Controlled Nuclear Fusion Investment Research

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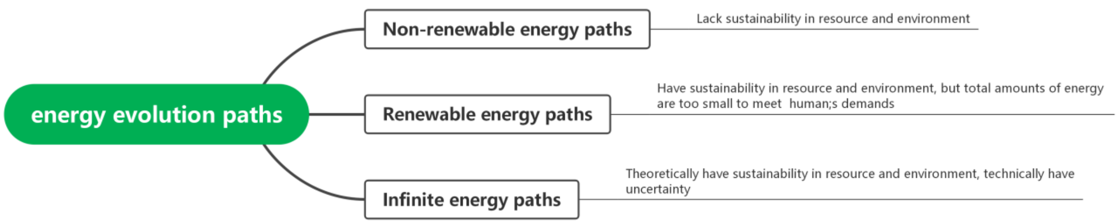
1. Industry Background and Technological Framework

1.1 Industry Overview

Nuclear fusion is an artificial process that combines light atomic nuclei under extremely high temperatures and pressures to form heavier nuclei, releasing vast amounts of energy. Compared to nuclear fission and traditional fossil fuels, fusion produces **four times more energy than nuclear power plants and nearly four million times that of burning oil or coal.** Additionally, it has the advantages of **producing no nuclear waste, emitting less radiation, and zero greenhouse gas emissions,** making it a rich, safe, and low-carbon energy source.

1.2 Industry Background

Based on economic theory, the theory of energy resource depletion, and environmental sustainability theory, energy evolution paths can be divided into three categories: **non-renewable energy paths, renewable energy paths, and infinite energy paths.** Each energy path has corresponding technological paths, and those paths depend on economic viability and risk controllability.



(1) **Non-renewable energy paths** include conventional non-renewable resources such as coal, oil, natural gas, and nuclear energy (controlled nuclear fission); and new non-renewable resources like shale gas and combustible ice. Conventional non-renewable resources are depleting, while new non-renewable resources are facing high technical difficulties, extraction costs, and geological risks. Additionally, both conventional and new non-renewable resources lack sustainability in resource and environment.

(2) **Renewable energy paths** include hydropower, wind energy, solar energy, and bioenergy, which are all derived from or transformed forms of solar energy. While renewable energy are mature in technologies and sustainable in environment, their total or practically utilizable amounts of energy are too small to meet

human's demands of energy in the short term. Additionally, instability is another significant issue of renewable sources.

(3) **Infinite energy path** sees controlled nuclear fusion as the greatest hope, characterized by high energy production efficiency, abundant raw materials, and good environmental acceptability. However, controlled nuclear fusion faces the challenges in technological paths. Hence the commercialization processes of controlled nuclear fusion are filling with uncertainty, thus presenting a contradiction between infinite energy, environmental friendliness, and technological uncertainty.

1.3 Technological Paths

To achieve controlled nuclear fusion, three conditions must be met:

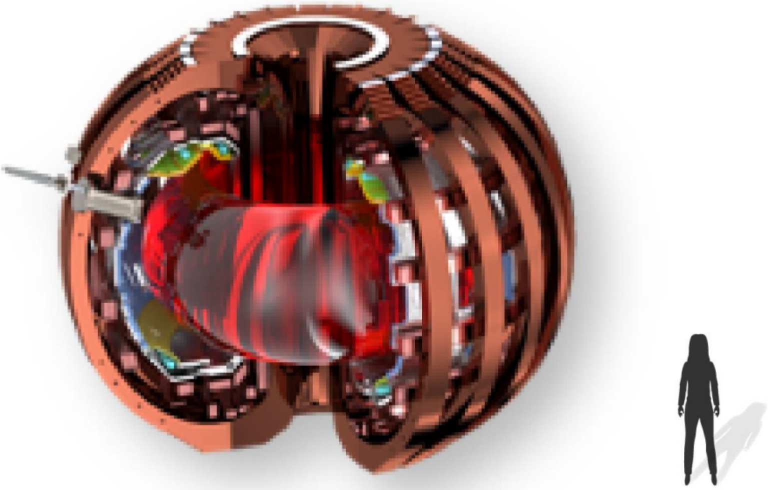
(1) **temperature,** which is high enough to turn fusion fuel into plasma.
(2) **fuel density,** which is sufficient to store the energy of alpha particles produced in fusion for continued reaction.
(3) **containment,** which keep the plasma within a limited space for a sufficiently long duration.

Nuclear fusion technology can be mainly divided into three categories based on the method of meeting these conditions:

(1) **Magnetic Confinement Fusion (MCF)** uses magnetic fields to confine fusion materials within a limited space, allowing controlled large-scale nuclear fusion reactions and energy release. The main devices include **Tokamaks, Stellarators, and Field-Reversed Configurations (FRC).**

① **Tokamak:** An annular container named from the Russian words for toroidal, vacuum vessel (kamera), magnets, and coil (kotushka). This is currently the mainstream fusion device, represented by the Joint European Torus (JET), China's Experimental Advanced Superconducting Tokamak (EAST), and the International Thermonuclear Experimental Reactor (ITER). The advantage of this device is high technological maturity and the symmetrical structure which is easy to simulate. However, because it is controlled by current, any interruption in the current or magnetic field could destroy the reactor, posing safety issues.

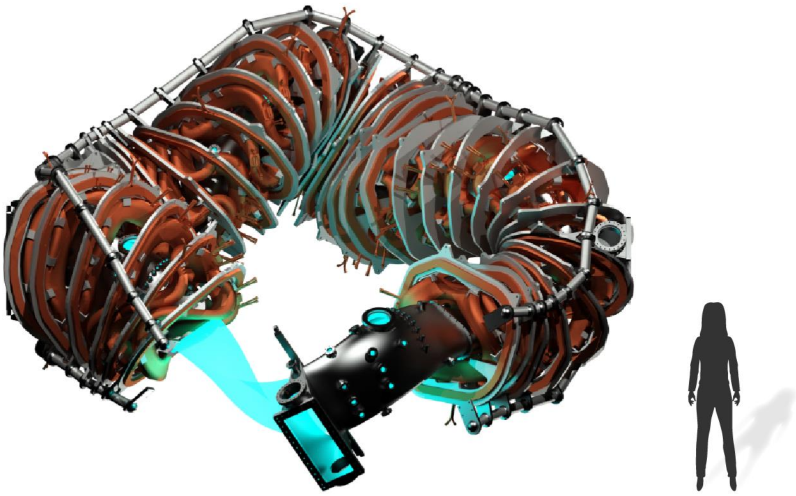
Figure 9: Tokamak fusion concept



Sources: General Atomics (tokamak), GAO (silhouette). | GAO-23-105813

② **Stellarator:** Compared to the Tokamak, the Stellarator has a more complex structure made up of multiple spiral coils, necessitating greater design computation and higher manufacturing cost. However, this complex design can avoid the safety issues of the Tokamak and enhance stability. A typical example is Germany's Wendelstein 7-X Stellarator.

