design, its projected cost of $2.27 billion is achieved by the fifth unit. Accounting for the fact that the earlier units are more expensive, the total expenditure on these first five units would probably be around $12 billion. This is a substantial commitment. However, it would deliver 2.35 GW of generating capacity, albeit with some technical risk. If the reactors are built sequentially rather than in parallel, and each takes 500 days as the company

estimates, it would require about 7 years to construct five units.

For another comparison, the first of TerraPower's 345 MW Natrium reactors is expected to cost $4 billion, but subsequent iterations should reduce this to $1 billion each[xix].

In contrast, the conventional Hinkley Point C station, with 3.6 GW of capacity, started construction in 2016, is estimated to be ready in 2029 (if there are no further delays) and its cost is now estimated at $58 billion (at current exchange rates). The Wylfa plant in Anglesey is estimated to cost from $18-21 billion for 2 GW[xx], and to be ready at best in the early 2030s. On this basis, it is easy to see the attraction for the UK government of sponsoring the development of a national champion technology with much lower unit costs, faster time to market, and lower exposure.

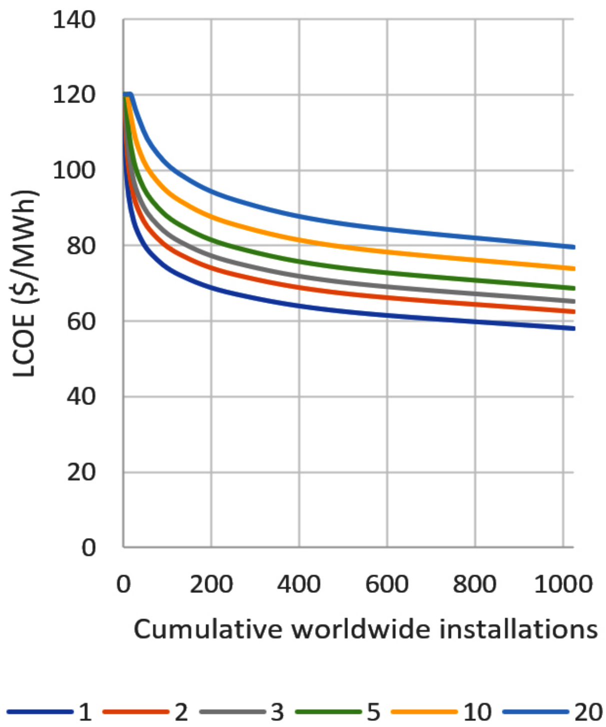
However, in countries able to build large conventional reactors well, such as China and South Korea, the economies of scale suggests that large reactors would continue to be preferred as the primary plant type.

If multiple SMR designs are built, learning will be slower. Assuming these is no cross-learning between different designs, and that the first-of-a-kind (FOAK) cost for a 77 MW design starts at $120 per MWh, Figure 4 shows the nth-of-a-kind (NOAK) cost depending on cumulative global installations. The total number of installations runs up to 1024, or 10 doublings of capacity, to the IEA's target of 120 GW from about 1000 SMRs.

It can be seen that achieving most of the projected cost reductions require the installation of at least 100 SMRs (about 12 GW at the assumed average size of 120 MW per reactor), if a single design is standardised on.

That would reduce the LCOE from the initial $120 per MWh to about $78 per MWh. In contrast, if 20 designs are built globally, the cost of electricity would be about $100 per MWh, and it would only fall to about $78 after 1000 installations (i.e. 50 installations of each type, on average).

Figure 7 Levelised Cost of Electricity, by Number of Reactor Designs



At this point, SMRs would be an economically attractive alternative to renewables plus battery back-up. Depending on the average size of the SMRs, that would require the installation of seven to twenty GW of capacity. That would already be a large fraction of the 25 GW the IEA expects to be installed globally by 2050 under today's policies.

This cost estimate is based on NuScale, a quite conventional design. FOAK for the innovative designs would likely begin significantly higher, particularly given the need to establish specialist supply chains and gain operating experience. The ultimate NOAK cost, though, may be lower. If a conventional SMR design is first to gain general acceptance, it may be hard for the innovative models to catch up, unless they demonstrate much superior cost or performance, can find a specific niche, or unless safety reasons make the conventional models unacceptable in some places.

