MACRO POLO

# Splitting or Fusing Atoms: Revitalizing Nuclear

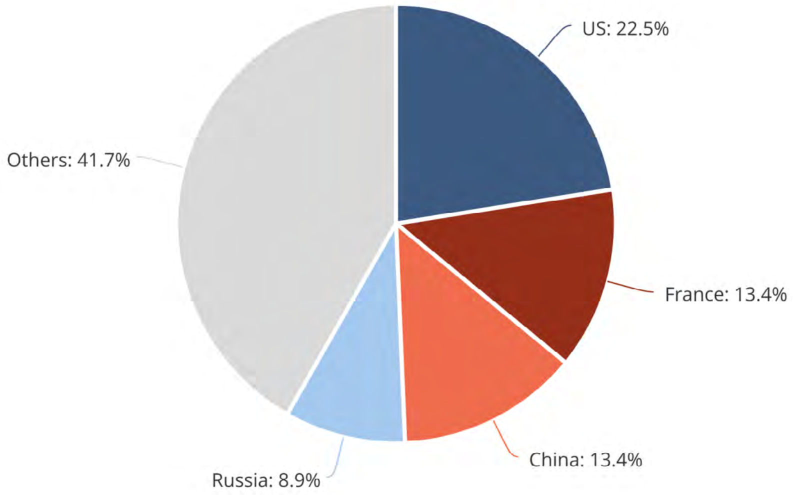
Amy Ouyang

# Nuclear Series (Part I):

## A Nuclear Renaissance Around the Corner?

In the 70 years since the first civilian nuclear plant came online in 1954—deployed by the former Soviet Union—the nuclear industry has matured and become global. Today, there are 416 active nuclear reactors in the world, of which almost 60% are concentrated in four countries: United States, China, France, and Russia (see Figure 1).

**Figure 1. Commercial Nuclear Reactors Concentrated in Just Four Countries**



Source: International Atomic Energy Agency (IAEA).

Yet while the global distribution of commercial nuclear has changed significantly, the industry itself has changed little. On cost, in addition to steep regulatory barriers and national security concerns of accessing uranium, nuclear power's unit economics are still far from competitive with similar-sized coal plants. On technology, light water reactors are still the prevailing model, though with more advanced designs and safety features. On perception, the industry has yet to shake the image of being defined by the rare accidents rather than by the abundant record of safe operations.

These limiting factors on unleashing the full potential of nuclear power underscore why it remains just 10% of the global energy mix. But now more than ever, nuclear power may be on the cusp of a renaissance where emerging business model innovations, fundamental technology breakthroughs, and significant private and public capital commitments all conspire to drive the industry to new heights.

No net-zero scenarios are achievable without accounting for a significant increase in nuclear power capacity—projected to exceed 800 gigawatts (GW) by 2050—more than doubling from today. That's because nuclear power remains the best low-carbon baseload alternative to coal—solar and wind are simply insufficient. It can power cities and data centers alike, all of which require constant and reliable electricity.

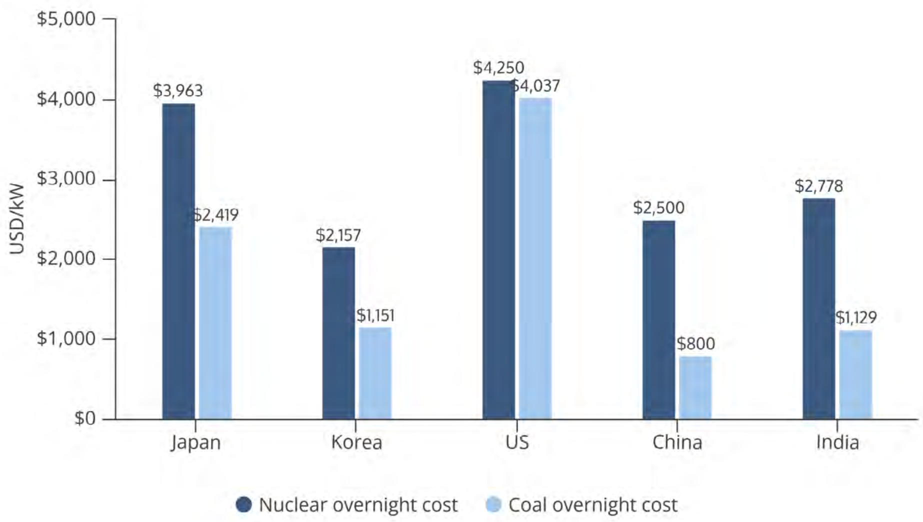
As such, the coming decade is likely to bring more dynamism in the nuclear power industry than seen in many decades. This mini-series will examine the industry's potential renaissance, starting with this scene-setter on the current state of play. Future installments will focus on small modular reactors' (SMRs) potential effect on cost and on the real and intense race toward capturing that elusive holy grail: commercial fusion.

## 1. Cost: Economies of Scale Still Elusive for Nuclear

Nuclear has always been touted as the optimal baseload alternative to coal—it is clean and reliable, can power medium-sized cities, and has no intermittency like solar and wind. But when compared to coal plants, nuclear power plants on average are still 2-3 times more expensive.

For instance, a 1 GW nuclear power plant can cost anywhere between $5.5 billion to $10.5 billion, whereas a coal plant with similar capacity runs about $1 billion to $4.5 billion (see Figure 2). The cheapness of coal, despite its negative externalities, means that globally coal plants outnumber nuclear by a factor of 16:1.

**Figure 2. US Nuclear Plants Are Twice as Expensive as South Korean Plants**

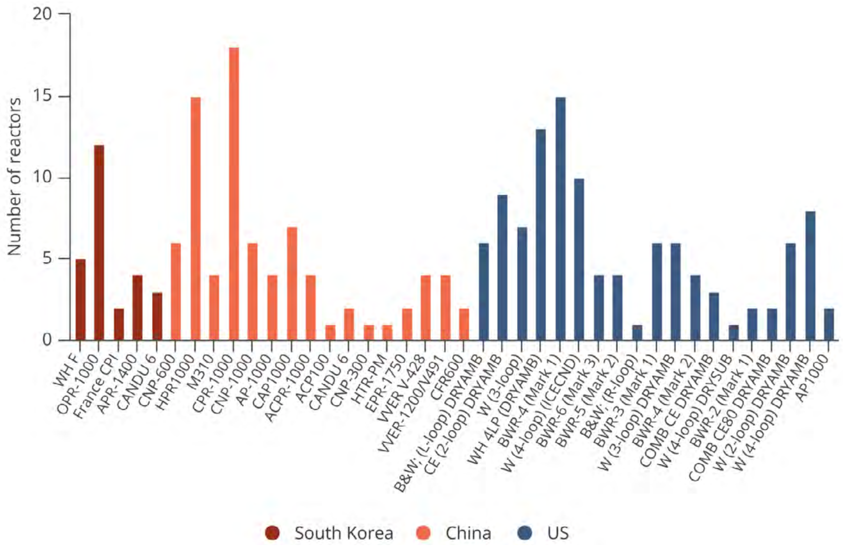


Note: Overnight cost compares plant construction costs—such as materials, labor, and permitting/licensing—excluding capital costs like interest payments.
Source: International Energy Agency (IEA).

Various factors contribute to cost differentials across countries. Take South Korea, which owes some of its lower cost to reactor standardization and modest economies of scale—that is, it focuses on fewer reactor models but larger plants housing multiple reactors with identical designs and specifications (see Figure 3). For instance, 35% of US nuclear plants have only one reactor, whereas nearly half of South Korean nuclear plants have six reactors with one or two models.

This approach makes it easier to regulate and build plants, because many of the components can be mass produced as there's little variance. Moreover, by using just five reactor models, the construction workforce is familiar with them, making plant-building more standardized to keep projects on budget and on time.