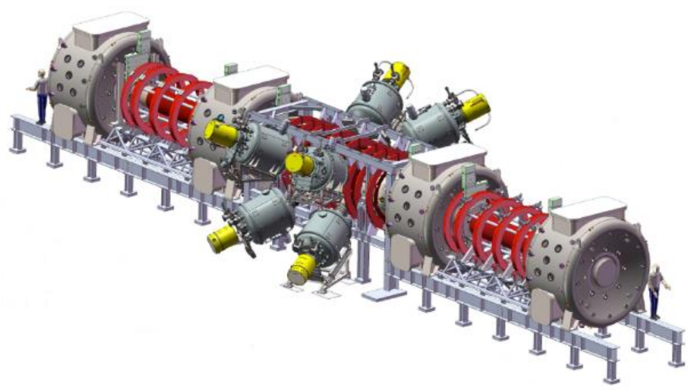
Figure 10: Stellarator fusion concept



Sources: Helically Symmetric eXperiment, University of Wisconsin at Madison (stellarator), GAO (silhouette). | GAO-23-105813

③ **Field-Reversed Configuration (FRC):** Compared to the Tokamak, the FRC is simpler. Its principle is reversing the magnetic field within the plasma to create a compact toroidal plasma surface and use this instead of an external magnetic field to confine the plasma. The advantage of this device is its simple design and low cost, and it can offer fuel options other than deuterium-tritium. However, this simple design also makes it more susceptible to plasma instability and has lower performance than the Tokamak.

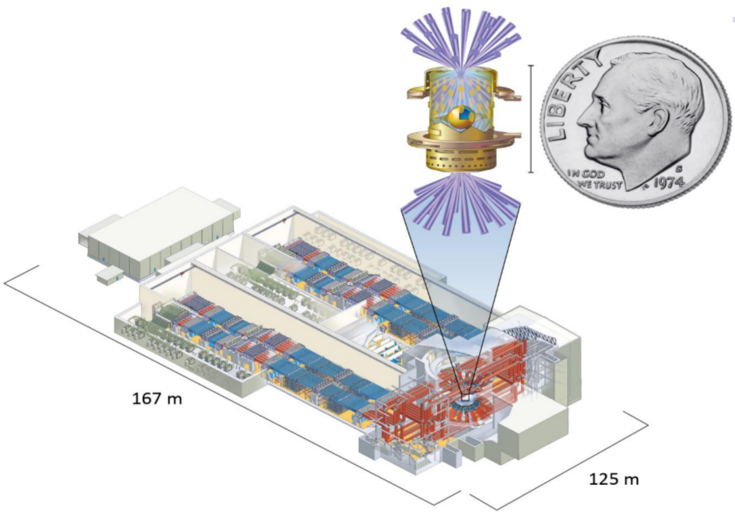
Figure 12: Field reversed configuration concept



Source: TAE Technologies. | GAO-23-105813

(2) **Inertial confinement fusion** uses lasers or electrical discharges to compress a small capsule of fusion fuel to extreme temperatures and pressures for a short time. A notable example is the National Ignition Facility (NIF) in the United States. It achieved a historic breakthrough in December 2022 by realizing "net energy gain" for the first time in a nuclear fusion reaction. A drawback of this method is that the laser beams are typically pulsed, maintaining the confinement only for a very short period, which presents challenges in achieving continuous energy supply.

Figure 8: Inertial confinement fusion concept



Sources: Lawrence Livermore National Laboratory (facility and hohlraum), BillionPhotos.com/stock.adobe.com (dime). | GAO-23-105813

(3) **Magnetized Target Fusion (MTF)** aims to combine the benefits of Magnetic Confinement Fusion (MCF) and Inertial Confinement Fusion (ICF). It uses magnetic fields to initially stabilize the plasma, as well as uses compression to increase the density and temperature of energy. However, as a new technological approach, MTF has a lower technological maturity and requires further research and validation.

In addition to MCF, ICF and MTF, there are other technological paths. These paths have unique advantages but, at the same time, have lower technological maturity and are still in the early stages of development.

1.4 Commercialization Practices

Controlled nuclear fusion has the potential to completely solve energy issues, but due to its high technical difficulty and substantial funding requirements, related research projects are usually led by nations or even multiple countries together, while ordinary businesses and private capital rarely involved.

However, **since 2021, private capital has also seen the research progress and potential in the controlled nuclear fusion, moving heavily into this area.** The United States, China, France, Germany, the United Kingdom, Israel, Italy, and Japan have over thirty private nuclear fusion companies exploring the commercial viability of nuclear fusion. As of July 2022, private companies have attracted approximately 5 billion USD in investment. These companies also form a complementary division of labor with national research teams: national research teams focus on large devices to ultimately build controlled nuclear fusion power plants; while startup companies focus on small devices, attempting to pioneer new business models, initially building prototype machines at lower costs, using engineering means to enhance performance, and striving for early realization of commercial power generation. For the details of these companies, see 3.1.1 Leading Companies section.

2. Controlled Nuclear Fusion Market and Industry Analysis

2.1 Current Development Status of Controlled Nuclear Fusion

The global nuclear fusion industry is **currently experiencing a rapid growth phase,** with significant expansions in the number of enterprises and the scale of investments. According to a July 2023 report from the American Fusion Industry Association, the number of global nuclear fusion enterprises has grown from 33 in 2022 to 43, reflecting the vitality and diversity of the field.

In these companies, the United States leads with 25 enterprises, and the total global funding has exceeded $6.2 billion, an increase of 27% compared to 2022. Additionally, at least 18 companies have begun or plan to initiate cooperative projects with governments, with government-funded amounts surpassing $70 million.

Internationally, countries like the United Kingdom, the United States, Japan, and Germany are advancing new strategies and plans to support the development of nuclear fusion energy, accelerating research and development in this area. This model of public-private cooperation not only fosters technological progress but also creates broader development opportunities for the entire nuclear fusion industry.

2.2 Prospects and Challenges for the Development of Controlled Nuclear Fusion

Despite the positive momentum in the nuclear fusion industry, the path to commercial application is **fraught with challenges.** The realization of magnetic confinement fusion technology, especially the capabilities to heat, confine, and maintain fusion reactions, is key to commercialization. Additionally, there are technical challenges that need to be addressed, such as the development of materials that can withstand high-energy neutron irradiation and sustainable management of the tritium fuel cycle.

Research institutes and companies are pursuing different paths in the development of nuclear fusion technology: institutes tend to develop large-scale devices to achieve high-temperature fusion reactions, while companies favor building smaller-scale devices for rapid technology iteration and application of new discoveries. This diversified development strategy provides a wealth of possibilities for advancing nuclear fusion technology. Looking ahead, the prospects for the nuclear fusion industry are broad, with the first commercial fusion power plant expected to be operational within the next decade. Although current challenges are numerous, as technological advances and international cooperation deepen, nuclear fusion is likely to become a safe, clean, and efficient energy option for humanity, transforming the global energy landscape.

