The Lever

Making Fusion a Reality

FROM COLUMBIA ENGINEERING

The Lever

Welcome

We need new sources of energy. Climate change and geopolitical realities have long demanded a rapid transition from fossil fuels. Now, the explosive growth of data centers is driving energy demand even higher.

This requires an all-of-the-above energy strategy. The work we do at Columbia's Fusion Research Center is focused on making sure fusion is part of that mix.

In this short introduction to the fusion energy landscape, my colleagues from Columbia and beyond discuss fusion through the lenses of science, business, and public policy. Thanks for joining us.

CARLOS PAZ-SOLDAN,
DIRECTOR OF THE COLUMBIA FUSION RESEARCH CENTER

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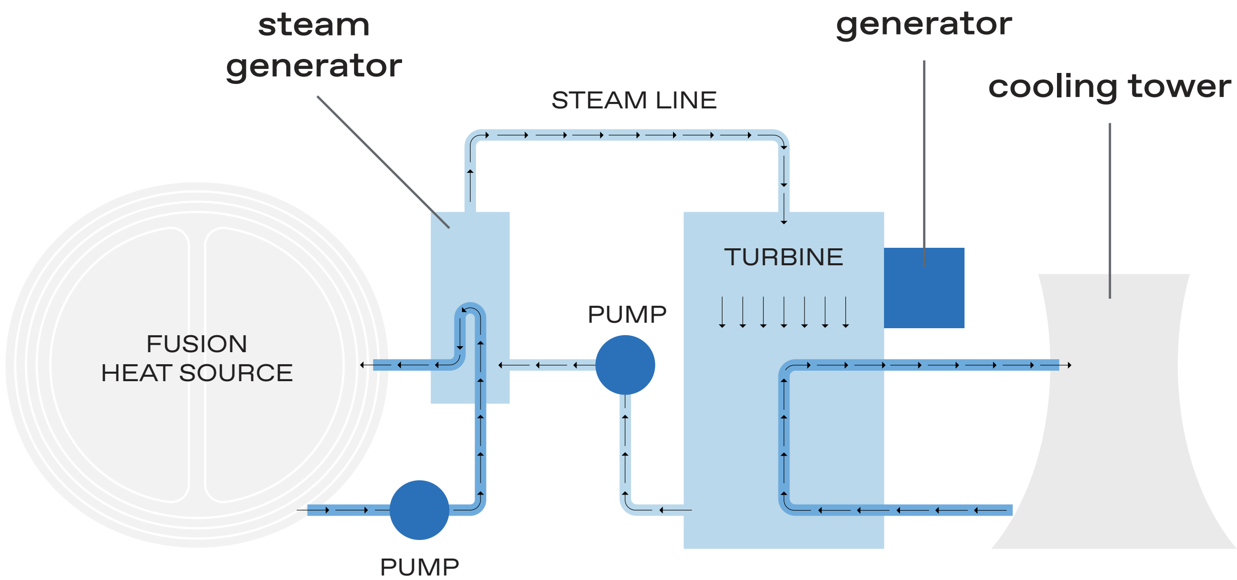
Why Fusion was Always 30 Years Away



Why fusion? It's the holy grail of energy sources. Each atom in the universe contains an enormous amount of energy. Fusion frees that energy by merging — that is, fusing — atoms that are readily available on Earth. It's the same process that powers the Sun. A fusion plant would produce clean electricity in almost any location with no direct carbon emissions, no risk of meltdown, and no long-lived radioactive waste — unlike conventional fission reactors. And unlike wind and solar, it wouldn't depend on the weather. You could build a plant somewhere, and it would produce energy steadily, even ramping up and down to meet demand. The fuel is made from common isotopes of hydrogen derived from seawater and lithium, and it's incredibly potent. One kilogram of fusion fuel contains as much energy as six million kilograms of natural gas.

So why don't we have it yet? Creating fusion conditions on Earth is extraordinarily difficult. The sun uses its enormous gravity to compress and heat its fuel. Engineers and physicists are racing to build machines that achieve temperatures of hundreds of millions of degrees — hotter than the center of the sun — and hold that superheated plasma in place long enough for fusion reactions to occur. At the same time, those machines must maintain extremely cold temperatures just feet away inside of a superconducting magnet. It is one of the great unsolved technical challenges of our time.