**Figure 3. South Korea Relies on Fewer Reactor Models and Larger Plants**

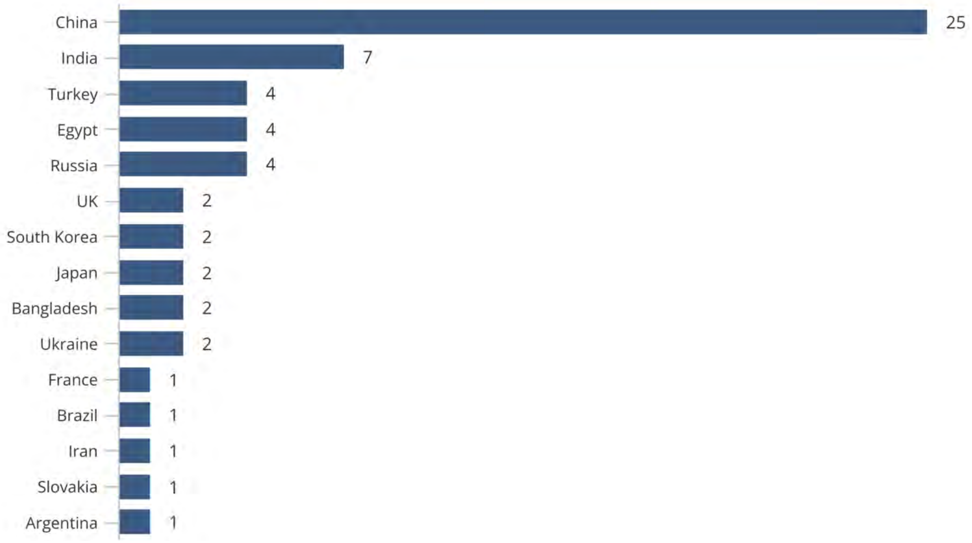


Source: IAEA & World Nuclear Association.

A more general reason for cost differentials is regulatory. China, for example, approves up to 10 reactors annually, because the nuclear industry is entirely state run and essentially doesn't have to deal much with regulatory snafus. The state monopoly on nuclear also means that the Chinese government typically shoulders the risk associated with high capital expenditure. The industry also benefits from cheap financing and land, further driving down the cost of plant construction.

Over that last decade-plus, China has quintupled its nuclear power capacity and currently has 42 units planned and 25 under construction, three times more than second-place India (see Figure 4). China is now nearly at parity with France on nuclear power capacity and is projected to surpass the United States by 2050.

**Figure 4. China Building More Reactors Than Next Six Countries Combined**

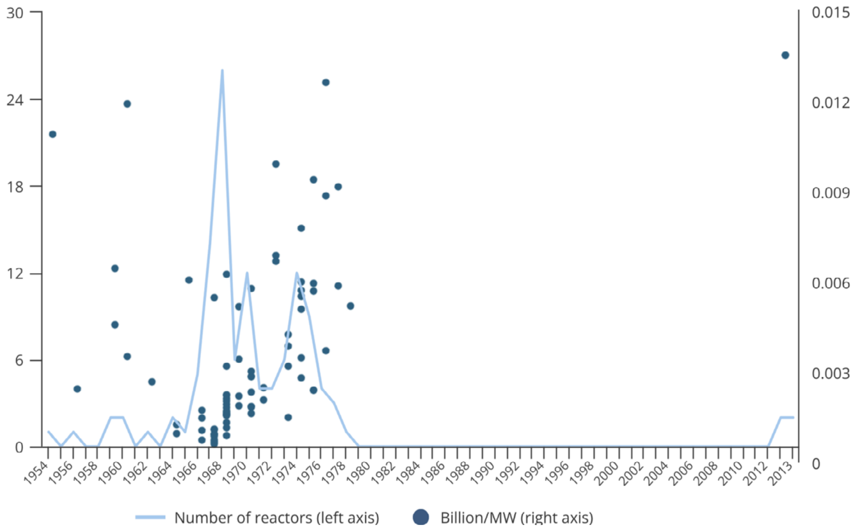


Source: IAEA.

By contrast, regulatory cost in the United States remains high. Not only is the approval process for new plants onerous and expensive, it can take up to a decade before they enter commercial operation. For instance, NuScale, a startup specializing in SMRs (the subject of the next installment in the series), spent over $500 million and more than two million work hours to get an approval.

On top of that, a three-decade drought in plant construction has led to more frequent cost overruns (see Figure 5). The latest American nuclear reactors Vogtle 3 and 4 in Georgia have racked up nearly $35 billion in cost since construction began a decade ago. Moreover, two Westinghouse projects in South Carolina and Georgia were cancelled as their costs ballooned from the initial $11.5 billion to $25 billion, resulting in Westinghouse’s bankruptcy in 2017.

**Figure 5. Three Decades of Nuclear Power Drought in the United States**



Note: Construction cost measured in 2018 US dollars.
Source: IAEA; author’s calculations.

Similar to the United States, second-largest nuclear power France also saw no new reactors since the 1990s. Perhaps unsurprisingly, France’s decades-long pause on building nuclear is also contributing to delays and cost overruns with its Flamanville 3 reactor currently under construction.

So with some exceptions, the unit cost of nuclear power in major markets has generally gone up instead of down. The general stasis across the industry likely has much to do with it, as the lack of building for decades means it is difficult to rapidly reconstitute that knowledge or bring the right labor skills to complete projects on time and on budget. Moreover, when few nuclear plants are being built, it’s difficult to deploy new business models and pursue major technological breakthroughs and iterative innovations.

## 2. Technology: Incremental Advancements and Hard to Scale

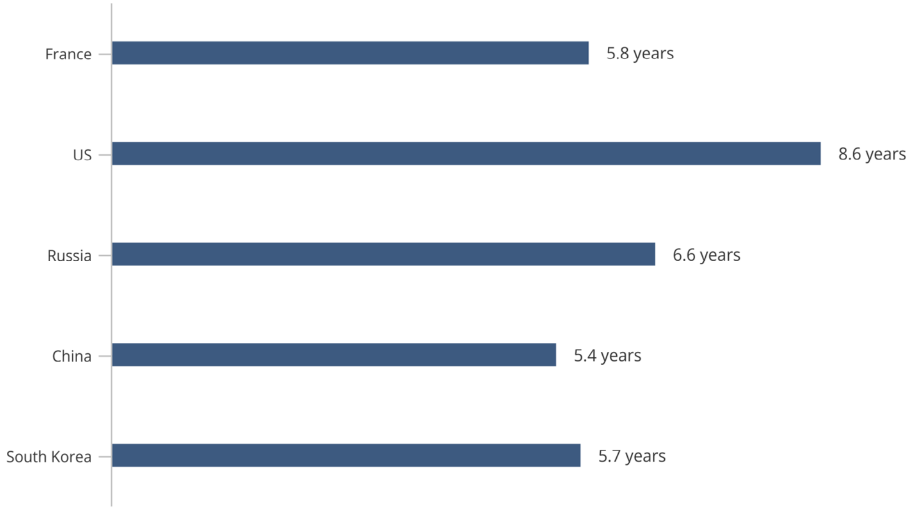
Indeed, the core nuclear fission technology has remained light water reactors, the same fundamental technology since the 1960s. To be sure, reactors have become more sophisticated and safer, as well as seen improvements in using heavy water as coolant for fuel flexibility. But the vast majority are still light water reactors, typically of the pressurized water or boiling water varieties.

The lack of a step-change in technology or significant business model innovations within the nuclear industry means that regulations are still largely based on paradigms established in the mid-20th century, with little incentive to expedite the deployment of nuclear power. If anything, recent nuclear accidents, such as Fukushima in Japan, have only convinced regulators to lengthen the approval process and requirements for building plants.