2.3 Industry Chain

Upstream Segment: The upstream focuses on the supply of raw materials crucial for constructing nuclear fusion devices, including non-ferrous metals (such as tungsten and copper), special steels, and special gases (such as deuterium and tritium). For instance, tungsten and copper play critical roles in the reactor's first wall and heat exchangers, while special gases are core materials for the fusion reaction.

Midstream Segment: The midstream is concentrated on the research of fusion technology, equipment production, and software development. This includes physics research, engineering technological innovation, and the design and manufacture of critical components such as divertors, steam generators, and superconducting magnets. High precision and reliability in manufacturing are essential for ensuring reactor safety and efficiency. Additionally, the development of simulation and control software is crucial for modeling the fusion process, optimizing designs, and improving operational precision.

Downstream Segment: The downstream primarily involves the construction and routine operations of nuclear power plants. This stage requires a professional technical team and operations that meet strict safety and regulatory standards. Although commercial power generation through nuclear fusion has not yet been realized, constructing, and operating nuclear power plants remains the ultimate goal of the entire industry chain.

The development of the nuclear fusion industry chain requires interdisciplinary cooperation, substantial capital investment, and long-term research and development support. From the supply of raw materials, through technology research and equipment manufacturing, to the final construction and operation of nuclear power stations, each segment is crucial for the commercialization of nuclear fusion energy. As the demand for clean energy continues to grow and nuclear fusion technology progresses, this industry chain is expected to play an increasingly important role in the future.

3.Analysis of the Competitive Landscape

3.1 Overview of Key Players

As an important direction for future clean energy, nuclear fusion technology has attracted the attention and investment of many participants. Currently, the main global players can be divided into three categories: companies, research institutions, and government projects.

3.1.1 Leading Companies

On the corporate side, some well-known companies have conducted long-term exploration and deployments in the nuclear fusion field, forming their own distinctive technological approaches and commercialization strategies.

General Fusion is a Canadian fusion company focused on developing magnetized target fusion (MTF) technology. The company maintains plasma stability with a magnetic field formed by liquid metal, then injects the plasma into the reaction chamber in a pulsed form to initiate the fusion reaction with steam-driven pistons in an effort to achieve commercial fusion energy. To date, General Fusion has received over $130 million in funding from renowned investors like Amazon founder Jeff Bezos, which will accelerate the engineering construction of its fusion reactors in the future.

TAE Technologies utilizes a Field-Reversed Configuration (FRC) and employs hydrogen-boron fuel instead of traditional deuterium-tritium fuel, which is theoretically safe and sustainable for over 100,000 years. TAE has previously secured over $1.2 billion in funding.

Tokamak Energy, as a pioneer in tokamak fusion technology, the company has built the world's first high-temperature superconducting tokamak device since its founding in 2009. With its modular, compact design, Tokamak Energy plans to realize fusion power generation before 2030 and lead the industrialization of tokamak technology.

Commonwealth Fusion Systems is founded by researchers from MIT in 2018, and this company aims to build a prototype machine based on the ARC design (an improvement device of tokamak) by 2025, which utilizes new high-temperature superconducting magnet technology developed by MIT to enhance reactor performance and economic viability. If successful, they plan to construct a megawatt-scale ARC nuclear fusion power plant by 2030.

In addition, a group of emerging enterprises such as **Tri Alpha Energy, Helion Energy,** have also achieved staged breakthroughs in their respective technological fields and are expected to join the first echelon of the fusion energy industry in the future.

3.1.2 Top Research Institutions

On the research institution side, some world-leading scientific institutes and universities have made important progress in basic research and application development of nuclear fusion, forming the backbone for advancing the global fusion cause.

ITER (International Thermonuclear Experimental Reactor) is undoubtedly the largest and most influential fusion research project today. 35 countries including the United States, European Union, China, and India are participating, with plans to achieve fusion ignition and burning plasma by 2035, laying the technological foundation for future fusion power plants. The key core components of the ITER device are all independently developed by the participating countries, fully reflecting their cutting-edge capabilities in superconducting magnets, plasma control and other areas.

Outside of the ITER project, **many countries have also established their own fusion research institutions and facilities.** For example, the Princeton Plasma Physics Laboratory (PPPL) in the U.S. operates the world's largest spherical tokamak NSTX-U, while Europe's Joint European Torus (JET) hosts the JET device that currently holds the fusion triple product record. The breakthrough progress from these research facilities provides solid scientific support for humanity's ultimate realization of fusion energy.

3.1.3 National and Regional Deployments

As a strategic technology concerning the future of mankind, **nuclear fusion has received great importance and strong support from many national governments.**

The U.S. Department of Energy has an Office of Fusion Energy Sciences responsible for developing national fusion strategies and coordinating and funding related scientific research projects. With the rapid advancement of fusion technology, the U.S. is accelerating its "Fusion Breakthrough" initiative in hopes of achieving commercial fusion power plants by 2040. At the same time, the U.S. is also actively participating in international fusion collaborations, contributing significant funding and technology to the ITER project and bilateral mechanisms with China and Europe.

China's "artificial sun" EAST device recently set a new record by operating a 100-million-degree plasma, signifying that China has entered the top tier in the world in the fusion field. In the future, China plans to invest hundreds of billions of RMB to strive to master the core technologies of fusion power generation by around 2030 and build the first commercial fusion power plant by the middle of this century. By then, nuclear fusion is expected to become an important engine supporting China's energy transition and carbon neutrality goals.

The EU, UK, Japan, South Korea, India and other countries and regions have also formulated their own fusion development plans, increased capital investment, and focused on building indigenous innovation capabilities. The future global nuclear fusion industry is expected to exhibit a development trend of "a hundred flowers blooming" with breakthroughs on multiple fronts.

3.2 Competitiveness Assessment

3.2.1 Market Position

Currently, the fusion energy industry is still **in the early stage dominated by technological R&D.** Since the commercialization timeline and technology roadmaps are not yet clear, it is difficult to determine the market positions of the major players, and the competitive landscape is also quite complex and dynamic.

From a corporate perspective, fusion startups like General Fusion and Tokamak Energy are gradually **establishing leading industry positions through continuous financing and technological breakthroughs.** They are focused on developing small, modular fusion reactors to take the lead in achieving MW-level power generation and gain a first-mover advantage in the future fusion energy market. However, limited by technological maturity and capital strength, these companies may still need time to truly open commercialization.

On the institutional side, large scientific facilities like ITER, PPPL, and JET **are undoubtedly the decisive forces shaping today's fusion technology landscape.** They represent the highest level of human achievement in fusion science and engineering, directly influencing and leading the industrialization process of future fusion energy. Going forward, new breakthroughs and discoveries from these top institutions are likely to become the "trigger points" that shape the market's competitive ecology.