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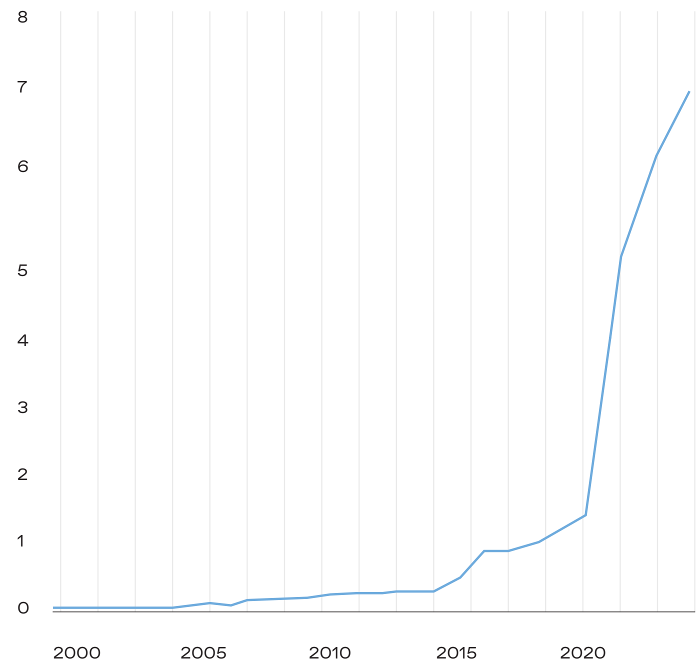
So why has fusion been "thirty years away" for decades? The honest answer is that, for much of that time, it was funded at a sub-critical level. Fusion's fortunes have roughly tracked societal pull — such as the price of oil — sometimes with a time lag. The 1970s energy crisis triggered a surge of funding, but when prices fell in the late 1980s, budgets collapsed. For twenty years the program stagnated, not because the physics was impossible but because nobody was investing enough to solve all the necessary problems.

That has changed. Breakthroughs in superconducting magnets and laser-driven fusion ignition have compounded in recent years. An explosion of private-sector startups has brought billions in new venture capital funding. The federal government has launched a milestone-based program — modeled on the approach that helped build SpaceX — in which companies receive public funding only when they hit defined technical targets, though it needs to grow. Also, a landmark regulatory decision means fusion plants will not be governed under the same framework as fission reactors, which could matter more for the economics of fusion power than any advance a physicist makes in the lab.

These forces are converging on what the field calls a "decadal timescale." This isn't a promise that fusion will arrive in exactly ten years, but it shows that a credible path to pilot plants is on the horizon. The timeline still depends on sustained investment and technical progress. If we fund this work seriously and create the fusion workforce of the future, it will happen. If we don't fund it, other companies will, and they could reach the goal ahead of the U.S.

In this collection, you'll hear from colleagues with expertise in fusion science and technology, government, and the private sector. Whether you're new to fusion or looking to learn more, I hope their insights sharpen your thinking about the future of this transformative technology.

Cumulative Funding $B



COURTESY S. WURZEL & ARPA-E

CARLOS PAZ-SOLDAN IS THE DIRECTOR OF THE COLUMBIA FUSION RESEARCH CENTER AND AN ASSOCIATE PROFESSOR OF APPLIED PHYSICS AND APPLIED MATHEMATICS AT COLUMBIA ENGINEERING.

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Building a Star on Earth

A central challenge of fusion is controlling plasma at temperatures that far exceed even the Sun's core, while keeping the device walls cool and extracting the plasma's energy. Today, my colleague Elizabeth Paul is pioneering new approaches to that problem, designing the magnetic geometries that could make fusion reactors more stable, compact, and efficient.

