AT A GLANCE

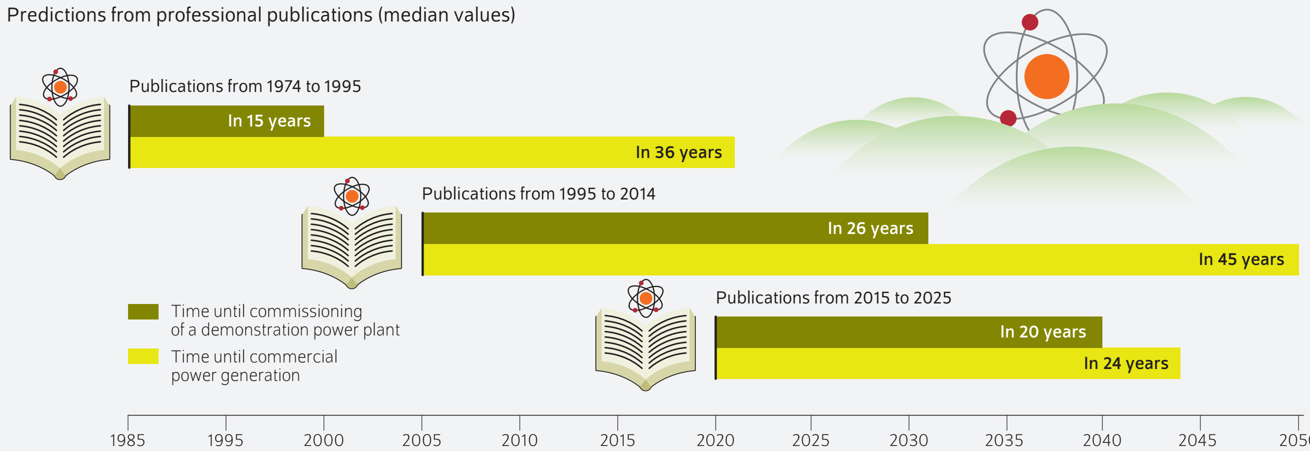
Power generation from nuclear fusion not expected in the foreseeable future; applied research developing dynamically

By Alexander Wimmers, Fanny Böse, Alexander Buschner, Claudia Kemfert, Johanna Krauss, Julia Rechlitz, Björn Steigerwald, and Christian von Hirschhausen

- The media often portrays successes in nuclear fusion research as breakthroughs
- Despite these partial successes, commercial power generation is not foreseeable
- ITER, a major international nuclear fusion research project, has been delayed for decades
- Privately co-financed companies are investing in research, creating momentum
- These companies are focusing on nuclear fusion research for developing usable products such as magnets and lasers

Predictions for the use of nuclear fusion: Expected timeframes for operational reactors are regularly delayed

Predictions from professional publications (median values)



Source: Authors' depiction.

FROM THE AUTHORS

"The use of nuclear fusion for power and electricity generation is, as it has been for the past 70 years, unforeseeable. Unlike the traditional pilot projects of public major research institutes, which are often delayed and have little success, new, private co-financed companies are focusing their research on the applications of nuclear fusion."
*— **Christian von Hirschhausen** —*

MEDIA

Audio Interview with Christian von Hirschhausen (in German)
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ABSTRACT

Research into nuclear fusion for military purposes has been regularly conducted since the 1940s. However, the idea of being able to use nuclear power for power generation within mere decades has not come to fruition. While some successes have been highlighted by the media, such as the experiments at the National Ignition Facility in California at the end of 2022, the main problems remain as challenging today as they were in the past. An analysis of expert opinions shows that there is still no concrete path to commercial power generation from nuclear fusion. The former flagship project, the Thermonuclear Experimental Reactor (ITER), a prime example of the pervasive delays: Conceived by the United States and the Soviet Union in 1985, the research of the ITER project has been repeatedly postponed since the 1990s. As of 2025, the nuclear fusion experiments are not scheduled for operation until the late 2030s. At the same time, new, privately co-financed companies are emerging that focus on specific applications of nuclear fusion, such as the development of magnetic coils and laser technology. German, European, and international research funding must adapt to these new developments and critically scrutinize the large research institutes with regard to the goal of nuclear fusion.