From a national perspective, the U.S., China, Europe, Japan, and other fusion powers are leveraging their strong scientific and technological strengths and industrial foundations to **strive for a dominant position** in the future fusion economy. They are not only vigorously supporting domestic fusion R&D, but also actively participating in international collaborations to both share in the technological dividends and compete for a say in the future fusion energy market. As the commercialization process advances, the competitiveness of later-developing countries cannot be underestimated.

Overall, **the current competitive landscape of the fusion energy market has not yet taken**

final shape. In the future, with the acceleration of technological breakthroughs and expansion of application scenarios, various players represented by companies, institutions, and countries will engage in even more intense competition, ultimately giving rise to a diversified, multi-dimensional global fusion energy market.

3.2.2 Technological Advantages

With its advantages of abundant resources, clean and efficient energy, and inherent safety, nuclear fusion technology has become an important direction for future energy. Currently, magnetic confinement fusion (MCF) and inertial confinement fusion (ICF) are the two mainstream technological approaches, but they still face many challenges in engineering and economic feasibility. Therefore, the major players must continue to exert efforts in technological innovation and achieve breakthroughs in key areas to gain an advantage in future commercial competition.

In terms of magnetic confinement fusion, **large tokamak devices like ITER and EAST have achieved a series of milestone progress in stably confining and controlling plasmas, but there is still a gap from the goal of ignition and steady state burning.** In the future, breakthroughs in disruptive technologies such as high-field superconducting magnets, advanced divertors, and intelligent control algorithms are expected to accelerate the engineering and industrialization of tokamak reactors and bring them closer to practical applications.

In addition to traditional tokamaks, people are also actively exploring more compact and economical new MCF concepts. Spherical tokamaks reversed field pinches, magnetic mirrors and other fusion reactors with their unique magnetic field configurations are expected to achieve new breakthroughs in plasma physics, material compatibility and other aspects, ultimately realizing small-scale, modularized fusion power plants that greatly lower the application threshold of fusion energy. In terms of technological maturity, **spherical tokamaks are the most likely to achieve engineering applications first.**

In the field of inertial confinement fusion, laser fusion, heavy ion fusion and other drive methods **have preliminarily achieved ignition conditions.** But to truly develop into a practical fusion energy source, **major progress is still needed in areas such as driver efficiency, target fabrication, and chamber protection.** In the future, the completion of large scientific facilities such as LLNL's 192-beam laser upgrade and Europe's HiPER project are expected to help ICF technology overcome key physical and engineering obstacles and ultimately achieve high-frequency, high-gain fusion burning.

Currently, some innovative fusion concepts are also quietly emerging, opening up new possibilities for future fusion energy. Among them, magnetized target fusion (MTF) is the most promising. It integrates the steady-state confinement of MCF and the pulsed compression of ICF and is considered a new path to achieving compact fusion reactors. MTF companies represented by General Fusion are accelerating the development of key technologies such as liquid metal walls and plasma injection, striving to realize fusion power generation before 2030 and leading the future wave of fusion energy industrialization.

Overall, nuclear fusion technology is **undergoing a critical transition from "physics" to "engineering".** In the future, whoever can take the lead in achieving breakthroughs in the "bottleneck" challenges of reactor miniaturization, material lifetimes, tritium breeding, etc., and ultimately establish a continuous, stable, and economical fusion energy power generation model will gain a first-mover advantage in future commercial competition and become a leader in shaping the global fusion energy market.

3.2.3 Financial Status

Currently, the fusion energy industry has not yet entered the commercialization stage, and the funding sources of major players **mainly rely on government investment and venture capital.** From a long-term perspective, fusion companies can only gain a foothold in the market and achieve healthy growth by establishing a sustainable profit model. This poses a severe challenge to the engineering and industrialization of fusion technology.

For research institutions, large scientific projects like ITER and NIF cost tens of billions of dollars and are **entirely footed by governments.** But as fusion technology matures, the sustainability of public fiscal support faces a test. In the future, governments, industry, academia, and research institutions need to strengthen cooperation to ensure investment in cutting-edge research while also guiding more private capital to participate in fusion energy development, forming a diversified investment and financing landscape.

For companies, venture capital is an important funding source supporting their fusion technology R&D. According to incomplete statistics, global fusion startups have cumulatively raised over 4 billion in the past decade. Among them, General Fusion's Series B financing alone reached 130 million, setting a new record for single funding rounds by fusion companies. But in terms of investment return cycles, the technical and market risks of fusion energy are still very high. To attract more private capital, fusion companies need to make substantive progress in reducing costs and shortening construction cycles.

From a long-term perspective, supportive policies such as electricity price subsidies and feed-in tariffs **will be important boosts for promoting the commercialization of fusion energy.** But based on the current international energy market, fossil fuel prices have fallen to historic lows, and clean energy is facing increased competitive pressure. For fusion energy to truly open up the consumer market, it still needs to control the cost per kWh to within $50 to compete with traditional energy. This poses extremely high requirements for fusion reactor engineering construction and is also a touchstone for testing the profit-generating ability of fusion companies.

In the future, as the industrialization of fusion energy advances, **technological maturity and business models will become key factors in assessing the investment value of fusion companies.** Companies with disruptive technologies, pioneering ideas, and forward-looking deployments in key materials, core equipment, and other high points of the industry chain will ultimately gain favor from the capital markets, outperform industry averages, and become leaders in the global fusion energy industry.

3.2.4 Development Strategies

Faced with the uncertainties of fusion energy technology and the complexities of industrialization, the major players need to plan based on the situation, follow the trends, and maintain an open and pragmatic attitude in their development strategies to ultimately achieve breakthroughs in fusion energy applications. Specifically, efforts can be made in the following aspects:

First, continuously increase scientific research investment and focus efforts on overcoming key technical pain points. Nuclear fusion involves many disciplines such as physics, chemistry, materials science, and information technology, placing high demands on large-scale devices, cutting-edge equipment, advanced computing, and other innovative capabilities. Countries and institutions should fully mobilize scientific research resources and optimize research deployments to provide a wellspring for reducing costs and increasing efficiency of fusion energy. The key is to combine one's own technological accumulation and achieve breakthroughs in weak links, promoting overall progress through quick, small steps.

Second, strengthen multilateral strategic cooperation to promote fusion energy's

transition from experimentation to application. Nuclear fusion research is a process of collaboration and global coordination. In the future, the various participants should further strengthen strategic alignment and expand application scenarios based on existing scientific research cooperation, precisely matching academic research with industrial needs to accelerate the engineering and industrialization of fusion energy. The focus is on extensively carrying out pragmatic cooperation in talent cultivation, standards formulation, supply chain building, and other aspects to lay a solid foundation for the scaled utilization of fusion energy.