And of course one of the obvious reasons is that civilian nuclear power still cannot be separated from national security because nuclear fissile materials are uranium and plutonium, which have clear dual use concerns for weapons. So long as civilian nuclear projects—from facilities to technologies to fuel—can be potentially used to produce nuclear weapons, the industry will be inevitably subject to stringent regulations under the non-proliferation framework.

It's no surprise, then, that high regulatory cost and lengthy construction times still plague the industry. Even for China, considered a "fast builder", it takes at least five years to build a nuclear plant, whereas it was building about 10 coal plants/month for much of the past two decades (see Figure 6).

**Figure 6. Nuclear Plants Can Take Nearly a Decade To Begin Operations**



Sources: IAEA; author's calculations.

## 3. Perception: Cognitive Dissonance on Nuclear Safety Remains Bottleneck

While the nuclear industry has a safety-first culture and a demonstrated record of generating a lot of clean energy without incident, the rare, high-profile accidents have shaped public perception of the risks. This is similar to the aviation industry. Despite flying being widely acknowledged as the safest form of transportation, a single fatal plane crash disproportionately heightens people's fears associated with flying.

Nuclear power is subject to the same cognitive dissonance. The empirical reality is that nuclear power has had 18,500 cumulative reactor-years of safe operations globally, with only two major accidents, namely Chernobyl and Fukushima (Three Mile Island was a less significant incident).

Nonetheless, that perception of nuclear risk has had a significant impact on the industry. Following Fukushima, for example, Japan shut down and suspended a majority of its nuclear reactors, drastically lowering the nuclear share in its energy mix from 30% prior to the accident to a mere 6% now. In a more extreme move, Germany, once a staunch advocate for nuclear energy, responded to Fukushima by completely phasing out its nuclear power.

But on the flip side, the state of Illinois has operated the largest nuclear fleet in the United States for decades without major incident. As a result, nuclear energy accounts for almost 55% of Illinois' energy mix, while the percentage of the state's electricity generated from coal sharply declined to just 15%. That has helped the state avoid 82 million metric tons of carbon emissions.

Perhaps more than ever, new technological advancements and business model innovations are emerging that have the potential to overcome the constraints faced by the nuclear industry. As the bottlenecks in the nuclear power industry loosen, a renaissance seems more than simply wishful thinking. We will look toward those potential greener pastures in the next installments in the series.

## Nuclear Series (Part II):

# Can Business Model Innovation Lower Cost?

A key bottleneck of the nuclear industry is its unit economics, as noted in our previous scene-setter. The cost of nuclear simply hasn't fallen much, despite deep and distributed knowledge globally of designing and building reactors for seven decades.

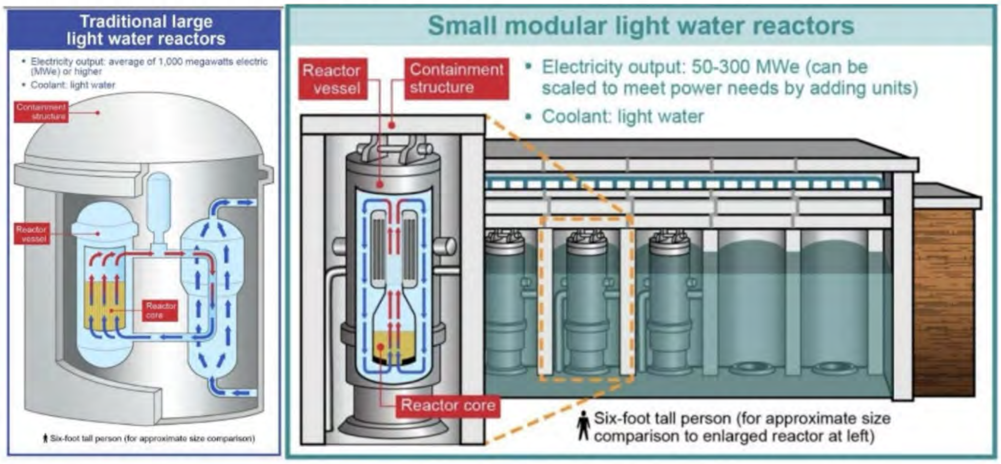
Without overcoming the cost challenge, the nuclear renaissance will fizzle out before it even gains much steam. Bending the cost curve of nuclear over the medium term, however, is less about technology and is almost entirely about business model innovation that's focused on achieving the two Ss: standardization and scale.

In other words, nuclear plants need to be built differently and many more reactors need to be built. There are essentially two ways to do that: build much larger conventional nuclear plants with up to half a dozen reactors a la the South Korean model or build many small modular reactors (SMRs) that can provide distributed baseload power. In Part II of this nuclear renaissance series, we focus on SMRs to examine its potential in lowering the cost of nuclear.

## SMR 101

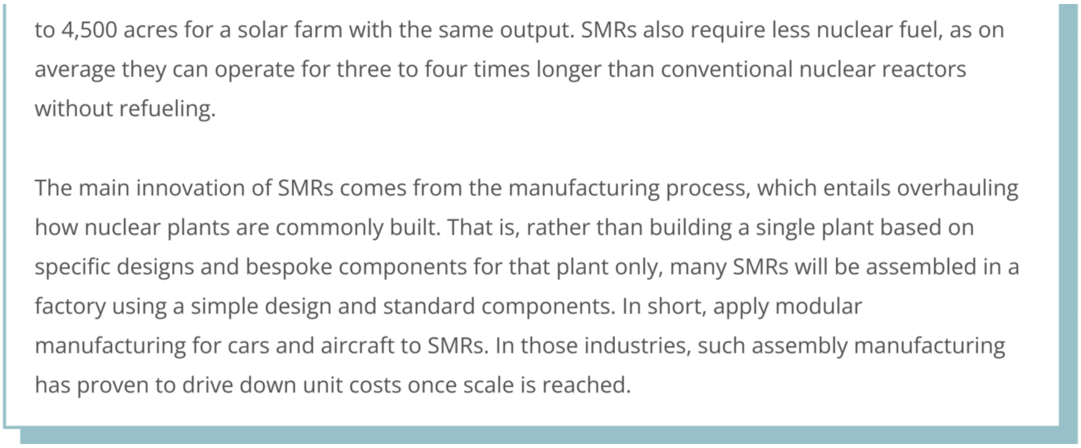
**S**mall – roughly one-third the size (up to 300MW/unit) and requires just 7% of the land of conventional large nuclear reactors;
**M**odular – single, standardized design with relatively fixed components and supply chain so that many can be manufactured in the same factory;
**R**eactor – mainly the same gen-3 and gen-4 reactors that conventional nuclear uses.

**SMRs Have Similar Reactor Design to Conventional Nuclear Reactors**



Source: US Government Accountability Office; Nuclear Regulatory Commission; and NuScale Power.

Miniaturization and modularity, while not technological breakthroughs, would pave the way for a new business model for nuclear power. For instance, an SMR plant with three reactor units would just need 35 acres of land, compared to nearly 500 acres for conventional nuclear and up



> to 4,500 acres for a solar farm with the same output. SMRs also require less nuclear fuel, as on average they can operate for three to four times longer than conventional nuclear reactors without refueling.
>
> The main innovation of SMRs comes from the manufacturing process, which entails overhauling how nuclear plants are commonly built. That is, rather than building a single plant based on specific designs and bespoke components for that plant only, many SMRs will be assembled in a factory using a simple design and standard components. In short, apply modular manufacturing for cars and aircraft to SMRs. In those industries, such assembly manufacturing has proven to drive down unit costs once scale is reached.