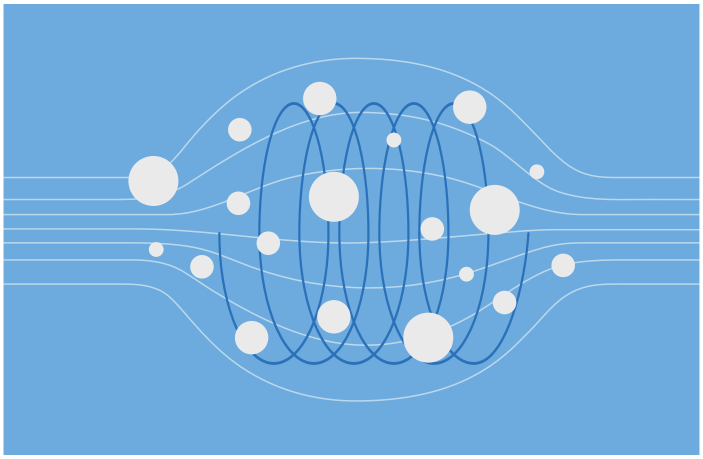
CARLOS PAZ-SOLDAN,
DIRECTOR OF THE COLUMBIA FUSION RESEARCH CENTER

Fusion depends on an unusual state of matter: plasma. If you're thinking about the entire universe, plasma is actually very common. It's the stuff of stars, supernovae, lightning, and the aurora borealis.

However, when compared to solids, liquids, and gases, plasma is strange. It forms when gas is heated to such high temperatures that atoms break apart, with electrons separating from nuclei. The result is a fluid-like substance that responds to electric and magnetic fields and spontaneously organizes into filaments and spirals.

The Sun is made of plasma and powered by continuous fusion reactions in its core. If we manage to confine and control plasma well enough to have a sustained fusion reaction here on Earth, we can transform small amounts of matter into vast amounts of energy. But that's far easier said than done — creating plasma and confining it long enough for fusion reactions to occur are enormous engineering challenges.

The leading approach uses powerful magnets to trap plasma inside a donut-shaped chamber that could fit inside a small house. When the reactor is operating, the plasma reaches temperatures of hundreds of millions of degrees. Just a few meters away, the magnets that contain the plasma operate near absolute zero. It is one of the most extreme temperature gradients in the universe.



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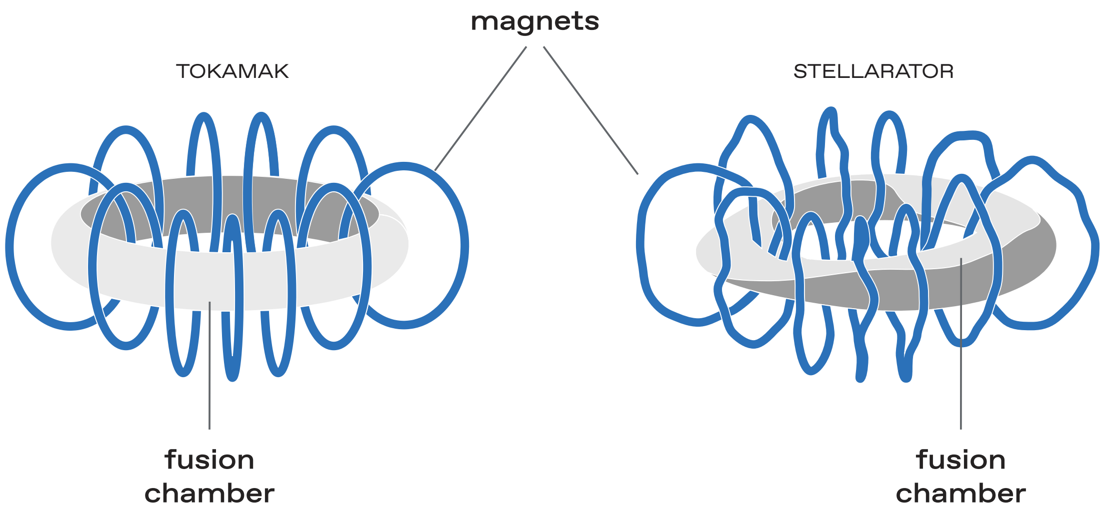

We call the devices that contain plasma magnetic bottles, and there are two main designs. The tokamak, which looks like a normal donut, works by driving an electrical current through the plasma. The design I work on, called a stellarator, uses a twisted doughnut shape to confine plasma without the need for a current. By relying on the geometry of the magnetic field itself, a stellarator avoids some of the instabilities that occur within tokamaks. We use numerical optimization to design these shapes, searching for configurations that keep the plasma stable and confined as long as possible. Another set of approaches uses lasers to compress and heat plasma.

