RECENT PROGRESS IN NUCLEAR FUSION TECHNOLOGY AND EVALUATION OF VIABLE PATHWAYS TOWARD COMMERCIAL DEPLOYMENT

Fusion technology is a promising scientific concept that humanity may be able to apply as a future energy source. In recent years, growing international collaboration, increased funding, and the involvement of private startups have accelerated research in the field of fusion. As a result, several important advances have been achieved, including improvements in plasma confinement, record device performance, and net energy gain in laboratory experiments. This paper examines recent advances in fusion energy technology and evaluates potential pathways toward its commercial deployment, as well as the limitations that currently prevent fusion energy from becoming a viable large-scale power source.

Introduction

Modern society relies heavily on energy in daily lives of people, industrial processes, and scientific development. In the last several decades, the world has seen record-high rates of growth in energy use, power demand, and scientific production. This is because technology is moving quickly and industries are growing. High energy input is required to support this level of development, and unfortunately, traditional energy sources are starting to become obsolete.

Limitations of Conventional Energy Sources

Fossil fuel–based power plants still provide most of the world's energy and are a major source of greenhouse gas emissions. As shown in Figure 1, coal and natural gas produce ten times more carbon dioxide per unit of power than renewable and nuclear energy sources. These environmental issues, together with the fact that resources are limited in the long run, have led to more scientists becoming interested in alternative low-carbon energy solutions.

Nuclear energy stands out among these options because it offers high energy output as well as minimal carbon emissions during operation, making it a good choice for large-scale power production. However, despite nuclear energy being at its peak currently, it has its certain drawbacks that prevent humans from investing all their resources and time into it.

The primary resource utilized for this sort of energy, Uranium-235, is finite, generates a lot of toxic waste, and has significant safety hazards. Modern fission reactors have a lot of safety features built in, but there are still big problems with accident scenarios, getting rid of decay heat, and long-term waste storage. This is why over the past 30 years, a lot of study and development has also been done on thermonuclear energy, particularly on fusion and moving the notion of fusion from theory to reality.

Fusion Energy as a Long-Term Solution

The theory behind fusion energy is that in a highly heated plasma, which contains many particles, two light nuclei collide, resulting in the formation of a new heavier nuclei and a release of a large amount of energy. This reaction is responsible for an extremely high energy output as observed in stars.

The most common element for fusion reactions that is presently being heavily investigated is hydrogen, specifically its isotopes deuterium and tritium. One of the biggest advantages of this process is that deuterium and tritium are nearly infinite on the planet. Deuterium can be obtained from saltwater, which is abundant on Earth, while tritium can be produced artificially from reactions with lithium. The second main benefit of fusion energy compared to others is its safety. Fusion reactions cease if the required conditions are not met, potentially helping to avoid any major accidents. Fusion is also environmentally friendly, as it does not emit carbon dioxide.

Despite these advantages, fusion energy has not yet been demonstrated in a fully operational, large-scale reactor. Research is currently being conducted in more than 40 countries, with each team focusing on a specific engineering challenge to subsequently combine results and transition to a new, completely advanced energy system.

Growth in Fusion Research and Funding

As research activity and funding have increased – for instance, U.S. government funding for fusion research has gone up by around 60% in the last ten years – recent years have seen important advances in experimental fusion performance and thermonuclear technologies, bringing fusion energy closer to practical application. France is currently building the world's largest fusion experiment facility ITER. The construction started in 2010 and is expected to finish by 2035, with the first trial plasma experiments to be conducted by teams from seven different nations. In parallel, several countries including South Korea, China, the United Kingdom, and others are developing demonstration fusion devices intended to bridge the gap between