## Getting To a Dozen SMRs

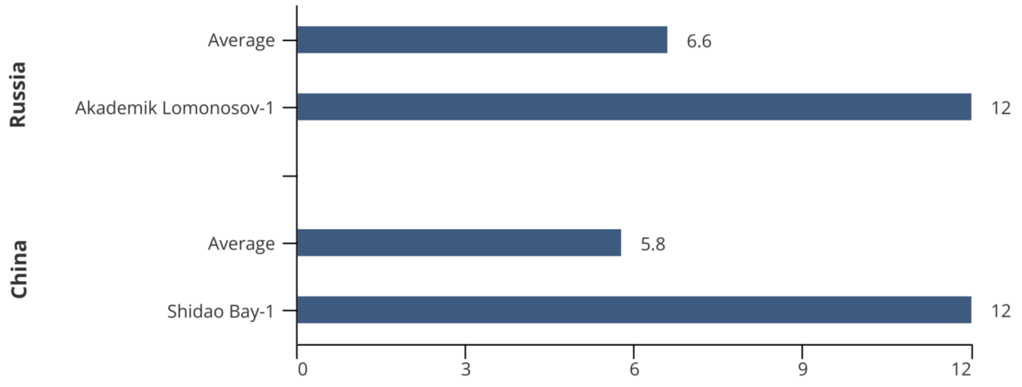
It is notoriously difficult to determine cost curves of an embryonic industry, especially one where few real-life projects are in play at the moment. That said, the promise of SMRs is to halve the cost/kW of electricity generated compared to conventional nuclear reactors, which translates into roughly a fall from $5 billion to $2.5 billion for a 1 GW plant.

In other words, SMRs are pushing nuclear to become a volume business. That scale isn't an outlandish number either—various estimates suggest that SMRs will reach cost parity with conventional nuclear reactors and achieve commercial viability after about a dozen reactors are built, according to US Department of Energy projections. After that inflection point, the cost curve is expected to continue falling if the manufacturing pace is sustained at five to ten reactors per year.

The problem, of course, is the current lack of volume. Only two projects, one Russian and one Chinese, are operational. Russia's floating Akademik Lomonosov plant is composed of two tiny 35 MW SMRs that began commercial operation in May 2020, and Russia is already starting on its first land-based SMR. Meanwhile, China's Shidao Bay SMR project (a 150 MW high-temperature gas-cooled reactor) went online in 2023 while its ACP 100 Linglong One is expected to come online by 2026.

The sparse data on these so-called "first-of-a-kind (FOAK)" projects aren't promising so far. The Russian and Chinese projects took twice as long to build as the average conventional nuclear plant that are much larger (see Figure 1). But at least they're built, whereas the fate of SMR projects in the United States has been worse. For instance, US startup NuScale canceled its once-promising SMR project near Idaho Falls due to cost overruns. What was supposed to be $4.2 billion ended up being $9.3 billion, or more than $20 million/MW, about 2-4 times the average cost of conventional nuclear reactors.

**Figure 1. SMRs Today Take Longer to Build Than Conventional Nuclear Reactors**



Source: International Atomic Energy Agency (IAEA); author's calculations.

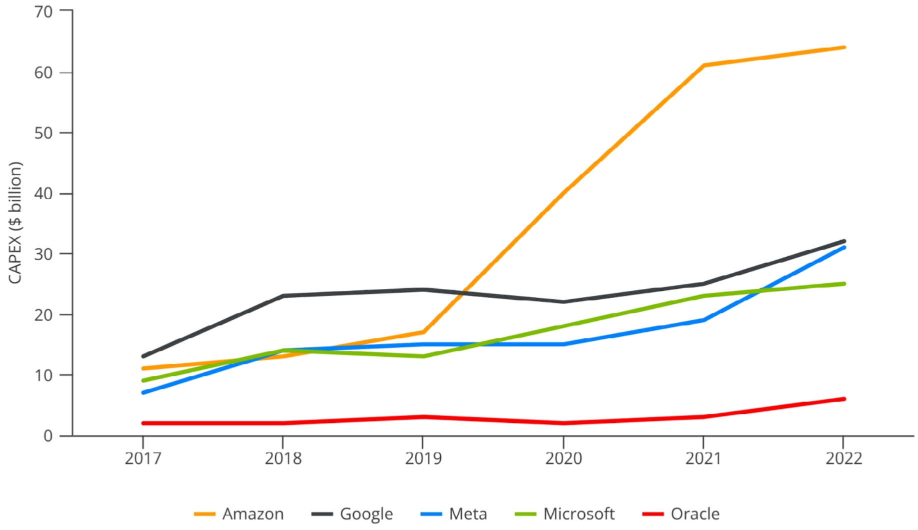
Of course, FOAK projects are inherently risky and cost prohibitive. Being a first mover in a capital expenditure-driven industry like nuclear is often about paying for the steep learning curve. So while SMRs carry with them similar types of challenges associated with capex-intensive energy segments—from lack of funding and astronomical costs to delays and labor force deficiency—there are silver linings on the horizon that could make SMRs realize its intended potential.

## Demand and Fordism

For SMRs to move from the FOAK proof-of-concept stage to scale, demand holds the key. Like for most long-term energy projects, investors and funders like to see stable and guaranteed markets for that energy source. That much-needed demand for SMRs could well come from the explosion in artificial intelligence (AI) growth.

It's well-known by now that sustaining AI is as much a software story as it is an energy one. The electricity that data centers need to power and train AI could double to 35 GW by 2030 in the United States alone. Globally, data centers already consumed an estimated 460,000 GWh of electricity in 2022, which is also projected to more than double in two years. This can be seen in the capex of top "hyperscalers" or large-scale data centers for cloud services and AI—they have grown at an average CAGR of 30% over the past five years (see Figure 2).

**Figure 2. Hyperscalers' CAPEX Have Substantially Gone Up**



Source: Bank of America Global Research; Newmark Market Report.

This matters for SMRs because data centers need 24/7 electricity, and for many big tech companies, they would prefer to reduce their carbon footprint by having clean energy rather than coal to power their data centers. SMRs can meet both of those criteria much better than solar and wind. If current data center energy demand projections hold up, it would require more than 1,000 100 MW SMRs to power them. In other words, data center demand alone would easily allow SMRs to get to scale.