Recent technical breakthroughs have injected new energy into the field. In 2022, researchers at the National Ignition Facility reached a milestone by creating a fusion reaction that released more energy than the laser energy absorbed by the target. More recently, a research team demonstrated that the magnets we use don't have to be as ultra-cold as we had thought. That breakthrough opens the door for smaller, cheaper power plant designs that can be built more quickly.

The questions have shifted from whether fusion is possible to how a reactor should be engineered to provide electricity to the grid. For those of us who are working down the list of outstanding scientific questions and technical problems, it's an incredibly exciting moment in the history of this transformative technology.

ELIZABETH PAUL IS AN ASSISTANT PROFESSOR OF APPLIED PHYSICS AND APPLIED MATHEMATICS AT COLUMBIA ENGINEERING AND A CORE FACULTY MEMBER OF THE COLUMBIA FUSION RESEARCH CENTER.

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How Fusion Fits into our Energy Portfolio

The case for fusion is strongest when measured against the alternatives. My colleague Matt Bowen at the Columbia University School of International and Public Affairs (SIPA) brings a rare perspective. Now a senior research scholar at the Center on Global Energy Policy, Matt spent years in the federal government working on nuclear energy policy, nonproliferation, and the practical realities of deploying new power sources.

CARLOS PAZ-SOLDAN,
DIRECTOR OF THE COLUMBIA FUSION RESEARCH CENTER

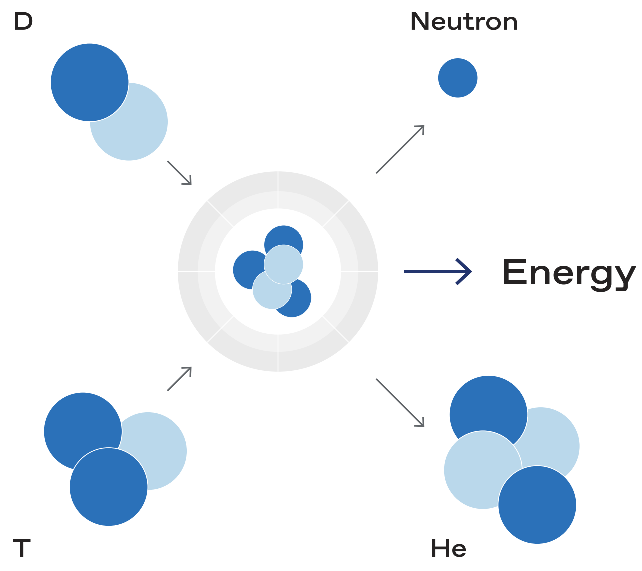
I spend most of my time thinking about fission, not fusion. But when I compare the two energy sources, three issues come to mind: safety, waste, and nonproliferation. On each count, fusion seems like it would have some real advantages.

Fission, which currently provides nearly one-fifth of U.S. electricity, splits heavy atoms like uranium. This produces isotopes that are intensely radioactive and hot. Fusion, on the other hand, joins light nuclei. The primary byproduct is helium, a noble gas with no particular safety concerns. While both processes generate energy, the materials involved, the associated risks, and the policy implications diverge sharply.

First, fusion has some appealing safety features. In a fission plant, systems are required to cool the nuclear fuel and keep it from melting. Failure to keep the fuel cool can result in large releases of radiological material to the surrounding environment, such as what happened at the Fukushima Daiichi nuclear power plant in 2011. While fusion plants would still have flammable and radioactive materials on site, the inherent safety challenges are less severe, certainly in comparison to today's light water reactors.

Second, when it comes to nuclear waste management, fusion would also have advantages. Spent nuclear fuel (SNF) from commercial fission reactors is radioactive for many thousands of years, and the societal challenge to disposing of these materials has proven to be formidable. While technical solutions exist, no country has managed to dispose of SNF, though Finland has built a facility and appears close to starting operations. Conversely, we already have facilities for disposing of the low-level nuclear waste that fusion will produce.