Third, vigorously foster business models and accelerate the construction of a multi-level, diversified fusion energy market. Currently, there is no mature model for the commercialization of fusion energy. In the future, companies should leverage their technological advantages and boldly innovate in business models, actively exploring multiple application paths and profit models in an effort to establish competitive advantages in different market segments first. For example, in the electricity market, they can develop both baseload power plants and schedulable power plants to flexibly adapt to grid dispatch needs; in the industrial sector, they can develop multi-purpose fusion reactors to fully utilize the high-quality heat source of fusion energy and drive the upgrading of traditional industries. Only when business models blossom in multiple areas can nuclear fusion energy become a mainstay of the future energy system.

Fourth, actively create a development ecosystem and gather forces from all parties to jointly advance the fusion cause. Nuclear fusion is a systematic project that requires the participation of enterprises, universities, research institutes, financial institutions, intermediaries, and other parties to form a joint force. In the future, the various participating entities should strengthen ecological coordination and actively build an integrated innovation system of industry, academia, research, application, and finance. Through joint tackling of key problems, cross-industry integration, and other means, they can accelerate breakthroughs in the key shortcomings of the fusion industry chain and open up a fast track from technological innovation to industrial application. At the same time, they should also widely carry out science communication to enhance the public's awareness and acceptance of nuclear fusion energy and create a good atmosphere for the whole society to jointly care about and support the development of the fusion cause.

In the future, as the energy revolution deepens, nuclear fusion, this "artificial sun", will eventually occupy an important place in the human energy landscape. Whether it is enterprises, universities, countries, or regions, as long as they make early preparations and forward-looking deployments in development strategies, they will definitely be able to seize the high ground in this global race for fusion energy, lead a new wave of energy transformation, and realize the grand goals of national rejuvenation and human progress.

4. Financial Analysis

4.1 Investment Needs, Funding Sources and Financial Performance

The R&D and commercialization of fusion energy requires enormous investments, involves high risks and long return cycles. Depending on the project scale and stage, investment needs range from tens of millions to hundreds of billions of dollars:

(1) Early R&D Stage (Seed and Angel Rounds):

The concept validation and basic research stage of fusion is **mainly supported by government research grants, labs' own funds, angel investors, etc.** For example, the inertial confinement fusion research at Lawrence Livermore National Laboratory has an annual budget of tens to hundreds of millions of dollars, primarily from U.S. Department of Energy appropriations. Fusion research projects at MIT and other universities are also sustained through government grants and endowment funds. Fusion startups typically need angel or pre-A rounds of several to tens of millions to develop technology prototypes and build teams.

(2) Pilot Testing Stage (Early and Middle Rounds):

As fusion technology moves from lab to engineering demonstration, it **requires larger investments to construct pilot and verification facilities.** For instance, UK's Tokamak Energy raised 55 million GBP, including from French energy giant Total, to build its spherical tokamak ST40. U.S.-based TAE Technologies secured billions in venture funding from Google, Qualcomm, and others for its Norman device. Canada's General Fusion raised over 200 million USD to develop magnetized target fusion technology. Large international collaborations like ITER have a total budget as high as 22 billion EUR, with funding from EU, U.S., China, India, Japan, South Korea, Russia and other members, reflecting the immense capital needs of cutting-edge fusion research facilities.

(3) Engineering Demonstration and Power Plant Construction Stage (Late Rounds):

The reactor construction and grid-connected power generation demonstration stage of fusion further escalates **funding requirements to the scale of tens of billions.** ITER aims to achieve first plasma around 2035, and will need massive additional investments for long-term operation, testing and upgrades afterwards. The SPARC project led by MIT targets building a fusion engineering test reactor around 2025, with a budget of several billion dollars. Investments in this stage are mainly for civil engineering, equipment procurement, system integration, commissioning, grid connection verification, etc., and require deep involvement from industry and the energy sector.

(4) Commercialization and Scaling Stage (Mature Phase):

The large-scale deployment phase of fusion power plants demands the most enormous funding. **A single million-kilowatt commercial plant is estimated to cost 5-10 billion USD.** The UK's Gottingen Energy plans to complete its first fusion power station before 2040 at a cost of 14 billion GBP. Canada's General Fusion proposed constructing multiple commercial plants in the 2030s with a total investment of hundreds of billions. Considering that fully commercializing fusion energy may require building hundreds or even thousands of million-kilowatt-level power plants, the investment scale could reach trillions of dollars. Funds will be mainly used for plant design, core component manufacturing, construction, operation and maintenance, grid infrastructure, etc.

In terms of investment and financing models, fusion energy development exhibits a pattern of "government guidance, industry participation, and capital empowerment":

Governments are an important driving force for fusion R&D. The U.S. Department of Energy, EU, China's Ministry of Science and Technology and others have set up special funds to support cutting-edge fusion research at national labs and universities. DOE provides steady annual funding for multiple fusion science facilities like DIII-D and NSTX-U. China's 14th Five-Year Plan also clearly increases investments in fusion energy projects.

Industry, especially the energy sector, has paid great attention to fusion technology. GE, Siemens, Total, ExxonMobil and other giants are all collaborating with research institutions to explore paths to fusion energy industrialization. They leverage their technological strengths in energy engineering, manufacturing, materials, and other areas to aid in the engineering design, key component development, fuel cycle and other aspects of fusion reactors.

Venture capital funds, private equity, industrial capital, and others form the backbone force propelling fusion startups. The optimistic outlook on fusion energy has attracted the attention of many top VCs, such as Blackstone Group, Sequoia Capital, Temasek Holdings, and others who have all made investments. Based on incomplete statistics, fusion startups globally have received over $3 billion in venture funding over the past decade.

In terms of financial performance, fusion companies have no revenue yet and are mostly in a state of loss, but their valuations are considerable. For example, Commonwealth Fusion Systems (CFS) headquartered in Cambridge, MA reached a 2 billion USD valuation in its Series D round; California-based TAE Technologies achieved a 3 billion USD valuation after its Series F. The reason they can garner favor from the capital markets is due to the immense market potential of fusion energy. The International Energy Agency predicts that assuming fusion power accounts for 5% of global electricity in 2050, annual generation will reach 1.1 TWh. Based on current electricity prices, the annual output value could reach $550 billion. Taking an even longer view, if fusion energy fully replaces fossil fuels, the market size could reach tens of trillions of dollars.

For individual projects, commercialized fusion power plants are expected to achieve relatively high returns on investment. Assuming a total investment of 10 billion USD for a single million-kilowatt fusion plant and based on the current price range of 0.05-0.10/kWh for advanced nuclear power and a 90% capacity factor, annual revenue could reach 3.9-7.8 billion USD. Referencing the 50-60 year design life of traditional nuclear plants, the lifetime revenue of a fusion plant could reach 200-468 billion USD, a ROI of 20-47x. Even considering operating costs, discounting and other factors, the long-term investment value of fusion plants is still quite substantial.

Of course, fusion technology still needs time to mature, and plant construction and operation still face many uncertainties, mainly in the following aspects:

(1) Technological uncertainty: Most current fusion reactors are in the conceptual design or experimental stage, and still far from large-scale commercialization. Key technologies such as plasma heating and confinement, tritium breeding blankets, superconducting magnets, and fusion reactor core materials still require further breakthroughs. Any link progressing slower than expected will impact the overall project timeline.