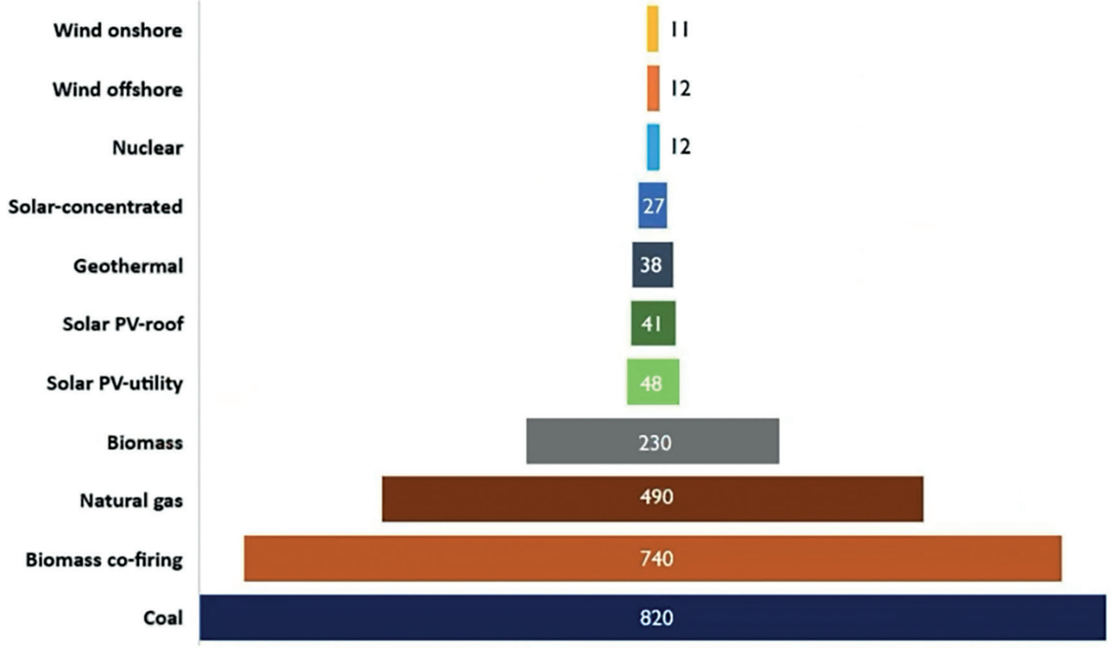

Figure 1. Carbon dioxide emissions (g CO$_2$ equivalent/kW) from various energy sources. Reproduced from Mohamed et al. (2024) Global Development and Readiness of Nuclear Fusion Technology as the Alternative Source for Clean Energy Supply, Sustainability*, 16(10), 4089*