Third, there are considerations related to the global nonproliferation regime (i.e. trying to prevent the spread of nuclear weapons). Creating fuel for fission requires transforming natural uranium into enriched uranium (that is, enriched in the isotope uranium-235). The same type of facilities that create this material can also be modified to create highly enriched uranium, however, which can be used in a nuclear weapon. Fission reactors also produce plutonium, which, if separated from the spent nuclear fuel, could similarly be used in a nuclear explosive device.



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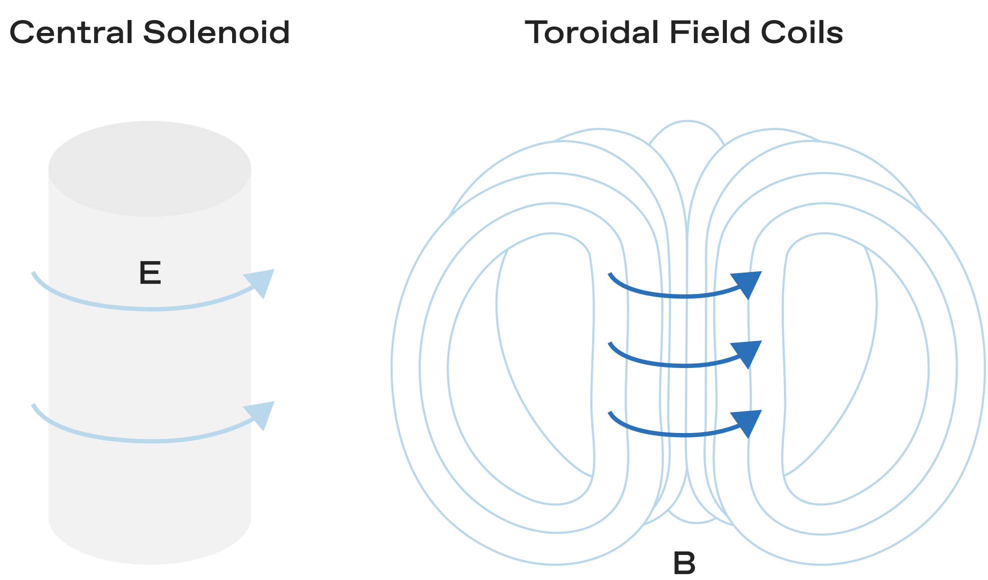


Fusion systems do not involve uranium or uranium enrichment facilities, nor do they produce plutonium. A fusion plant using deuterium-tritium fuel would still produce energetic neutrons that could be used to irradiate uranium or thorium and produce fissile material. And fusion lifecycles still involve materials and facilities that are export-controlled, given their relevance to potential nuclear weapons programs. Still, on the whole, fusion presents fewer nonproliferation concerns than fission.

These are real advantages. But for the moment, only fission is a commercial reality. Even if and when fusion is commercialized, nobody knows what the plants will cost. Cost estimates at this stage carry enormous uncertainty, and historically in the nuclear world, estimates tend to rise over time. The policy environment matters too: without strong environmental policies, fusion will have to compete against cheap natural gas — a difficult proposition for any low-emission energy technology.

A serious, comprehensive strategy to address climate change cannot rely on commercial fusion arriving at a known date. But if the engineering succeeds and the costs come in at a manageable level, fusion could be transformative. I root for it to succeed. The world could surely use this kind of breakthrough.

MATT BOWEN IS A SENIOR RESEARCH SCHOLAR IN COLUMBIA'S SCHOOL OF INTERNATIONAL AND PUBLIC AFFAIRS. HE SERVED AS ASSOCIATE DEPUTY ASSISTANT SECRETARY IN THE OFFICE OF NUCLEAR ENERGY AT THE U.S. DEPARTMENT OF ENERGY AND AS A SENIOR ADVISOR IN THE OFFICE OF NONPROLIFERATION AND ARMS CONTROL AT THE NATIONAL NUCLEAR SECURITY ADMINISTRATION.

Betting on Fusion

The science of fusion has advanced enormously, but science alone doesn't build power plants. Turning breakthroughs into a commercial energy source requires capital, industrial strategy, and a clear theory of how fusion enters the energy market. Andrew Holland brings that perspective — years of experience at the intersection of fusion technology, policy, and private capital.