Since the 1950s, there have been expectations that commercial nuclear fusion could be used to generate electricity within a few decades. However, these expectations have never been met.[1] In fact, there are still no foreseeable solutions to fundamental technical challenges that would make it possible for nuclear fusion to be profitable in the energy industry. As was the case 70 years ago, it is still unclear which reactor concept offers the best long-term prospects and could actually be used one day (Box). The situation is particularly critical for the former flagship project, the International Thermonuclear Experimental Reactor (ITER), and its successor, the demonstration power plant (DEMO). Both projects have fallen decades behind schedule.

On the other hand, momentum in nuclear fusion research has been observed in the research landscape for several years. This momentum is coming from privately co-financed companies and the participation of private actors in public pilot projects in particular. For example, over the past ten years, tens of billions of USD have been invested in around 80 small and medium-sized private companies in the sector. This makes a shift in the structure of actors foreseeable, which could give momentum to the development of fusion technology and call existing research structures into question.

This Weekly Report uses two datasets to analyze the current and long-term sector trends: Using a comprehensive literature review, expert predictions regarding the timeline for the commercial use of nuclear fusion are evaluated. In addition, an analysis of current development projects shows the dynamics of private sector companies whose research focuses on applications of nuclear fusion and the short-term commercialization of by-products.

Historical overview: Controlled nuclear fusion was a goal of large research institutes

During the Cold War, many countries established large research institutes for researching military as well as civilian

1 Shutaro Takeda, Alexander Ryota Keeley, and Shunsuke Managi, "How Many Years Away Is Fusion Energy? A Review," *Journal of Fusion Energy* 42, no. 1 (2023): 16.

DOI: https://doi.org/10.18723/diw_dwr:2025-14-1

uses of nuclear fusion. In Germany, the Max Planck Institute for Plasma Physics (*Max-Planck-Institut für Plasmaphysik*, IPP) at the Garching and (from 1991) Greifswald sites as well as the nuclear research centers in Karlsruhe and Jülich are large permanent research institutes focusing on nuclear fusion.

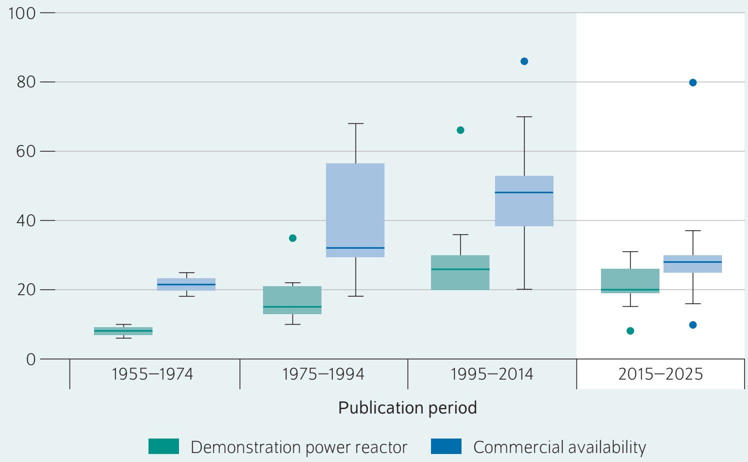
The development of expensive basic research infrastructure was regularly accompanied by recurring tech-hype phases in which progress was celebrated publicly, even if the goal of commercial use was barely any closer.[2] This began at the first conference on the commercial use of atomic energy in 1955, the Geneva Conference on the Peaceful Uses of Atomic Energy. There, it was announced that commercial nuclear fusion would be available in 20 years.[3] Most recently, the National Ignition Facility (NIF) in California made headlines when they achieved fusion ignition for the first time in December 2022: More energy was released via nuclear fusion than was required to trigger its ignition. While the media portrayed this as a breakthrough, a commercial breakthrough is not predicted for even the distant future; the fusion ignition was carried out on only a single fuel pellet with a very low energy yield. Moreover, the primary energy required to generate the laser energy was not accounted for in the energy balance.[4]