In reality, it's very unlikely that the world will standardise on a single SMR design. Strategic reasons will make countries unwilling to rely on a geopolitical rival's design. Major countries will also insist on a full licensing process for foreign-developed reactors. At least, China, Russia, the US, and probably South Korea, Japan and one or more European countries are likely to take forward their designs. There may be more than one design per country, even though the Russia examples have quite a lot of commonalities. The U.S. is likely to see multiple competing versions. There will also be different use-cases, with the micro-reactors, the small reactors designed for mobile use, and the medium-sized reactors, each having different applications.

Given China's manufacturing prowess, and its good record on large nuclear construction, it's likely that China will be a very competitive provider of SMRs to other countries, particularly in the developing world. Russia also has significant experience both in domestic SMRs and in exporting conventional large nuclear reactors to countries including Egypt, Turkey and Iran. But the future of Russian SMRs is doubtful as sanctions and financial restrictions will exclude it from many countries, and other customers may doubt its reliability. South Korea, another leading exporter of conventional nuclear power, would need to accelerate efforts on its SMART or another SMR design to be a successful player. France, Canada and Japan, as traditional large-scale users of nuclear power, have made less progress with SMRs, and EDF's Nuward did not qualify for the UK shortlist (see below). Germany, another major historic centre of nuclear expertise, now has no significant activity in SMRs.

Fast reduction of costs would encourage more deployments, accelerating learning and creating the classic "snowball" effect. This will also favour those designs which are able to get to market earlier, even if they are not necessarily the technically superior solution.

19 RISKS AND CHALLENGES

The main risks SMRs face are economic, technological and socio-political. On the economic side, costs are likely to be higher initially than for well-built large reactors. This demands a commitment from government or large utilities or other offtakers to buy relatively expensive electricity with the expectation that the cost will fall over time.

This will not be so problematic if SMRs can indeed deliver on their promise of fast, problem-free installation, and steady falls in costs. But the record of one of the most advanced developers so far, NuScale, is not promising, even though some of the reasons for cost inflation are out of its hands.

Reducing costs will depend on a large and steady order book. The list of nuclear-accredited equipment manufacturers is short, so this raises risks of bottlenecks and cost squeezes[xxi].

The technological side mainly applies to the advanced or Generation IV designs. Despite their novelty, many are variants on previous experimental versions built in the 1950s and 1960s, such as sodium-cooled fast reactors and high-temperature reactors. These were not technological successes. SMR developers are therefore betting that subsequent improvements in areas such as modelling and simulation, and materials science, will overcome past problems.

The sociopolitical aspect covers issues such as the regulatory regime, and how reasonably it will assess the greater safety and simplicity of SMRs. It also includes the issue of public acceptability, and whether the general public will be comfortable with the widespread deployment of SMRs, particularly close to populated areas or on ships. It includes the requirement for consistent long-term political support for SMRs, to build the supply chain and gain experience.

If early SMRs experience major technological problems, cost overruns, delays, or safety concerns, then public and government support could quickly disappear. So far, the most advanced SMR outside China and Russia, that of NuScale, has undergone several redesigns, costs have risen substantially, and it has struggled to obtain and hold to offtake contracts.

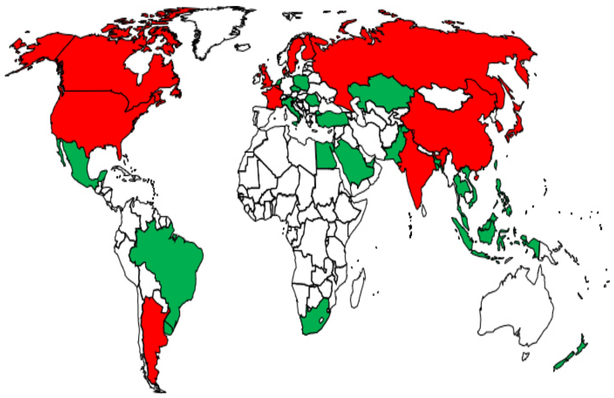
The main international nuclear developers today are China, Russia, South Korea, Canada, Japan and France. The US has fallen out of contention but would like to return, while the UK would like to develop a nuclear export capability. Most of these countries export large conventional reactors of around 1000 MW, such as Korea Electric Power Corporation's APR-1400 and Rosatom's VVER-1200. However, most also have ambitions to build and export SMRs. These may be scaled-down versions of their traditional designs, as with the Westinghouse AP300, or they may be innovative.