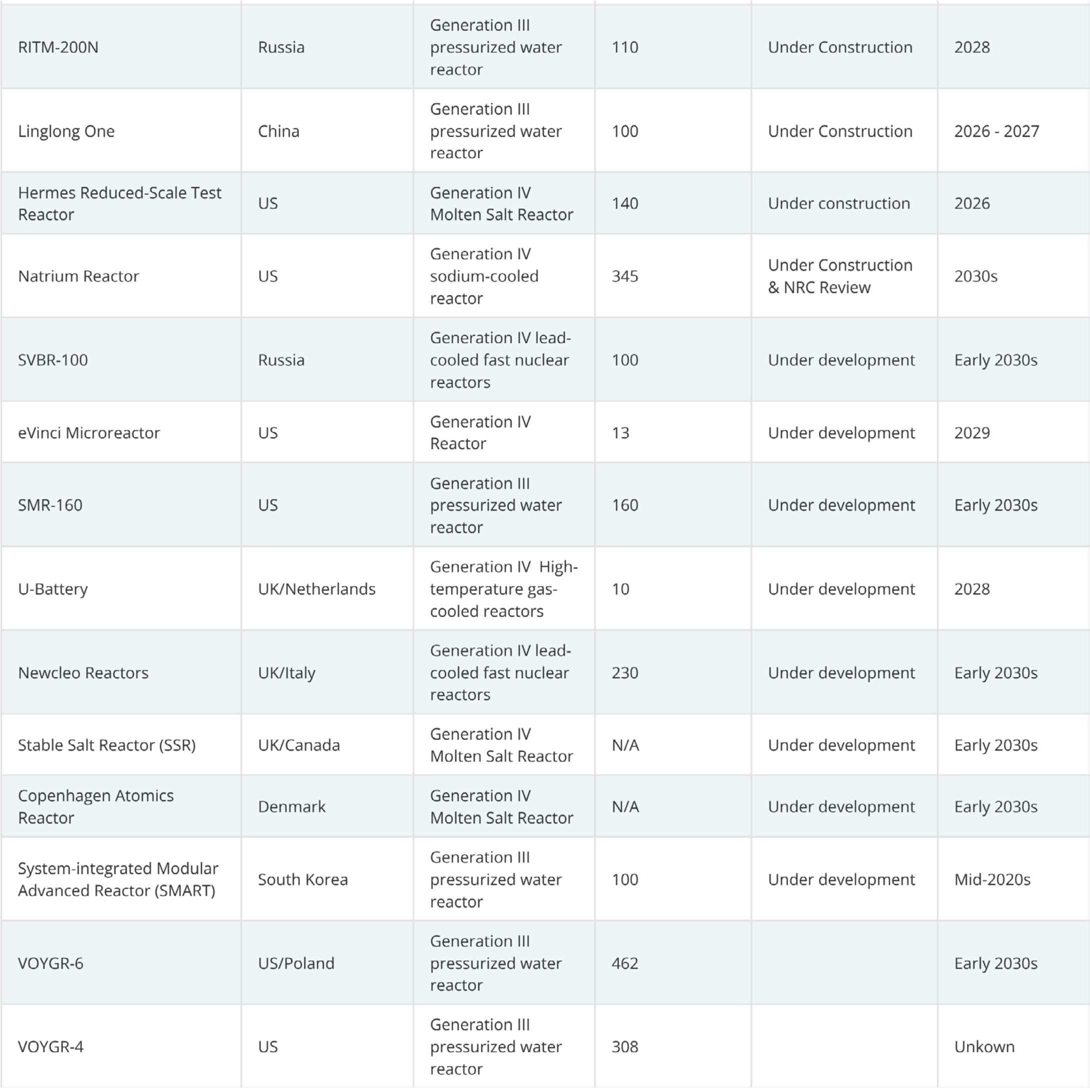
But that is not all. SMRs can also be part of the coal phase-out solution in various countries. Some 2,000 GW of installed coal capacity globally need to be replaced in the coming decades, and China alone would need between 3,500 to 10,000 units of SMRs to break up with coal. For instance, phasing out old coal plants in rural areas provide promising opportunities to tap the unique advantages of SMRs, as the case of an SMR project in Wyoming is demonstrating.

It would appear that, "if you build (SMRs), they will come," as demand does not seem to be a huge obstacle. What is more difficult to achieve is to standardize and scale the manufacturing process. In this sense, the SMR industry needs more Fordism.

To wit, there are currently over 80 different SMR designs under various stages of development across 19 countries (see Figure 3). Assuming all such projects pan out, that amounts to over 14 GW of SMRs over the next decade.

## Figure 3. Most Planned SMR Projects Are Set To Be Completed by the 2030s

| Name | Country | Reactor Design | Total plant capacity (MW) | Current Stage | Completion Date |
|---|---|---|---|---|---|
| Shidaowan High Temperature Gas-cooled Reactor (HTR-PM) | China | Generation IV High-temperature gas-cooled reactor | 200 | Operational | 2023 |
| Akademik Lomonosov Floating Nuclear Power Plant | Russia | Generation III pressurized water reactor | 70 | Operational | 2020 |
| RITM-200N | Russia | Generation III pressurized water reactor | 330 | Agreement Reached & Construction Starts This Summer | Unkown |
| BWRX-300 | US/Canada/Poland | Generation III Boiling Water Reactor | 7200 | Construction Permit Obtained | 2029 |
| Molten Salt Research Reactor (MSRR) | US | Generation IV Molten Salt Reactor | 1 | Construction permit application submitted | Late 2020s |
| Project PELE Mobile Nuclear Reactor | US | Generation IV High-temperature gas-cooled reactors | 1 to 5 | Construction permit application submitted | 2025 |
| HTMR-100 | South Africa | Generation IV High-temperature gas-cooled reactors | 100 | Financing and construction | 2029 |
| VOYGR-12 | US/Romania | Generation III pressurized water reactor | 924 | Licensing | Unkown |
| VBER-300 | Russia | Generation III pressurized water reactor | 300 | Licensing | Early 2030s |
| PRISM | US/UK | Generation IV sodium-cooled reactor | 311 | Licensing | Early 2030s |
| ARC-100 | Canada | Generation IV sodium-cooled reactor | 100 | Licensing | Early 2030s |
| Integrated Molten Salt Reactor (IMSR) | Canada | Generation IV Molten Salt Reactor | 195 | Licensing | Early 2030s |
| Nuward | France | Generation III pressurised water reactor | 170 | Licensing | Early 2030s |
| Atmea1 | Japan/France | Generation III pressurized water reactor | 1100 | Licensing | Early 2030s |
| Rolls-Royce Small Modular Reactor (SMR) | UK | Generation III pressurized water reactor | 470 | Planned | Early 2030s |
| Xe-100 High Temperature Gas-cooled Reactor | US | Generation IV High-temperature gas-cooled reactors | 80 | Pre-application activities | 2028 |
| SMR-300 | US | Generation III pressurized water reactor | 600 | Pre-application activities | Mid-2030s |
| CAREM | Argentina | Generation III pressurized water reactor | 25 | Under Construction | Originally 2024 but currently delayed |

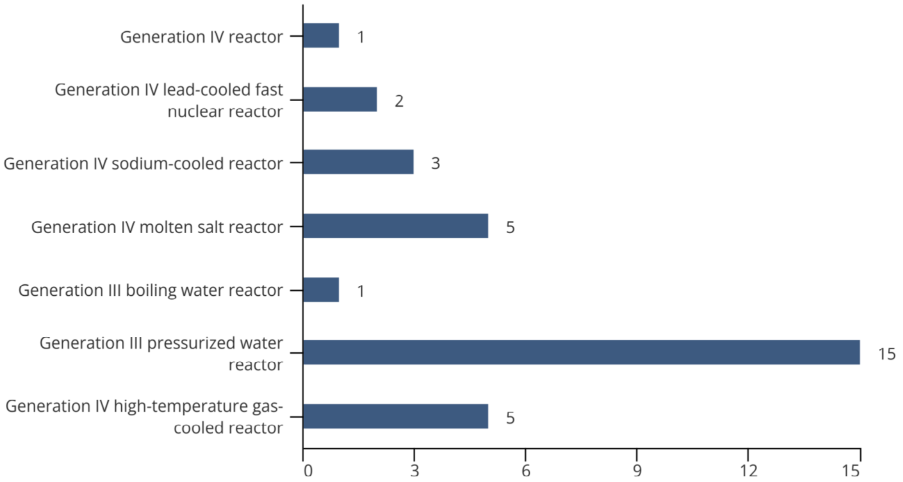


| | | | | | |
|---|---|---|---|---|---|
| RITM-200N | Russia | Generation III pressurized water reactor | 110 | Under Construction | 2028 |
| Linglong One | China | Generation III pressurized water reactor | 100 | Under Construction | 2026 - 2027 |
| Hermes Reduced-Scale Test Reactor | US | Generation IV Molten Salt Reactor | 140 | Under construction | 2026 |
| Natrium Reactor | US | Generation IV sodium-cooled reactor | 345 | Under Construction & NRC Review | 2030s |
| SVBR-100 | Russia | Generation IV lead-cooled fast nuclear reactors | 100 | Under development | Early 2030s |
| eVinci Microreactor | US | Generation IV Reactor | 13 | Under development | 2029 |
| SMR-160 | US | Generation III pressurized water reactor | 160 | Under development | Early 2030s |
| U-Battery | UK/Netherlands | Generation IV High-temperature gas-cooled reactors | 10 | Under development | 2028 |
| Newcleo Reactors | UK/Italy | Generation IV lead-cooled fast nuclear reactors | 230 | Under development | Early 2030s |
| Stable Salt Reactor (SSR) | UK/Canada | Generation IV Molten Salt Reactor | N/A | Under development | Early 2030s |
| Copenhagen Atomics Reactor | Denmark | Generation IV Molten Salt Reactor | N/A | Under development | Early 2030s |
| System-integrated Modular Advanced Reactor (SMART) | South Korea | Generation III pressurized water reactor | 100 | Under development | Mid-2020s |
| VOYGR-6 | US/Poland | Generation III pressurized water reactor | 462 | | Early 2030s |
| VOYGR-4 | US | Generation III pressurized water reactor | 308 | | Unkown |

Source: International Atomic Energy Agency (IAEA); author’s calculations.