The American experiment also resulted in more momentum in research policy in Germany. In 2024, the Federal Ministry for Education and Research (*Bundesministerium für Bildung und Forschung*, BMBF) published the Fusion 2040 funding program, the explicit goal of which is to achieve an operational German fusion power reactor.[5] Furthermore, the Bavarian state government has launched a "nuclear fusion mission." It is planning to set up its own fusion campus with chairs, junior research groups, and a separate degree program.[6] Hessen has also implemented a research strategy for nuclear fusion.[7]

Figure 1

Expectations for the technical and commercial implementation of nuclear fusion

Selected estimates since the 1950s



Notes: The horizontal lines through the box plots show the median predicted time until the first demonstration power reactor is operational or nuclear fusion becomes commercially available. The boxes show all of the median times in the 50 percent interval, the t-shaped lines show the 1.5-fold distance of the box from its ends, and the dots represent the outliers.

Source: Authors' depiction based on original literature.

Scientists predict it will take 20 years or more until the first demonstration power reactor is operational.

Commercial use is still not foreseeable in concrete terms

From the beginning, independent analyses have been very critical of the possible competitiveness of nuclear fusion reactors. For example, the 1960 book *Atomkraft* concluded that fusion reactors were "likely to be much more costly than fission reactors," which were far from competitive themselves.[8] As of 2025, this remains true.[9]

Over the past decades, nuclear fusion experts have repeatedly predicted that nuclear fusion will contribute to energy production in the near future despite the unresolved technical and physical challenges.[10] This has prompted some scientists to refer to this as the "fusion constant," which states that predictions for the commercial viability of fusion power plants are always 20 to 40 years away, regardless of when

2 Cf. Vaclav Smil, *Invention and Innovation: A Brief History of Hype and Failure* (Cambridge: 2023) as well as Jascha Bareis, Maximilian Roßmann, and Frédérique Bordignon, "Technology Hype: Dealing with Bold Expectations and Overpromising," *TATuP – Zeitschrift Für Technikfolgenabschätzung in Theorie und Praxis* 32, no. 3 (2023): 10–71 (in German; available online; accessed on March 2, 2025. This applies to all other online sources in this report unless stated otherwise).

3 Cf. Joachim Radkau, *Aufstieg und Krise der deutschen Atomwirtschaft 1945–1975: Verdrängte Alternativen in der Kerntechnik und der Ursprung der nuklearen Kontroverse* (Reinbek bei Hamburg: Rowohlt, 1983) (in German).

4 The energy surplus of 1.1 megajoules is equal to the energy that is released when burning around 32 grams of hard coal, cf. Laqurence Livermore National Lab, "A shot for the ages: Fusion ignition breakthrough hailed as 'one of the most impressive scientific feats of the 21st century,'" press release from December 14, 2022 (available online). Also cf. Reinhard Grünwald, *Auf dem Weg zu einem möglichen Kernfusionskraftwerk – Wissenslücken und Forschungsbedarfe aus Sicht der Technikfolgenabschätzung. TA-Kompakt* (Berlin: Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag (TAB), 2024) (in German; available online).

5 Bundesministerium für Bildung und Forschung, *Förderprogramm Fusion 2040 – Forschung auf dem Weg zum Fusionskraftwerk* (2024) (in German; available online).

6 Staatsministerium für Wissenschaft, *Bayern startet die Mission Kernfusion: Ministerpräsident Dr. Markus Söder und Wissenschaftsminister Markus Blume stellen Masterplan vor* (2024) (in German; available online).