CARLOS PAZ-SOLDAN,
DIRECTOR OF THE COLUMBIA FUSION RESEARCH CENTER

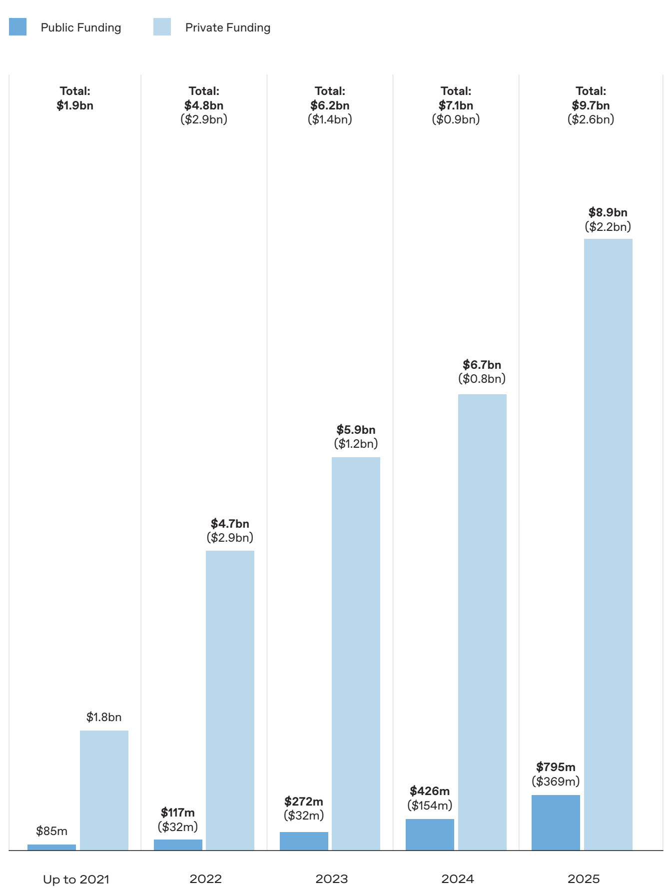
Five years ago, private investors had put less than two billion dollars in fusion companies. Today, the figure exceeds ten billion. What drove that rapid growth? The risk profile of fusion energy changed. Scientists are now confident that the next generation of machines can achieve break-even or better performance. In other words, plasma physics has been de-risked. The challenges that remain revolve around engineering and integration, and capital is flowing in to solve exactly those problems. And, speaking for my own interests as the CEO of the Fusion Industry Association, the companies decided to affiliate together under the Association's banner.

Fusion will be a remarkable technological breakthrough, but its funding is maturing similarly to other technologies' trajectories. After decades of government funding set the stage, family offices provide the first significant tranches of private investment, taking a chance on a technology after its scientific viability has been proven, but before it was obvious it was a business. As the biggest risks were addressed, new sources of funding would become available. Venture capital firms, which operate on the logic that a few spectacular successes will pay for far more failures, then begin making major investments in the space. As engineers continued to address outstanding challenges, fusion companies became ideal investments for large corporations making long-term bets. More recently, fusion companies have begun to explore raising capital through public markets, like the New York Stock Exchange.

RIGHT: COURTESY FUSION INDUSTRY ASSOCIATION

Total Funding

(Annual increase in brackets)