While that capacity sounds impressive, it’s not clear whether many of the proposed projects are built with a single design or assembled in a factory, certainly not the two FOAK SMRs that are currently operational. In fact, the proposed SMRs include seven different reactor designs, though pressurized water reactor appears to be the winning design so far (see Figure 4).

**Figure 4. Currently Planned SMRs Rely on Various Designs**

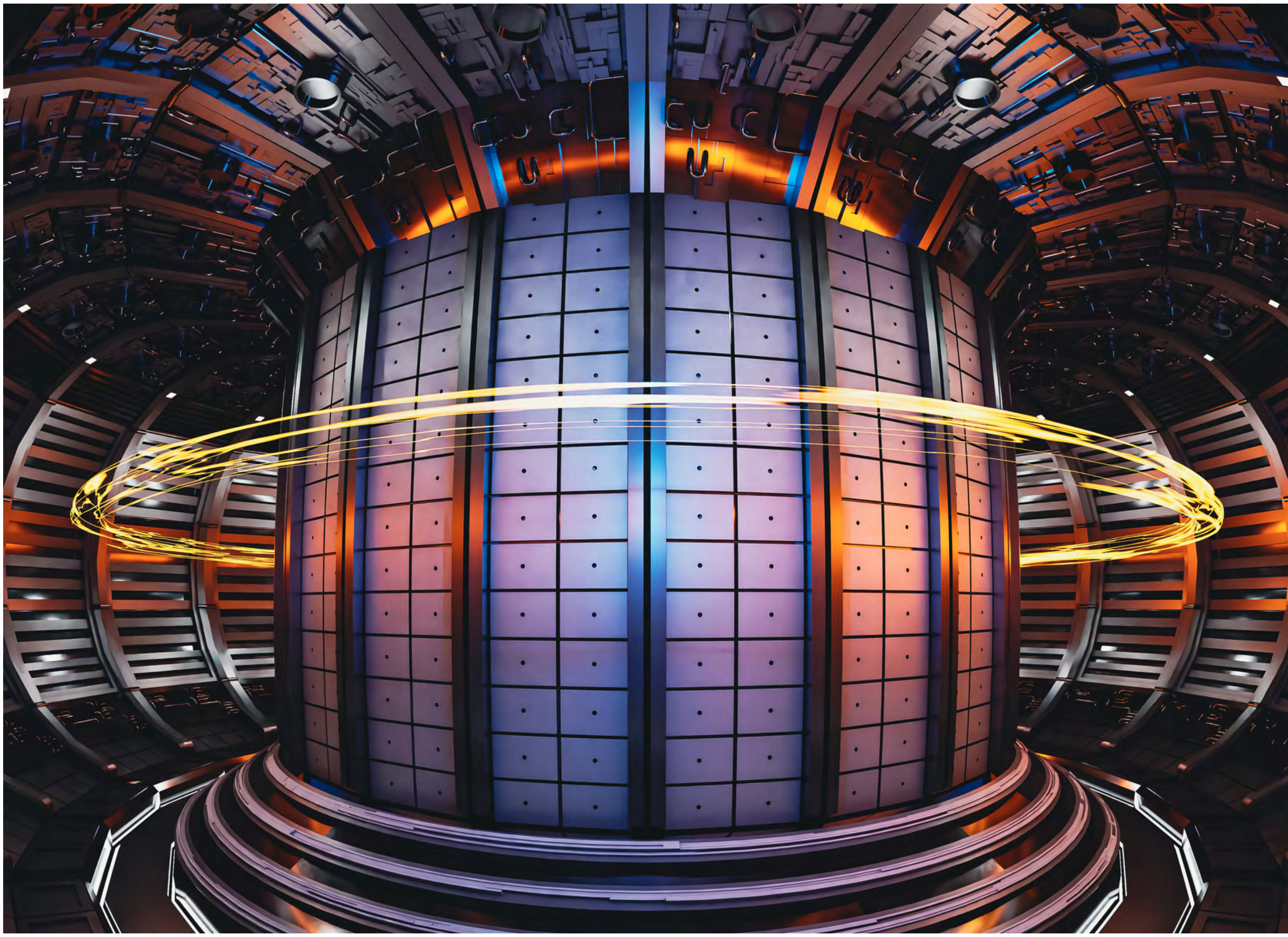


Source: World Nuclear Association; company websites and filings; various media; and author's calculations.

Such heterogeneity in SMR projects is the exact opposite of how the emergent industry intends to drive down costs. Like Ford's Model T of its time, SMRs need to be built in modular fashion under a giant factory roof with uniform components and standardized processes. The efficiencies from that assembly line approach were responsible for lowering the Model T's cost by 60% in a decade. Of course, SMRs aren't cars, but to lower cost and reach scale requires the same Fordism concept of simplifying design and standardizing production.

Herein lies the chicken and egg problem. Building SMRs alone are already capex-heavy, it is difficult for startups to also invest in large factories without some assurances of future demand. In this sense, SMRs are closer to aircraft, in that new aircraft developments are expensive because they require new processes and materials, with each aircraft being at least a 20-year asset. This is why aircraft manufacturers often sign deals on new models that are still in development to ensure demand.

That demand for SMRs does seem to be there, so will SMR factories now follow? Given the number of projects in the pipeline, the "factory-ization" of SMRs isn't as much of a pipe dream as it was a few years ago. The next 5-7 years could well see this new business model of building nuclear reactors take root. And should it be realized, it would transform swathes of the suburban American landscape, dotted with data centers flanked by miniature nuclear plants.



## Nuclear Series (Part III):

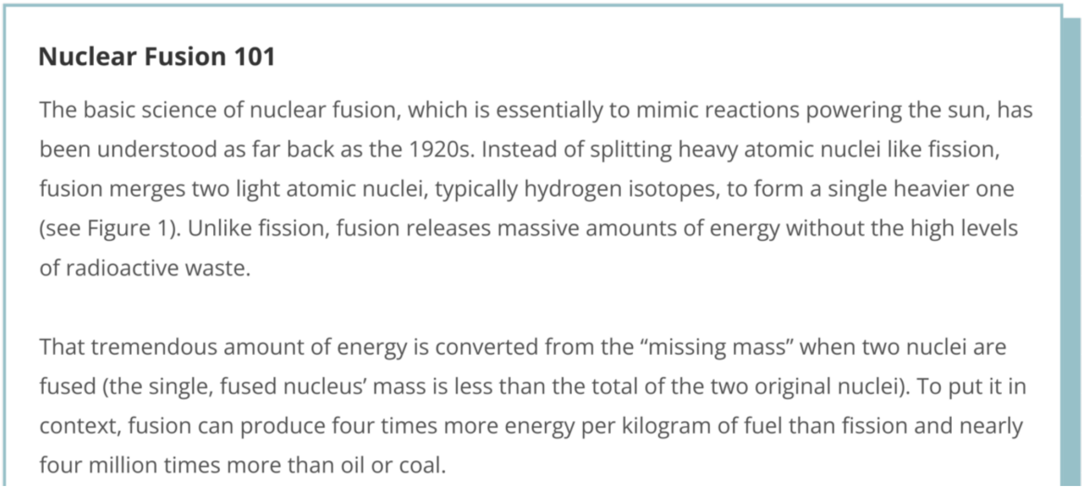
# Getting Serious about Fusion

Nuclear fusion, or replicating the atomic reactions in our sun, has long been touted as the “holy grail” of energy solutions. Solving fusion would finally lead to an age of energy abundance as it will deliver nearly limitless carbon-free energy with minimal radioactive waste. Every major economy with the scientific and engineering wherewithal has been chasing fusion breakthroughs for many decades.