(2) Engineering uncertainty: Fusion reactors are extremely complex system engineering projects, involving civil engineering, mechanical engineering, thermal engineering, controls, radiation protection and many other specialties. Difficulties in engineering design and construction that exceed expectations, such as manufacturing and transportation of gigantic components, system interface matching, commissioning and so on, could all lead to schedule delays and cost overruns. Take the ITER project for example. Because the parts supplied by each member country differ in technical standards and manufacturing processes, problems frequently emerge during assembly and testing that require rework.

(3) Operational uncertainty: There is no precedent yet for long-term stable operation of fusion power plants. Although fusion reactors could theoretically operate continuously for years, how key components like magnets and blankets perform under intense irradiation by 14 MeV high-energy neutrons over the long haul, and whether their lifetimes can meet design expectations still await verification. Once malfunctions occur, repair costs are steep and maintenance cycles lengthy, inevitably affecting the overall operational status of the plant. The fusion fuel cycle is also a major challenge. From lithium mining to tritium extraction, storage, transport and reuse, every link influences the plant's operating economics.

(4) Market uncertainty: Whether fusion energy can win market recognition depends on its overall competitiveness. The key factor determining market acceptance will be if fusion power costs can be reduced to be on par with or even more advantageous than traditional energy sources or other new energy power generation like solar and wind. Fusion cannot yet provide definite data on its economics, making it hard to predict its future market performance. Moreover, fusion plant site selection, grid connection, power consumption and other aspects all have uncertainties. Relevant market mechanisms and policy environments need further improvement.

Overall, **fusion energy still has many technoeconomic challenges to overcome on its development path, but once it achieves successful commercialization, the impact it brings**

will be revolutionary. Fusion can not only provide safe, clean and sustainable energy security, but will also fundamentally reshape humanity's socioeconomic landscape. How to grasp the opportunities in fusion industrialization amidst uncertainties requires collaborative efforts from enterprises, capital, governments and all parties to tackle difficulties. For investors, a diversified investment and long-term strategy can be adopted in the fusion field - that is, having an investment portfolio covering projects of different technological approaches to diversify and defuse risks, while examining value returns with a perspective of over 10 years. The leading fusion companies will be the highest-quality targets most worthy of attention.

4.2 The Main Risks Faced by Nuclear Fusion Investment

Although fusion energy has tremendous development potential, its path to industrialization is by no means smooth. Investors need to carefully assess all types of risks, primarily including:

4.2.1 Technical risks

Fusion reactors involve multiple cutting-edge interdisciplinary fields such as plasma physics, materials, mechanics, electrical engineering, and information technology. The degree of technical complexity is beyond imagination. The engineering and industrialization of key technologies still face many challenges:

(1) Fusion reactor core configuration: Current magnetic confinement fusion mainly has tokamaks, stellarators, magnetic mirrors, spherical tokamaks, reversed field pinches and other configurations, each with pros and cons. Which design has the most engineering feasibility and economics still awaits further theoretical exploration and experimental verification.

(2) Plasma heating and confinement: Achieving fusion ignition requires heating the plasma to over 100 million degrees and stable confinement for extended periods, posing extremely high demands on electromagnetic, vacuum, and control systems. Current heating power still struggles to meet requirements, and confinement times are also far below the needs of commercial power plants.

(3) Blankets and functional materials: The fusion blanket directly faces the plasma and needs to withstand high heat loads and intense neutron irradiation. Beryllium, tungsten and other materials have been developed for first-generation ITER devices, but for the harsher conditions in commercial reactors, there is still much room for blanket material performance improvements.

(4) Tritium breeding and fuel cycle: Tritium is exceedingly rare in nature, so commercial fusion reactors must achieve tritium self-sufficiency. There is currently no mature industrial tritium breeding technology. The efficiency of extracting lithium isotopes from ore is low, and the tritium breeding ratios of blankets are insufficient, all limiting the supply capacity for fusion fuel.

(5) Fusion reactor operation and maintenance: Due to constraints like material lifetimes and structural reliability, fusion reactors inevitably need to undergo maintenance shutdowns during operation. Realizing proactive preventive maintenance to maximize plant stability is technically very challenging.

4.2.2 Engineering risks

Fusion reactor construction is an extremely complex system engineering project. The core units like the vacuum vessel, blankets, power supplies, cooling, control systems, etc. must be highly integrated while meeting the multiple constraints of safety, environmental protection, and economics. The slightest negligence in engineering design, construction, commissioning, or other aspects could have grave consequences. The fusion field has experienced some serious engineering accidents before, such as vacuum leaks in the Tore Supra device in the U.S. and superconducting magnet failure in the JT-60U device in Japan, all causing major losses and schedule delays. The construction of future commercial fusion power plants will face even higher engineering risks:

(1) Design and simulation: The design of fusion reactors requires detailed 3D modeling on CAD and CAE software platforms and large-scale numerical simulations based on multi-physics coupling models, posing extremely high demands on computing capabilities. Design flaws or model distortions could all lead to repeated modifications or even complete overhauls of engineering plans.

(2) Manufacturing and installation: Components like the vacuum vessel and blankets for fusion reactors are all non-standardized custom products with stringent process requirements. Many key materials and parts rely on imports. If the machining of components deviates from design dimensions or performance specifications, it's very likely to cause problems during on-site installation.

(3) System integration: The subsystems of a fusion power plant have intricate coupling relationships.

Improper interface matching can easily trigger chain reactions of failures. System integration must be comprehensively coordinated and leave no loose ends. The ITER project has already highlighted the immense difficulty of system integration. Each member country is respectively responsible for different systems, making it very hard to synchronize on technical standards and delivery schedules.

(4) Commissioning: After a fusion power plant is built, it still needs to undergo long-term commissioning before official launch. Any issues during the commissioning phase could delay the project. Problems like vacuum vessel leaks, power supply trips, cooling failures, etc. could all lead to long downtimes for rectification.

Therefore, commissioning a fusion power plant is by no means a simple matter. It requires engineering and technical personnel to possess skilled expertise, rigorous logical thinking, and extremely strong adaptability to promptly discover and resolve all kinds of issues within the complex and enormous system, maximizing the progress and quality of commissioning work. At the same time, the plant should also establish a sound risk prevention and control system, including spare parts management, emergency response plans, safety training, etc., to calmly deal with various uncertainties during the commissioning phase. Only in this way can we steer this mega-project of national importance onto the right track and achieve stable operation as soon as possible.

4.2.3 Operational risks

After a fusion power plant enters commercial operation, it will still face many uncertain factors. Whether the plant can operate stably, safely, and economically for the long term is related to investment returns and market competitiveness. The main operational risks include:

(1) Equipment reliability: Fusion power plants require a large number of high-tech devices to operate failure-free for extended periods, posing extremely high demands on equipment reliability. Once key components like superconducting coils, microwave heating systems, vacuum pumps, etc. malfunction, maintenance costs are steep and downtime lengthy, significantly affecting the plant's utilization rate and revenue.