The US, though, has the greatest variety of SMR developments, both in reactor design and company, with large established nuclear players, notably Westinghouse, smaller companies and start-ups, and those backed by wealthy investors such as TerraPower, supported by Bill Gates. Also of interest are the designs from Denmark, Switzerland and Argentina, not traditionally players in large nuclear reactors.

As noted, outside the military sector, China and Russia have today the most experience with operating SMRs.

Several countries mention SMRs in their Nationally Determined Contributions under the Paris Agreement on Climate Change. These include the UK, US, Canada, China, Indonesia, Philippines, Brazil, Switzerland, New Zealand, the UAE and Uruguay. New Zealand does not have any nuclear reactors today, while nuclear power in Uruguay is currently forbidden by law. Therefore, the successful development of SMRs could broaden the use of nuclear power to new countries.

Figure 8 Countries Developing SMR Designs (red) or with Interest in SMR Deployment (green)



The recent surge of interest in nuclear power in general and SMRs in particular has been triggered by the awareness of growing electricity demand from data centres. Data centres account for about 1% of global electricity consumption today. 25 GW of SMRs for data centres have been announced worldwide, mostly for the US, but also in India, Japan, South Korea and Sweden. SMR developers involved in supplying data centres include NuScale, Oklo, Kairos Power and X-energy. Amazon anchored a $500 million investment in X-energy in October 2024[xxii], and in the same month, Google agreed to purchase power from Kairos's fluoride salt-cooled high temperature SMR, starting by 2030, with 500 MW of capacity by 2035. Swiss firm Deep Atomic has launched an SMR specifically for data centres, with 60 MW of power generation plus 60 MW of cooling[xxiii].

The UK's Great British Nuclear conducted a competition to choose an SMR design. In October 2024, this short-listed GE-Hitachi, Holtec Britain, Rolls-Royce and Westinghouse. EDF's Nuward and NuScale were dropped from the first long list[xxiv]. The short-listed designs are all based on conventional pressurised or boiling water reactors.

The competition is part of an overall plan to have 25% of the country's electricity coming from nuclear by 2050, up from 15% today (and accounting for retirements of old existing nuclear plant). Beyond known large-scale plants, the gap of about 14 GW could be met with 40-50 of the larger SMRs[xxv].

South Korea's 11th Basic Plan for Electricity Supply and Demand includes 700 MW of SMRs to be installed by 2038[xxvii]. Thailand intends to have 600 MW of SMRs in its Power Development Plan of July 2024.

Saudi Arabia has cooperated with South Korea on its SMART reactor design[xxvii]. In October 2024, the King Fahd University of Petroleum and Minerals announced plans to design a Generation IV reactor in cooperation with the Paul Scherrer Institute of Switzerland, considering sizes from 10-300 MW[xxviii]. In December 2024, the Emirates Nuclear Energy Corporation (ENEC) of the UAE signed memoranda of understanding with several SMR developers, including MoltexFlex of the UK, and X-energy and Ultra-Safe Nuclear Corporation of the US. It had previously concluded cooperation agreements on SMRs with GE Hitachi, TerraPower, General Atomics and Westinghouse. These agreements could cover the deployment of SMRs in the UAE or in international joint ventures.

There is widespread interest in SMRs, and they offer hope for a revival of the nuclear power industry, particularly in the West. China and Russia are more advanced in deploying SMRs, but their conventional large nuclear industries have also progressed well, therefore SMRs are relatively less important to them domestically.