7 Hessisches Ministerium für Wirtschaft, Energie, Verkehr, Wohnen und ländlichen Raum, *Focused Energy erhält 2,5 Millionen Euro* (2024) (in German; available online) as well as the statement for the Hessian Climate Council by Matthias Englert and Anna Kopp, *Übersichtsstudie Kernfusion für den Klimabeirat Hessen* (2024) (in German; available online).

8 Cf. Friedrich Münzinger, *Atomkraft: Der Bau ortsfester und beweglicher Atomantriebe und seine technischen und wirtschaftlichen Probleme. Eine kritische Einführung für Ingenieure, Volkswirte und Politiker* (New York: 1960): 169 (in German).

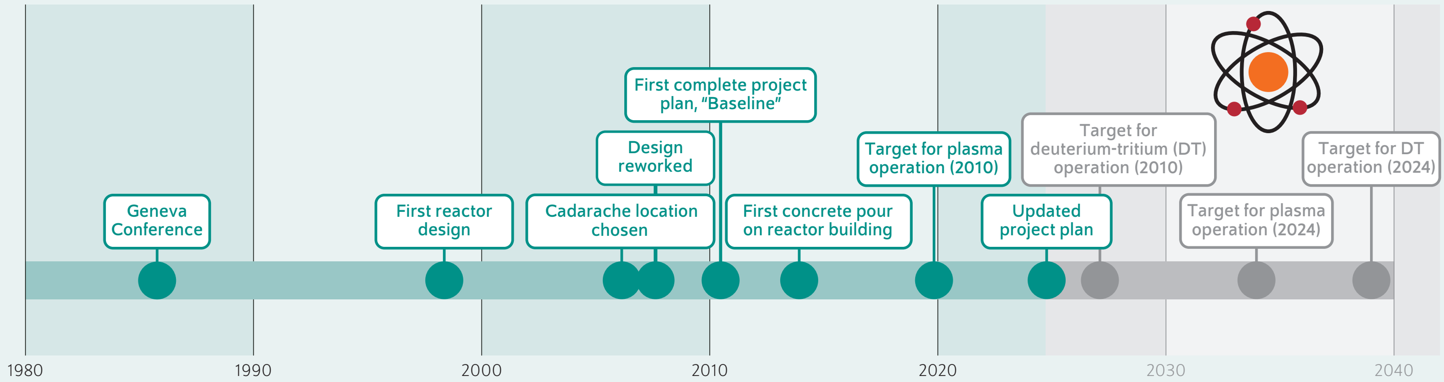
9 Cf. Sven Wurbs et al., "Kernfusion als Baustein einer klimaneutralen Energieversorgung? Chancen, Herausforderungen, Zeithorizonte," *Impuls* (2024) (in German; available online); Grünwald, *Auf dem Weg zu einem möglichen Kernfusionskraftwerk* as well as Axel Kleidon and Harald Lesch, "Kann Kernenergie zur Energiewende beitragen? Zukünftige Energieversorgung in Deutschland," *Physik in unserer Zeit* 55, no. 6 (2024): 286–293 (in German; available online).

10 Samuele Meschini et al., "Review of commercial nuclear fusion projects," *Frontiers in Energy Research* 11 (2023): 1157394 (available online).

Figure 2

ITER project development since 1985 including planned milestones

Selected results since 1985



Source: Authors' depiction based on the ITER website (available online) as well as Gibney (2014) (available online) and Gibney (2024) (available online).

Systematic delays in the ITER project since 1985 call the entire project into question.

the prediction is made.[11] A comprehensive literature review shows that the timeframes predicted in 2025 for achieving commercial nuclear fusion have not changed significantly compared to recent decades (Figure 1).[12]

In addition, the wide variation in the predicted timeframes is noticeable. When comparing the medians, it can be seen that the pure technological implementation of nuclear fusion (operation of a demonstration reactor) is expected on average around ten years before its commercial use is expected. Although it may be assumed that the predicted timeframes would decline as research progresses, the data do not confirm this. The predicted timeframes for demonstration reactors, as for the commercial viability of nuclear fusion, do not decline on average over the observation period. Predictions published after 2000 still assume an average period of a little over 24 years before a demonstration reactor is operational and of 40 years until commercial nuclear fusion is available.