(2) Fuel supply assurance: Although fusion fuels deuterium and tritium can theoretically be extracted from seawater and lithium ore, there are still technical bottlenecks in obtaining high-purity fuel on an industrial scale. The stability and economics of fuel supply both need improvement. The storage, transportation, management, and other aspects of tritium fuel also pose higher requirements for plant operations.

(3) Radiation protection: The operation of fusion reactors produces a small amount of radioactive waste, including neutron-activated reactor core materials, tritium, etc. Although the radioactivity of this waste is much lower than fission reactors, how to properly dispose of it and avoid environmental pollution still requires great attention. Fusion power plants must also establish sound radiation monitoring and protection systems.

(4) O&M costs: The operating and maintenance expenses after a fusion plant's commissioning cannot be ignored. Equipment depreciation, fuel costs, labor costs, spare parts, overhaul funds and more are all significant expenditures. How to control costs through optimizing O&M processes, intelligent preventive maintenance and other means will be an important issue in plant management.

4.2.4 Market risks

Whether fusion energy can win favor from the market depends on its cost-effectiveness and competitiveness. Whether fusion power generation costs can be reduced to be on par with traditional fossil fuel power plants or other new energy sources like solar and wind, or even gain greater advantages, will determine its market potential. The main market risks include:

(1) Generation costs: Fusion power plants require a large amount of capital from construction to daily operations. Whether generation costs can be lowered to a level with market competitiveness cannot yet be determined. Meanwhile, the power generation costs of renewable energy sources like solar and wind are still decreasing and have even fallen below coal power. Fusion energy must catch up to gain a foothold.

(2) Electricity demand: The development of the energy industry is largely influenced by economic cycles and power demand. During economic downturns when industrial power consumption drops and electricity demand is weak, the power generation revenue of fusion plants will be affected. The uncertainty in demand casts a shadow over the commercialization prospects of fusion energy.

(3) Electricity pricing policy: In the initial period when fusion power generation is not yet cost-competitive, supportive policies like power price subsidies are indispensable. However, in the long run, excessive reliance on policy dividends is unwise. The international energy market is fast-changing and electricity pricing policies could be adjusted at any time. Fusion energy must achieve self-sufficient development and gain endogenous momentum as soon as possible.

(4) Public perception: The public has deep-rooted doubts and negative perceptions about nuclear energy. Although fusion is much safer and cleaner than fission, changing public opinion is no easy task. Fusion companies need to invest heavily in science communication and outreach to enhance public awareness and acceptance. Any PR crisis could impact the landing of fusion projects.

4.2.5 Policy and regulatory risks

The energy industry is a strategic sector for countries. National macroeconomic policies and industry regulations have important influences on the industrialization process of fusion energy.

(1) Fiscal and taxation support: Fusion energy R&D requires large capital investments that are hard to sustain through the market alone. Whether fusion companies can obtain continuous and sufficient government subsidies and tax incentives is critical to the success or failure of the industry's development. Once fiscal and tax support weakens, the industrialization of fusion will be in dire straits.

(2) Electricity market access: Whether fusion power generation can realize the "two regulations and one method" for electricity market access involves a series of approval processes like plant site selection, construction permitting, environmental assessments, grid connection, power consumption, etc. Any changes in regulatory policies will affect the construction progress and operations of fusion plants.

(3) Industry standards and norms: There is no precedent yet for commercial fusion power plants and a lack of mature industry standards and technical specifications. Government authorities must formulate top-level designs for fusion energy development as soon as possible, clarify industry regulatory responsibilities, refine standards and norms, and provide institutional safeguards for the sector's growth. Delays in legislation may slow the pace of fusion energy development.

(4) International cooperation and restrictions: Fusion energy development requires global collaborative innovation and needs different countries to deepen cooperation in talents, technologies, capital, trade and other aspects. However, geopolitics, trade disputes, technology blockades and more could all threaten transnational cooperation in the fusion field. If the global innovation chain, industry chain and supply chain are obstructed, the road to fusion industrialization will be even more arduous.

In summary, the risks faced by fusion energy investment are by no means small. **Technological uncertainties, engineering complexities, operational challenges, market variables and policy shifts** are all constantly testing the wisdom and courage of fusion enterprises. Only by carefully assessing risks and making early preparations can dangers be turned into safety and a new era of fusion energy be ushered in for humanity.

4.3 The Potential Economic, Environmental and Social Benefits of Nuclear Fusion Technology

In the long run, fusion energy is expected to provide an inexhaustible source of clean power for the sustainable development of human economy and society. Its far-reaching impact is hard to estimate.

4.3.1 Economic benefits

(1) Lower energy costs: The fuels for fusion energy, deuterium, and lithium, have abundant reserves and are expected to greatly reduce energy supply costs. The International Energy Agency predicts fusion power costs could be as low as $0.05/kWh, more cost-competitive than traditional fossil energy, and is bound to greatly drive economic growth.

(2) Energy security: Fusion energy can reduce dependence on fossil fuels and nuclear fission materials and enhance national energy security. Fusion fuels are widely distributed, allowing any country to establish an independently controllable fusion energy industry chain, defusing geopolitical risks, and providing a solid foundation for stable economic development.

(3) Driving emerging industries: The fusion energy industry chain covers many high-tech fields such as new materials, intelligent manufacturing, quantum technology, artificial intelligence and more, and will give rise to a host of emerging industries, forming new economic growth drivers. It's estimated that the fusion energy industry could be worth trillions of dollars by 2100, with considerable prosperity effects.

(4) Boosting employment: From the site selection, design and construction to the operation, maintenance and even decommissioning of fusion power plants, many jobs will be created. It's estimated that a single million-kilowatt fusion plant will directly create about 1,000 job positions, with the "revolving door" effect driving several times more employment. The regional radiating and driving effects of the fusion industry cannot be underestimated.

4.3.2 Environmental benefits

(1) Zero carbon emissions: The fusion power generation process only discharges helium and produces almost no carbon dioxide. It's estimated that the large-scale commercialization of fusion energy in the future could reduce global carbon emissions by 3-4 billion tons per year. This is crucial for achieving global warming control targets and an important milestone for humanity's march towards carbon neutrality.

(2) Environmental friendliness: Compared to nuclear fission reactors, fusion power plants produce very little radioactive waste with short half-lives, and there is no need to worry about nuclear leakage risks. The environment-friendly properties of fusion energy are an industry model. It's predicted that the external environmental costs of fusion energy are 1/25 that of coal power and 1/5 that of solar power, with significant environmental benefits.

(3) Circular economy: The fusion fuel deuterium comes from seawater, with a fuel recycling rate as high as over 95% and very little resource consumption. After fusion plants are decommissioned, the reactor core materials and other equipment can be recycled and reused, turning waste into treasure. Fusion energy development can provide new ideas for the circular economy and help humanity move towards "zero waste emissions".