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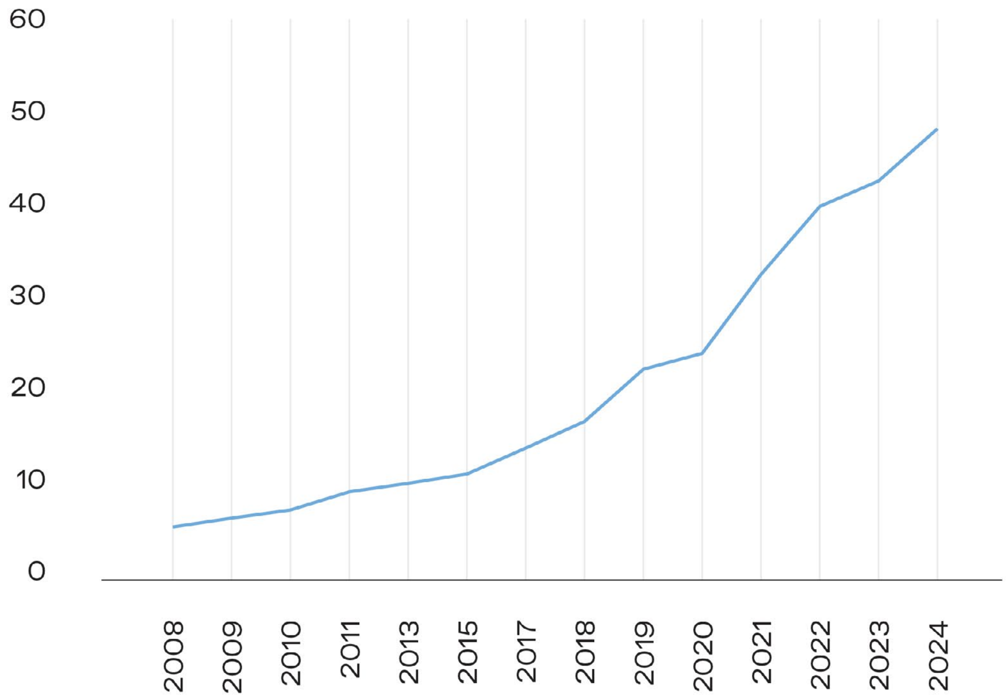
Total Number of Private Fusion Companies by Year



COURTESY FUSION INDUSTRY ASSOCIATION

BASED ON 2025 RESPONSES, EXCLUDES COMPANIES THAT HAVE SINCE FOLDED OR CONSOLIDATED

Of course, all of these investors are counting on returns once fusion energy is on the market. Where will it compete? Not really against wind or solar, which serve different roles on the power grid. Or even against natural gas or coal. Fusion's real competitors are other zero-carbon sources that don't vary with the weather: advanced fission, hydrogen, and natural gas with carbon capture.

The market is shifting in fusion's favor. For the first time in 20 years, electricity demand in developed economies is rising — driven by data centers and AI — and I don't meet anybody from the power sector who says they won't buy a clean, firm energy source if we can build one. Companies have already signed power purchase agreements above today's marginal cost because they need the capacity to meet their own goals.

As it stands today, enough fusion companies have enough shots on goal that some will succeed and some will fail. Regardless, I am confident multiple technologies will prove out fusion power in the next decade. My message to the researchers working on this, especially those whose head is down on one part of the system, is to look up and look around. It is all coming together.

ANDREW HOLLAND IS THE CEO OF THE FUSION INDUSTRY ASSOCIATION.

Fusion at Columbia

This is an exciting time in the 65-year history of the Plasma Physics Laboratory. With the path to fusion power plants coming into sharper focus, Columbia is scaling up our capacity to partner with the fusion industry and train the next generation of researchers, technicians, and leaders.

Last year, we formalized this momentum by launching the Columbia Fusion Research Center. Through sponsored research partnerships, we provide on-call technical expertise — such as specialized calculations, design assessments, targeted research — and place students directly inside partner companies.

At our facility on West 120th St., roughly 80 students work across plasma physics, mechanical engineering, electrical engineering, and computer science. They operate Columbia's student-run tokamak and work with faculty on projects like designing stellarator configurations and developing computational tools to predict plasma behavior.

Earlier this year, we launched a new minor that prepares engineering students from across disciplines to enter the fusion workforce and research community, where they will join the generations of fusion professionals who have trained at Columbia since 1961.

The challenges that stand between where we are today and a fusion-powered future will not be easily solved. That's why we built this Center to grow alongside the fusion industry. To explore a partnership, visit fusion.columbia.edu or contact us directly at fusioncenter@columbia.edu.

CARLOS PAZ-SOLDAN IS THE DIRECTOR OF THE COLUMBIA FUSION RESEARCH CENTER AND AN ASSOCIATE PROFESSOR OF APPLIED PHYSICS AND APPLIED MATHEMATICS AT COLUMBIA ENGINEERING.

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