ITER project in a never-ending crisis since 1985

The former flagship project ITER is good example of systematic delays and high cost increases.[13] The ITER project originally began as a cooperation between the United States and the Soviet Union in 1985. Since then, 33 countries have become involved in the project. In line with the plans from 1993, a test device was to go into operation as early as 2005, followed by a demonstration power reactor (DEMO) in the 2020s at the Cadarache site in southern France. However, the project was repeatedly delayed (Figure 2). When construction began in 2007— already after significant delays—the goal was to begin plasma experiments in 2016. After further delays, it can be assumed that deuterium-tritium fusion will not happen before 2039. ITER costs have also risen significantly.[14] While the initial costs were estimated to be five billion euros, they have increased to 20, and sometimes even over 40, billion euros.[15]

The ITER project conducts research on, among other things, the functionality of superconducting magnets, plasma behavior, and tritium incubation. Therefore, it is not suitable for demonstrating the technical implementation of magnetic confinement fusion for electricity generation. The successor project DEMO will be a demonstration power plant that will show nuclear fusion and electricity generation, including the necessary tritium incubation, in operation. Earlier plans predicted operation would begin in 2020; now, the timeframe has been shifted to the second half of the 21st century. All things considered, the entire planning of the DEMO project should be viewed critically. Publicly financed DEMO projects in China, Japan, South Korea, Russia, India, and the United States are planned for the 2040s to 2050s, which suggest a (re)nationalization of fusion research. This

11 Takeda, Keeley, and Managi, "How Many Years Away Is Fusion Energy?"

12 See Alexander Buschner and Julia Rechlitz, *Forecasting Nuclear Fusion Availability Using Experts' Assessment* (mimeo).

13 ITER, *On the road to ITER* (2024) (available online); Elizabeth Gibney, "Five-year delay would spell end of ITER," *Nature* (2014) (available online); and Elizabeth Gibney, "ITER delay: what it means for nuclear fusion," *Nature* 631 (2024): 488–489 (available online).

14 Meschini et al., "Review of commercial nuclear fusion projects,"; David Kramer, "ITER appears unstoppable despite recent setbacks," *Physics Today* 78, no. 8 (2023): 18–22 (available online) as well as ITER, *Why have ITER costs risen* (2024) (available online).

15 ITER, *Updated baseline presented* (2024) (available online) as well as Science & Business, *ITER fusion project confirms more delays and €5B cost overrun* (2024) (available online).

Box

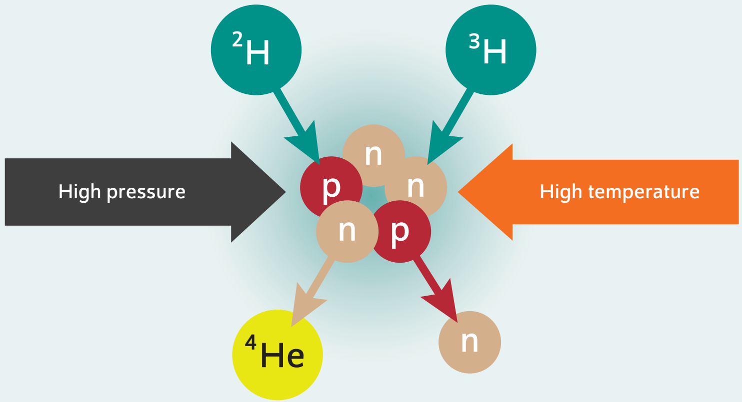
Basics of nuclear fusion and its implementation challenges

There are different types of nuclear fusion. The most common involves fusing together two hydrogen isotopes, deuterium and tritium, to form helium. This reaction releases large amounts of energy and a neutron (Figure). For the deuterium and tritium ions to fuse despite their mutual electrostatic repulsion, the hydrogen mixture must be in a plasma state and exposed to very high temperatures and sufficiently high pressure for a certain period of time. This requires suitable physical conditions and until today, such conditions have only been achieved for incredibly short periods in individual experiments and without energetic utilization.