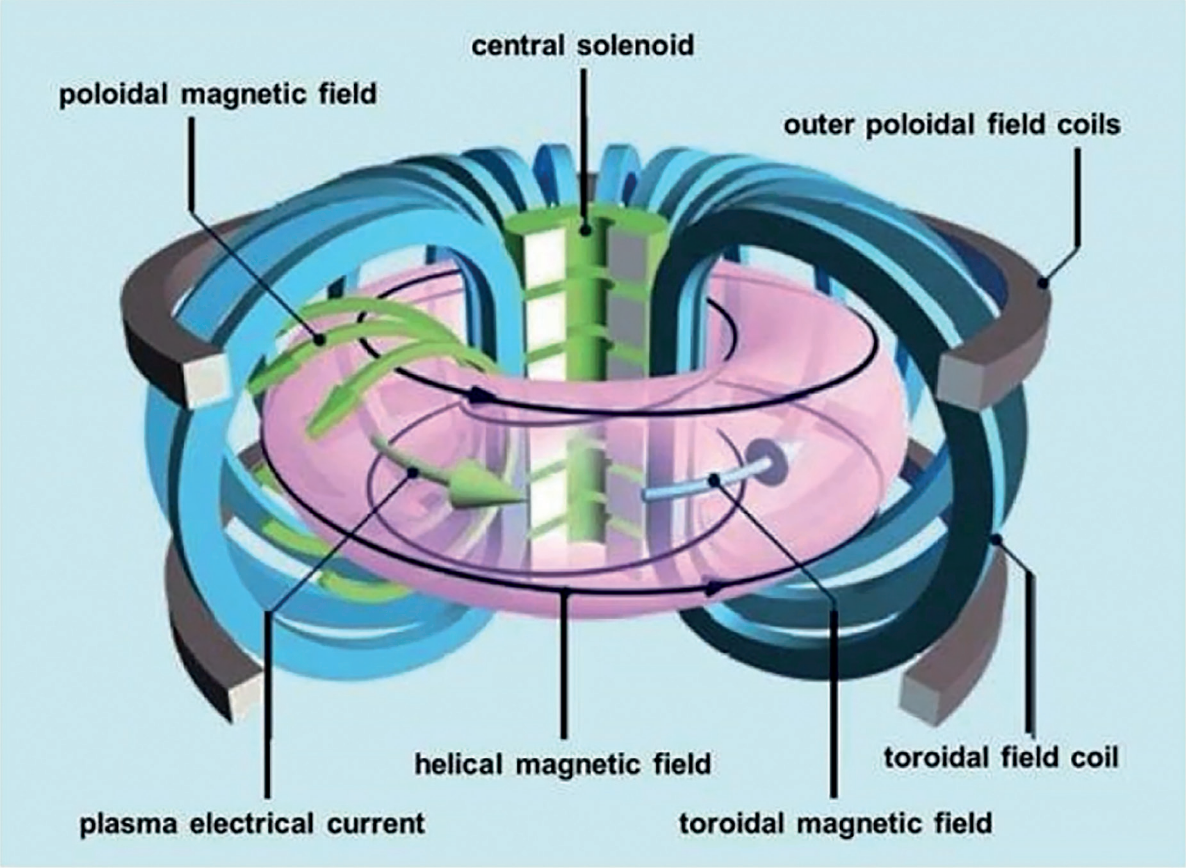

Figure 2. Schematic diagram of a tokamak illustrating the magnetic field coils, plasma current, and resulting magnetic field used for plasma confinement. Reproduced from the U.S. Department of Energy, Office of Science, "DOE Explains: Tokamaks," energy.gov

laboratory-scale experiments and commercial power plants, with completion targets also around 2035. At the same time, recent progress in smaller-scale fusion experiments gave us critical information on computational systems, plasma confinement, and energy gain necessary for realization of fusion energy.

Recent Advances in Fusion Research

Recent advancements in artificial intelligence (AI) and computational technologies have led academics to believe that these tools may heavily contribute to fusion research. AI can assist scientists with calculations and reactor design, as well as with data analysis and the development of computational models. A new project, STELLAR-AI, was initiated at the beginning of 2026. The initiative aims to develop a digital twin of the largest spherical fusion device in the United States. Rather than conducting experiments directly on the fusion device, scientists can use STELLAR-AI to first test hypotheses and perform simulations on the digital model, proceeding with experiments on the physical system only if the computational results are successful. This method can save time and money by moving some part of the experimental testing from the actual fusion device to computer simulations run on a digital twin.

Furthermore, in 2022, the National Ignition Facility (NIF) in Livermore, CA, completed its first experiment that generated more energy than was used to start it. This experiment generated roughly 3.15 MJ of fusion energy from an initial laser energy input of about 2.05 MJ, marking the first instance of net energy gain through fusion. To ignite fuel and reach the temperature needed, they used a much denser diamond lattice than before, as well as a more powerful laser. They repeated the same experiment in 2023 and were able to get even higher net energy gain of 3.4 MJ of fusion energy. This result is very important in the future development of fusion because it proves the process can be reproduced and energy produced can increase through continuous optimization of parameters. It has also been shown that there are no fundamental limitations to the fusion energy concept in a lab setting, indicating its potential for use in a full-scale reactor.

At the same time, important progress has also been achieved using magnetic confinement methods in tokamaks. Tokamak, as pictured in Figure 2, is a doughnut-shaped fusion device which is currently the most promising fusion device configuration that is being studied. Major national labs and international research projects, such as ITER, EUROfusion, and top research institutes in Asia and the US, are all working hard to make tokamak plasma confinement and magnets work better. Significant attention is now dedicated to improving tokamak magnet performance, because magnets allow plasma to be confined without losing temperature. Figure 2 shows that plasma current generates a magnetic field to form a spiral magnetic field structure. Maintaining the high temperatures and densities necessary for fusion reactions is possible because this magnetic field prevents the plasma from contacting the reactor walls. Recent experiments have focused on improving confinement conditions and increasing the time that plasma can remain stable inside the reactor.

Figure 2: Optical micrographs after exposure to 1 A/mm^2 [3].

Recently in China, a tokamak was able to sustain superheated plasma with a new record of 18 minutes. The process of plasma confinement is not continuous yet, but it is a huge step toward being able to retain plasma in place for numerous confinement cycles, which is essential for fusion reactions to run continuously.

Another team of Chinese scientists also achieved a world-record plasma pulse length, sustaining high-temperature plasma for approximately 403 s in the EAST tokamak. They were also able to operate at plasma densities about 20% above the Greenwald density limit. The Greenwald density limit is the maximum electron density that can be achieved in tokamak. If this density limit is exceeded, plasma instabilities and disruptions are likely to happen, which can terminate the confinement process. Maintaining high plasma density and long confinement times is important for increasing fusion reaction rates, which is necessary for making fusion energy economically viable.

Private Fusion Startups

Along with government-funded research projects and university partnerships, private startups have become key players in fusion development by exploring different engineering methods. The company that has attracted approximately one-third of all private capital investment in fusion energy, corresponding to about 3 billion dollars, is Commonwealth Fusion Systems. Their main goal is to build the first commercial fusion reactor, SPARC, in the US, which is going to prove that fusion energy works on a full scale. This device is meant to show net fusion energy gain and plasma conditions that are relevant to reactors in a small tokamak configuration. SPARC is not meant to provide energy, but it does attempt to prove the basic physics and technical needs for a commercial fusion power plant. They expect to have it working by the end of 2027, and by the 2030s they plan on building an actual commercial plant that produces electricity.