But creating “mini suns” on earth has turned out to be exceptionally difficult, even if the actual physics of fusion have been well known for a century. Meaningful progress on commercializing fusion seemed to be always “30 years away” as the joke goes. In addition to the technical challenges of producing sustained net positive energy from fusion, building actual fusion plants is another level of engineering complexity.

On both of those fronts, however, recent breakthroughs and investments have moved the needle on fusion that merit serious attention. For one, net positive fusion energy was produced at the US Lawrence Livermore National Lab. Two, the technology choice for getting to a commercial plant seems to be leaning toward the magnet-based Tokamak design at the moment. Finally, the number of startups and funding for fusion appear more vibrant than it had been for decades.

None of this means that commercialization is within grasp, however. But it may also mean that the reality of fusion is no longer perpetually 30 years away. In this final installment of the nuclear renaissance series, we examine both the renewed dynamism in fusion as well as its real, near-term constraints.



**Nuclear Fusion 101**

The basic science of nuclear fusion, which is essentially to mimic reactions powering the sun, has been understood as far back as the 1920s. Instead of splitting heavy atomic nuclei like fission, fusion merges two light atomic nuclei, typically hydrogen isotopes, to form a single heavier one (see Figure 1). Unlike fission, fusion releases massive amounts of energy without the high levels of radioactive waste.

That tremendous amount of energy is converted from the “missing mass” when two nuclei are fused (the single, fused nucleus’ mass is less than the total of the two original nuclei). To put it in context, fusion can produce four times more energy per kilogram of fuel than fission and nearly four million times more than oil or coal.

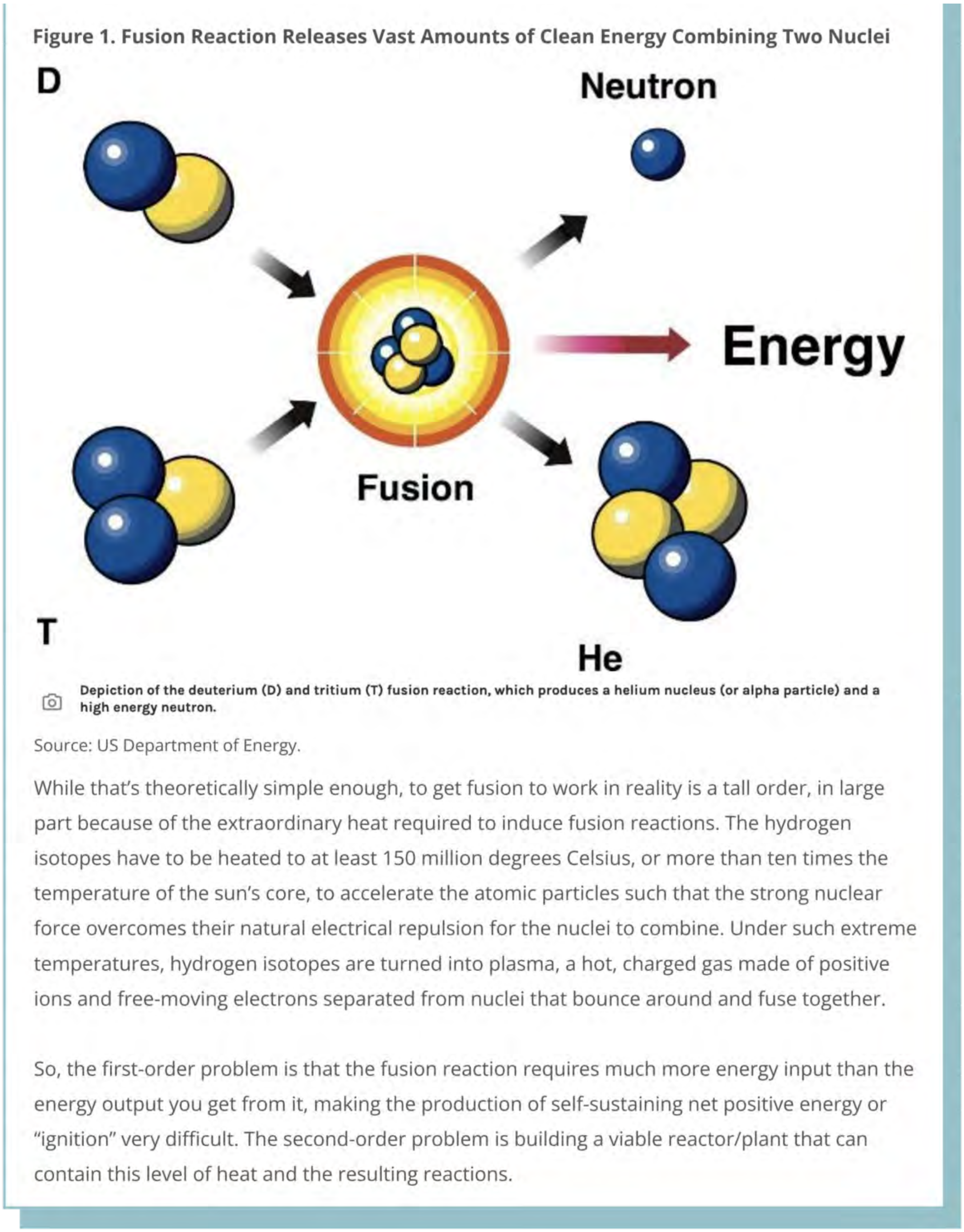


**Figure 1. Fusion Reaction Releases Vast Amounts of Clean Energy Combining Two Nuclei**

**Depiction of the deuterium (D) and tritium (T) fusion reaction, which produces a helium nucleus (or alpha particle) and a high energy neutron.**

Source: US Department of Energy.