Figure

How deuterium-tritium nuclear fusion works

Simplified visual representation of the fusion of deuterium-tritium to helium-4 and one neutron



Source: Authors' depiction.

During nuclear fusion, the hydrogen isotopes deuterium and tritium fuse to form helium and a (fast) neutron and release large amounts of energy.

There are two main approaches to generating fusion power:

- Magnetic confinement fusion uses magnetic coils to generate and maintain a hot plasma, which can lead to fusion. The leading reactor concepts using magnetic confinement are the tokamak and stellerator. While the tokamak requires a pulsed current to generate plasma, the stellerator can theoretically run in continuous operation due to the special twisting of its coils.
- In inertial confinement, the inertia of the plasma is used for confinement and the density of the plasma is maximized. High-energy lasers are shot at a very small fuel pellet, in which fusion then takes place.

There are also a number of other fusion concepts and technologies that use a combination of magnetic and inertial confinement, among other things. However, most of these concepts are still less technologically mature than magnetic and laser fusion. Depending on the technology, an ignited plasma must be kept permanently stable to enable continuous fusion processes. In magnetic fusion concepts, high-performance magnets are intended to ensure long confinement times, but these require external heating systems and can destabilize the plasma and damage the system due to interference. In inertial confinement concepts, a single target, a fuel pellet, is heated, which must be manufactured with extreme precision to guarantee ignition. Furthermore, fuel supply questions, primarily regarding tritium, remain unresolved. The planned incubation of tritium during operation has not yet been technically tested and tritium cannot be stored due to its short half-life. To date, there has been no successful technical demonstration of a fusion device in continuous operation; instead, previous experiments have run for single shots or only for a few minutes.

could call the continued financing of the ITER into question due to reduced research funding.[16]

Momentum in public-private financing and corporate development

While fusion research and site development was concentrated in public research institutes in the 1980s and 1990s, some new private and public-private corporations (new ventures) have been founded since the 2000s (Figure 3). Worldwide, around 80 new ventures are currently active in nuclear fusion. These new ventures operate privately financed research into the applications of nuclear fusion, which builds upon the results of the basic research performed at the experimental devices of major research institutes. Among other things, the focus is on developing powerful magnets and optimizing the efficiency of laser systems. Commercial nuclear fusion energy is not expected from these companies because they have only planned experimental devices.

According to the International Atomic Energy Agency's FusDIS database, 50 of the 169 fusion devices in planning or already built worldwide are privately owned.[17] Some of the devices listed can be described as reactors. They are exclusively experimental reactors, however, and thus are

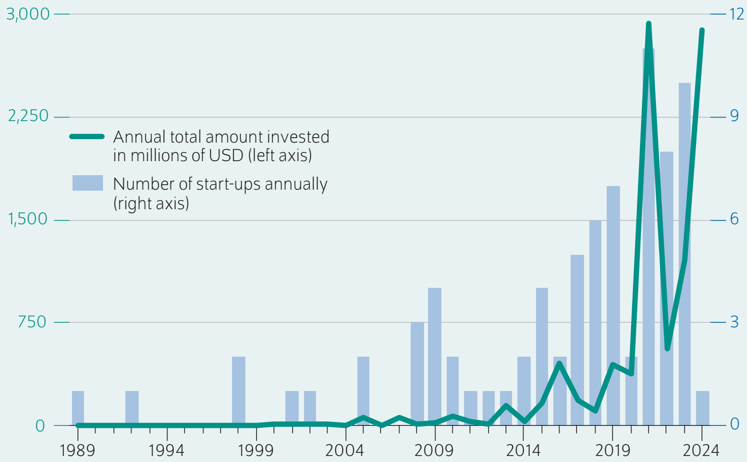
16 As early as 2002, the Office of Technology Assessment at the German Bundestag proposed terminating further development of tokamak concepts and reorienting nuclear fusion research. Armin Grunwald et al., "Kernfusion," *TAB-Sachstandbericht, Arbeitsnericht* no. 75 (2002) (in German; available online).