ZAP energy startup is working on plasma stability. They develop Z-pinch confinement technology, which means building a low-cost reactor. In essence, Z-pinch technology utilizes self-heating plasma, thereby requiring fewer parts compared to tokamaks.In this method, a strong electric current flows through the plasma, creating a magnetic field that pushes the plasma inward via the Lorentz force. This compression raises the plasma's temperature and density, which helps create the conditions needed for fusion processes. If this technology works, it can reduce costs needed to construct a working reactor.

Tokamak Energy in the UK is another startup company that recently achieved a milestone and built a new tokamak with the ion's temperature of 100M Kelvin, the highest temperature ever achieved in a spherical tokamak. Their tokamak DEMO4 recently achieved another milestone result and carried around 7 million ampere-turns of current, placing it among the most powerful high-temperature superconducting magnet systems demonstrated so far. They aim to build a pilot-scale fusion plant in the next 5–10 years as well.

Remaining Challenges to Commercial Fusion

Despite the promising nature of fusion, several obstacles exist that hinder the construction of a full-scale reactor, which may need much more than a decade to complete. The progression towards fusion energy has four stages, ultimately aimed at establishing a full-scale thermonuclear facility.

ITER in France represents only the first phase and is solely focused on research, therefore it will not generate any energy. The ITER Tokamak is designed only to replicate real fusion circumstances and evaluate core ideas, including positive energy gain and plasma heating. Upon success, during stage two, a demonstration device will be built to illustrate on a modest scale that fusion can effectively generate power and is environmentally sustainable. Upon successful completion, stage three will include the construction of a commercially viable unit that will generate electricity for sale. Its primary purpose is to attract investors and demonstrate the feasibility of constructing commercial fusion plants. Only upon achieving success in all three phases can a commercial fusion plant be constructed and start the replacement of current energy sources.

Fusion energy will need around 40 years to have a significant impact on the energy market, since research is still ongoing and many primary issues remain unresolved. A consistent net energy gain remains challenging, magnets continue to be enhanced for prolonged plasma confinement, and plasma stability is insufficient to guarantee a significant advancement in energy production.

Conclusion

Fusion energy is a very promising concept that has been gaining attention from scientists for the past years. A lot of new discoveries and new exciting upgrades have been made in the past couple of years, with much more coming for the next decade. The completion of construction of the world's largest fusion device, the development of small-scale systems by private startups, and continued laboratory advancements in fusion technology are expected to bring the world closer to a fundamentally new energy source. Although fusion energy is unlikely to become the main global energy source in the near future, it may play an important role in the world's energy system in the future.

References

Accessing the density-free regime with ECRH-assisted Ohmic start-up on east | science advances. (n.d.-a). https://www.science.org/doi/10.1126/sciadv.adz3040

Bickerton, R. J. (1993, December 1). IOPscience. Plasma Physics and Controlled Fusion. https://iopscience.iop.org/article/10.1088/0741-3335/35/SB/001/meta

Chant, T. D. (2025, December 31). Every fusion startup that has raised over $100m. TechCrunch. https://techcrunch.com/2025/12/31/every-fusion-startup-that-has-raised-over-100m/

Claessens, M. (2023). Iter, the giant fusion reactor: Bringing a sun to Earth. Springer.

Cohen-Tanugi, D., Delaporte-Mathurin, R., Handley, M., Meschini, S., Maris, A., Mouratidis, T., Mullen, J., Seltzman, A., Stapelberg, M., Short, M., Segantin, S., Wallace, G., & Zhou, W. (2024, February 15). Enabling commercial fusion: Venture & Technology Opportunities for a growing fusion industry. Enabling Commercial Fusion: Venture & Technology Opportunities for a Growing Fusion Industry. https://dspace.mit.edu/handle/1721.1/153524.3

Democratic engagement in Sustainable Energy Innovation: Applying the quintuple innovation helix to manage accelerating fusion energy through an IEA-backed Global Commission | IEEE Journals & Magazine | IEEE Xplore. (n.d.-b). https://ieeexplore.ieee.org/document/10599889/

Design of first experiment to achieve fusion target gain > 1 | physics of plasmas | AIP publishing. (n.d.-c). https://pubs.aip.org/aip/pop/article/31/7/070502/3304417/Design-of-first-experiment-to-achieve-fusion