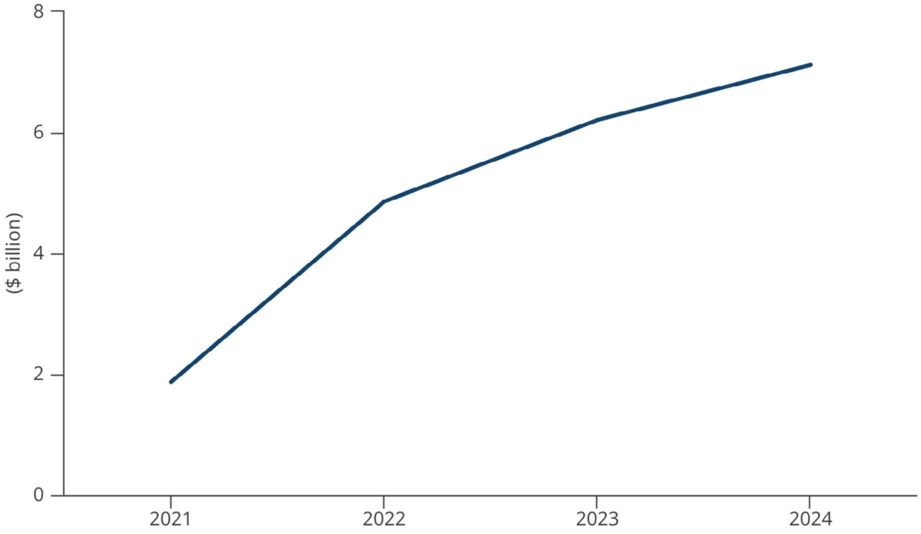
While that's theoretically simple enough, to get fusion to work in reality is a tall order, in large part because of the extraordinary heat required to induce fusion reactions. The hydrogen isotopes have to be heated to at least 150 million degrees Celsius, or more than ten times the temperature of the sun's core, to accelerate the atomic particles such that the strong nuclear force overcomes their natural electrical repulsion for the nuclei to combine. Under such extreme temperatures, hydrogen isotopes are turned into plasma, a hot, charged gas made of positive ions and free-moving electrons separated from nuclei that bounce around and fuse together.

So, the first-order problem is that the fusion reaction requires much more energy input than the energy output you get from it, making the production of self-sustaining net positive energy or "ignition" very difficult. The second-order problem is building a viable reactor/plant that can contain this level of heat and the resulting reactions.

## Fusion Industry Blossoming

On the dynamism side of the ledger, the fusion industry has experienced an unprecedented boom over the last few years—one that is predominantly private-sector driven. Since 2021, the number of fusion companies worldwide almost doubled from 24 to 45, more than half of which are headquartered in the United States. Funding for the industry has almost quintupled in a matter of three years, reaching over $7 billion so far in 2024 (see Figure 2).

**Figure 2. Fusion Industry Funding Has Grown Exponentially since 2021**



Source: Fusion Industry Association (FIA).

If this level of funding can be sustained, it will foster a quicker innovation cycle, allowing startups to iterate on different technological choices and experiment with engineering solutions. This level of activity in a frontier industry like fusion simply wasn't feasible until around 2020.

Investor optimism has certainly been influenced by the technological breakthrough at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory in December 2022. The NIF achieved a milestone that has eluded scientists for the better part of a century: producing net positive energy from fusion with its laser system. While the net gain of about one megajoule (MJ) of energy is just enough to power a 100-watt light bulb for two hours, the demonstration was an important proof-of-concept that controllable thermal fusion isn't just theory but a potential reality.

## From Ignition to Commercialization

On the constraint side of the ledger is the gulf between proof-of-concept and commercialization. Indeed, achieving ignition is simply a first step, and some experts have questioned whether NIF's demonstration had reached true breakeven on energy input versus energy output. Nevertheless, that positive energy production needs to be much higher than a few MJs and be sustained for much longer for a fusion plant to actually work. Any power plant, fission or fusion, needs to operate 24/7 and supply sufficient power for communities.

What's more, the economics of magnetically powered fusion reactors based on Tokamak designs remain murky. A hint of the unit economics of fusion plants comes from International Thermonuclear Experimental Reactor (ITER), the world's largest collaborative magnetic fusion project involving seven member countries. The project has pushed back its operations for a decade until 2034, citing first-of-its-kind project challenges and critical supply chain issues. It has also already tallied up over $16 billion in cost overruns.

Even with concentrated private investment, Tokamak reactors have yet to demonstrate positive energy from fusion (see Figure 3). For instance, while investors seem enthusiastic about Helion Energy's claim to deploy its first power plant by 2028, whether fusion can become truly commercially viable by 2035 remains to be seen.

**Figure 3. Tokamak Confines Plasma Using Magnetic Fields**

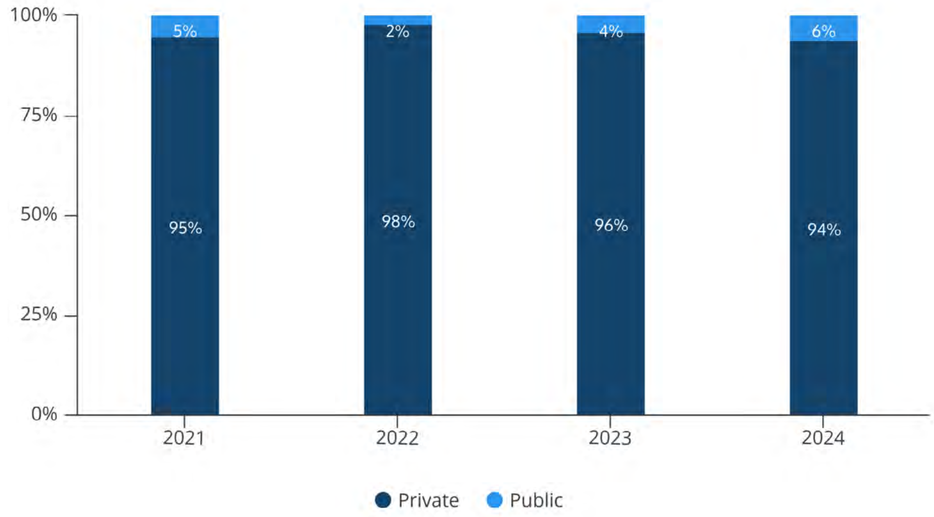
Note: Tokamak (an acronym from the Russian words for toroidal magnetic confinement) actually emerged in Russia as far back as 1958. Continued innovation and breakthroughs in superconducting magnets will be key as the strength of the Tokamak's magnetic field is crucial for containing and stabilizing the plasma that produces the fusion reaction.
Source: International Thermonuclear Experimental Reactor (ITER).

Like all frontier industries, fusion will need much more push to get it over the “valley of death” to put it on a path toward commercialization. That push likely can’t be left to the private sector alone and will require extensive government support, both in terms of clearing regulatory hurdles and providing significant funding.

In the United States, perhaps in recognition of the highest concentration of fusion startups to date, the US Congress has already passed legislation in 2023 (ADVANCE Act) on nuclear energy. Part of the legislation seeks to simplify the regulatory pathway for fusion technology given the different technological and safety standards of fusion reactors, potentially speeding up their licensing process and subsequent deployment. This appears to mark a rare instance of regulation getting a bit ahead of a nascent industry to support it.

But when it comes to funding support for fusion, the public sector has been punching substantially below its weight. In fact, public spending to support private fusion companies has been minimal, totaling <$500 million as of 2024 (see Figure 4).

**Figure 4. Public Funding To Support Private Sector Has Been Miniscule**



Source: FIA Annual Industry Reports.

While many private sector startups are preoccupied with the design and engineering of Tokamaks, for example, the capital expenditure for an actual plant is unclear. Public spending can help defray what will certainly be significant capex on a functional pilot plant, which would constitute a major milestone in proving the commercial viability of fusion. For example, the US Department of Energy has recently moved in that direction by awarding $46 million to eight private companies. In short, a more robust public-private partnership will be necessary to accelerate meaningful progress in fusion.

If there is such a thing as a “silver bullet” in tackling climate change, commercial fusion arguably comes the closest. That’s because it can reconcile the longstanding energy trilemma of “secure, affordable, and clean”. That potential of a fusion revolution, which now seems closer than it has been in decades, has probably brought as much enthusiasm to the energy technology world as Silicon Valley has lavished on the transformative potential of artificial intelligence. Commercialization won’t happen next year, but it isn’t a pipe dream either.

Ultimately, whether it is conventional fission, small modular reactors, or fusion, there appears to be a global reawakening over the necessity of nuclear power in achieving Net Zero Emissions goals by the middle of this century. We will continue to analyze and monitor various facets of the nuclear renaissance—from market and industry developments to funding and regulations.