SMRs are likely to play a supporting role to the overall required expansion of nuclear power globally, perhaps from 10-30% of capacity. In scenarios where nuclear power is highly successful, both SMRs and conventional large reactors are likely to see gains. It is possible to imagine a world where nuclear expansion outside Russia and China is very limited, and mostly comprised of SMRs, but in this case the SMR industry would still be fairly small.

SMRs, though, would be important in three ways. First, as noted, they could help re-establish nuclear power as a growing source of electricity in Western countries, where past budget and time overruns have made conventional large reactors unattractive. This would include serving new sources of electricity demand, notably data centres.

Second, they could bring nuclear power to new settings, including remote or mobile locations, and developing countries or those with small grids that would not accommodate a large reactor. That could help in decarbonising some hard-to-abate sectors such as mining, shipping, small island states, and the military.

Third, learnings from SMRs might return to the world of large reactors.

That could include demonstrating Generation IV designs, building the overall skills base and supply chain, increasing the amount of modularisation and factory build possible for larger reactors, or building overall confidence in nuclear power among the general public, regulators and financiers. Such outcomes would support the overall expansion of nuclear power.

Within the Middle East, the interest of the UAE and Saudi Arabia in SMRs is understandable. They have fast-growing electricity demand, low cost of capital, are comfortable with the technology's safety profile, and have proved their ability to deliver large projects reasonably on time and budget. The UAE also has already a successful programme of conventional large-scale reactors. SMRs' waste heat can be used in desalination.

However, given the Middle East's highly cost-competitive solar projects and the ability to use battery storage to provide 24-hour power at around $60 per MWh, SMRs face a major economic challenge. Even on quite an optimistic viewpoint, SMR costs will only be approaching $60 per MWh after hundreds of worldwide deployments. They will also struggle to compete with large conventional plants on cost in countries that can build them well, such as China, South Korea or the UAE. Nevertheless, their faster construction time may still make them attractive, especially where power is required more urgently.

Within the relatively long timescale to certify and deploy SMRs, particularly the innovative models, batteries and renewables will continue to improve. It is even possible that commercial nuclear fusion may be available by the 2040s and may be preferred to fission power. Therefore, SMRs need to be on the grid by the late 2020s to start benefiting from learning-by-doing.

While most attention on SMRs has focused on the different technologies, other aspects are also crucial for their success. These include the regulatory system, the supply chain, and the provision of expertise. Governments and industry need to work closely together to ensure the assembly of the supporting ecosystem for large-scale SMR deployment. Any safety problems with early SMRs could also have major negative implications for public acceptability and set back their adoption, as has happened with large reactors.

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xvii. Data from https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_66425.pdf. Note that one outlier microreactor with very high costs was excluded
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September – 2024

COP29: The "Finance COP" and the Road to Brazil

The 2024 United Nations Climate Change Conference (COP29) conference in Azerbaijan was the third in succession held in the wider Middle East region, and the third in a row to occur in a significant oil and gas producer.

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November – 2024

Oil and Upstream Investments

The oil industry is in an investment upcycle, even though the demand rebound after the COVID-19 pandemic has largely abated. Whilst the low-carbon energy system roll-out continues, oil will continue to meet global energy demand and define energy security for years to come.

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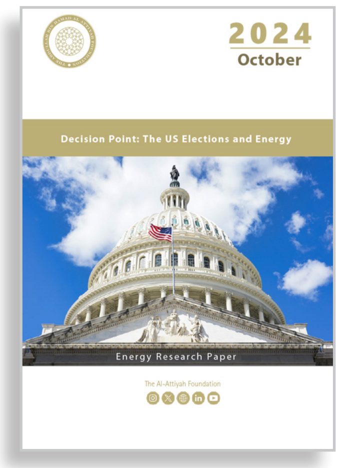

October – 2024

Decision Point: The US Elections and Energy

Almost half the world's population is expected to vote this year, marking an unprecedented turnout. Soon, it will be the United States' turn – on 5th November 2024, it will elect a new president and numerous legislators, including all 435 members of the House of Representatives and 34 of the 100 Senate seats, along with various state and local offices.

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