17 IAEO, *Fusion Device Information System (FusDIS)* (2024) (in German; available online. Accessed on December 12, 2024). The fusion devices belonging to the four German New Ventures Gauss Fusion, Focused Energy, Marvel Fusion, and Proxima Fusion are listed as being in planning. The Focused Energy and Marvel Fusion devices, however, will be in the United States.

Figure 3

Financing for private ventures in the nuclear fusion sector (1989 to 2024)

Financing amount in millions of USD (left axis) and number of start-ups (right axis)



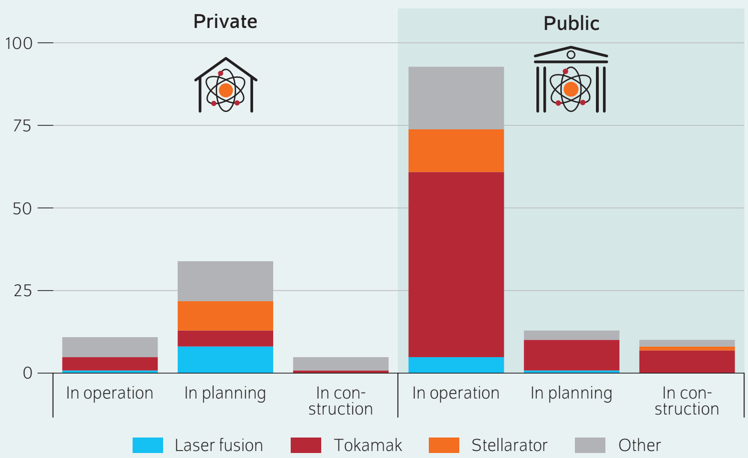
Source: Authors' depiction based on publicly available data.

The financing of private companies in the nuclear fusion sector has increased considerably over the past years.

Figure 4

Overview of the type and structure of the most well-known fusion devices

Number of devices by reactor concept, (main) type of financing, and current operational status



Source: Authors' calculations based on an evaluation of the IAEA FusDIS (as of December 12, 2024).

Today, most experimental devices are planned by the private sector.

not suitable for developing commercial energy generation from nuclear fusion. Furthermore, not every new venture can be assigned to a specific device. The devices listed differ in terms of operating status, financing structure, and concept (Figure 4).[18] Those still in the planning stages are predominantly privately financed.

Conclusion: Research focus should return to application-oriented research

Nuclear fusion research is generally still in the long-term basic research phase. Combining military interests with this basic research has led to the development of national and international large-scale research institutes since the 1940s. These institutes have had some success in understanding the science behind nuclear fusion and have made military applications possible. However, these applications have not been designed for commercial power generation. In fact, the research programs launched between the 1960s and 1990s have come up empty handed in regards to the commercial use that the public was promised. The decades-long delays in the ITER are symptomatic of this.

On the other hand, a rapidly growing number of smaller companies with substantial private co-financing have been researching certain applications for around one to two decades. Meanwhile, around one third of test sites have a private company structure, with this share rising. Their focus is on developments in magnetic research and laser technology. These companies are not focusing on power generation. And in view of the unresolved technical, institutional, and economic uncertainties, power generation is also not expected to become a focus.

Public national and international research funding needs to adjust to the new framework conditions. Instead of focusing on a hypothetical fusion power plant, the emphasis should be on other potential applications. Open-technology funding of various fusion concepts, such as magnetic, inertial, and other fusion approaches at all federal levels (state, federal government, EU, global) does not make sense due to a lack of funding and other energy concepts more worthy of research.

18 The FusDis does not include any devices that have already been shut down. For example, it does not include the Joint European Torus, which shut down at the end of 2023, cf. Daniel Clery, "European fusion reactor goes out with a bang," *Science*, 2024 (available online).

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