Griffiths, T., Pearson, R., Bluck, M., & Takeda, S. (2022, August 23). IOPscience. Progress in Energy. https://iopscience.iop.org/article/10.1088/2516-1083/ac84bf/meta

Guo, Z. (2024, February 3). Nuclear fusion: Overview of challenges and recent progress. NHSJS. https://nhsjs.com/2024/nuclear-fusion-overview-of-challenges-and-recent-progress/

Https://www.sciencedirect.com/science/article/abs/pii/S1047847720300046?via=ihub. (n.d.-d). https://www.med.upenn.edu/pmi/events/https-www-sciencedirect-com-science-article-abs-pii-s1047847720300046-via-3dihub

IOP. (n.d.-e). https://iopscience.iop.org/article/10.1088/1757-899X/775/1/012107/pdf

L. Ferreira Jr., M. (2012). Nuclear fusion reactor - clean and safe atomic energy. SciVee. https://doi.org/10.4016/48300.01

Lindley, B. & R. (1970, January 1). Can fusion energy be cost-competitive and commercially viabl. Energy Policy. https://ideas.repec.org/a/eee/enepol/v177y2023ics0301421523000964.html

McNamara, Asunta, Bland, Buxton, Colgan, Dnestrovskii, Gemmell, Gryaznevich, Hoffman, Janky, Lister, Lowe, Mirfayzi, Naylor, Nemytov, Njau, Pyragius, Rengle, Romanelli, … Marchuk. (2023, March 17). Achievement of ion temperatures in excess of 100 million degrees kelvin in the compact high-field spherical tokamak ST40. Nuclear Fusion. https://www.osti.gov/biblio/1962160

Meschini, S., Laviano, F., Ledda, F., Pettinari, D., Testoni, R., Torsello, D., & Panella, B. (2026, January 23). Review of Commercial Nuclear Fusion Projects. Frontiers. https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2023.1157394/full

Mohamed, A. et al. (2024). Global development and readiness of nuclear fusion technology as the alternative source for clean energy supply | sustainability. https://www.mdpi.com/2071-1050/16/10/4089

Mohamed, M., Zakuan, N. D., Hassan, T. N. A. T., Lock, S. S. M., & Shariff, A. M. (2024, May 13). Global development and readiness of nuclear fusion technology as the alternative source for clean energy supply. MDPI. https://www.mdpi.com/2071-1050/16/10/4089

Nigar Demircan Çakar, S. E. (2022, March 31). Nuclear energy consumption, nuclear fusion reactors and Environmental Quality: The case of G7 countries: DBpia. Nuclear Engineering and Technology. https://www.dbpia.co.kr/journal/articleDetail?nodeId=NODE11233879

Pester, P. (2025, January 21). China's "artificial sun" shatters nuclear fusion record by generating steady loop of plasma for 1,000 seconds. LiveScience. https://www.livescience.com/planet-earth/nuclear-energy/chinas-artificial-sun-shatters-nuclear-fusion-record-by-generating-steady-loop-of-plasma-for-1-000-seconds

Princeton. (n.d.). PPPL launches stellar-AI platform to accelerate Fusion Energy Research. EurekAlert! https://www.eurekalert.org/news-releases/1113740

Promises and limitations of nuclear fission energy in Combating climate change - sciencedirect. (n.d.-f). https://www.sciencedirect.com/science/article/abs/pii/S0301421518303318

Realization of thousand-second improved confinement plasma with super I-mode in Tokamak East | Science advances. (n.d.-g). https://www.science.org/doi/10.1126/sciadv.abq5273

Recent progress in Chinese fusion research based on superconducting tokamak configuration - sciencedirect. (2022). https://www.sciencedirect.com/science/article/pii/S2666675822000650

Sharwood, S. (2024, July 4). ITER delays first plasma for world's biggest tokamak. ITER delays first plasma for world's biggest tokamak • The Register. https://www.theregister.com/2024/07/04/iter_new_baseline_project_delays/

van de Loo, Koen (author). (2022). Understanding barriers towards the commercialization of nuclear fusion energy.

White, S. (2025, November 25). Tokamak Energy Announces Fusion Power Plant Magnet Technology Breakthrough. Tokamak Energy. https://tokamakenergy.com/2025/11/19/tokamak-energy-announces-fusion-power-plant-magnet-technology-breakthrough/

The Zap Energy Approach to commercial fusion | physics of plasmas | AIP publishing. (n.d.-h). https://pubs.aip.org/aip/pop/article/30/9/090603/2911595/The-Zap-Energy-approach-to-commercial-fusion

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