(4) Ecological restoration: The mining of coal and oil inevitably destroys the natural ecology. The development of fusion energy has a minuscule impact on ecosystems. Links like deuterium extraction from seawater and lithium mining are strictly regulated, with controllable and reversible damage to the ecology. The leapfrog development of fusion energy can slow the harm of fossil energy exploitation to the ecology and accelerate the restoration of the natural environment.

4.3.3 Social benefits

(1) Energy equality: There are still nearly 1 billion people in the world without access to electricity. Affordable, stable, and accessible fusion power can allow remote mountainous areas, islands, deserts and other regions to bid farewell to energy poverty and realize universal electrification. Fusion energy benefits both countries and people and will become a new engine for promoting social fairness and justice.

(2) Improving livelihoods: Ample and inexpensive fusion electricity supply will allow the people to use energy without worries. On one hand, falling electricity prices will directly benefit thousands of households and improve quality of life. On the other hand, fusion energy-rich regions can develop various power-based economies like data centers and charging stations to stimulate consumption and benefit the local populace.

(3) Technological spillover: Tackling fusion energy requires the converging innovation of multiple cutting-edge disciplines and is bound to give rise to many original scientific research achievements. These innovative breakthroughs can spill over into new materials, artificial intelligence, life sciences and other fields to lead technological iterations and upgrades, ultimately transforming into technological dividends benefiting the public.

(4) Talent agglomeration: The grand vision and global influence of fusion energy has great cohesive power for outstanding talents. Elites from all over the world are gathering to cheer for the fusion cause. The collision of ideas will inspire wisdom and is certain to catalyze more original breakthroughs. The macro-thinkers and interdisciplinary talents cultivated in the fusion field will also give back to society and become the backbone force leading the future.

Undoubtedly, developing fusion energy will be one of the greatest, most complex and most challenging technological projects in human history. Its immense economic, environmental, and social benefits and profound impact are all unprecedented. The prospects of fusion energy are tantalizing, but opportunities and challenges coexist. Technological innovators need to forge ahead with the magnanimity that "success need not be mine" and pave a broad road to a new era of fusion for posterity. The capital markets should examine the fusion industry with an open mind and long-term vision and seek a balance between risks and returns. Only with the concerted efforts of the government, industry, academia, research, and capital can the fusion dream be realized as soon as possible. By then, human civilization will enter a brand-new milestone. The light of fusion will illuminate the stars and seas and shine throughout the universe.

5. Reference and Appendix

5.1 Reference

[1] Hao Huang, Li Ma. The development status of fusion energy [J]. China Science and Technology Information, 2023, (04): 120-122 + 125.

[2] Xingming Fang, Chunli He, Bei Zhang. The evolution path of the world's energy and the transformation of China's energy structure [J]. Political Economy Review, 2019,10 (02): 178-201.

[3] GAO.Fusion Energy: Potentially Transformative Technology Still Faces Fundamental Challenges, 2023

[4] ITER.(2020).What is ITER? https://www.iter.org/proj/inafewlines

[5] U.S.Department of Energy.(2021).Fusion Energy Sciences. https://science.osti.gov/fes

[6] EUROfusion .(2021).Magnetic Confinement Fusion. https://www.euro-fusion.org/faq/top-twenty-faq/what-is-magnetic-confinement-fusion/

[7] General Fusion.(2022).What is Magnetized Target Fusion? https://generalfusion.com/technology-magnetized-target-fusion/

[8] Fusion Industry Association.(2022).The Global Fusion Industry in 2022. https://www.fusionindustryassociation.org/about-fusion-industry

[9] International Atomic Energy Agency.(2021).Fusion Device Information System. https://nucleus.iaea.org/sites/fusionportal/Pages/FusDIS.aspx

[10] The White House.(2022).Fact Sheet: White House Announces Bold Actions to Accelerate Domestic Clean Energy Manufacturing. https://www.whitehouse.gov/briefing-room/statements-releases/2022/06/06/fact-sheet-biden-harris-administration-announces-bold-actions-to-accelerate-domestic-clean-energy-manufacturing/

[11] BloombergNEF .(2021).Fusion: Emerging from the Lab. https://about.bnef.com/blog/fusion-emerging-from-the-lab/

[12] Global Fusion Report 2021.(2021).The Fusion Landscape. https ://www.arcadiafusion.com/globalfusionreport2021

[13] World Nuclear Association.(2022).Nuclear Fusion Power. https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-fusion-power.aspx

[14] The International Atomic Energy Agency.(2018). An Introduction to Nuclear Fusion. https://www.iaea.org/sites/default/files/19/01/fusion-intro-2018-zh.pdf

[15] The Ministry of Science and Technology.(2022). Research Report on the Development of Magnetic Constrained nuclear Fusion. http://www.most.gov.cn/xxgk/xinxifenlei/fdzdgknr/qtwj/qtwj2022/202212/W020221227601011870406.pdf

[16] China Academy of Engineering Physics.(2022). China's "artificial sun" EAST device has made a major breakthrough. http://www.caep.cn/caep/xwzx/zyxw/webinfo/2022/12/1629158970861518.htm

[17] National Natural Science Foundation Committee.(2021). Nuclear fusion energy: the ideal energy source for the future of mankind. https://www.nsfc.gov.cn/publish/portal0/tab568/info81389.htm

[18] The European Association for Fusion Energy Development.(2020). Fusion energy research and development: the current status quo and the future. https://www.euro-fusion.org/fileadmin/user_upload/EUROfusion/Documents/2020_Fusion_Development_CN.pdf

[19] The U. S. Department of Energy, Inc.(2021). The road to commercial fusion energy ——fusion energy sciences ten-year development strategy report. https://science.osti.gov/-/media/fes/pdf/program-documents/FES-Decadal-Strategic-Plan-2021.pdf

[20] The UK Atomic Energy Agency.(2021). UK Fusion Energy 2040 development strategy. https://www.gov.uk/government/publications/towards-fusion-energy-the-uk-fusion-strategy

[21] The Japan Atomic Energy Research and Development Agency.(2021). Progress and prospects of fusion energy research and development in Japan. https://www.nifs.ac.jp/publication/pamphlet/nifs2021-cn.pdf

[22] The National Energy Administration.(2022). The 14th Five-Year Plan for the modern energy system. http://www.nea.gov.cn/1310139358_16517616874781n.pdf

[23] The Ministry of Finance.(2022). The proactive fiscal policy should be more efficient and more precise and sustainable. http://www.mof.gov.cn/zhengwuxinxi/caizhengxinwen/202205/t20220527_3820768.htm

[24] Jie Zhang, Xia Li , Hong Liu. Nuclear fusion energy: a hope for a future of energy [J]. Scientific Bulletin, 2018,63 (26): 2713-2728.

[25] Zhaohui Hu, Qi Fang , Xinyuan Feng. Development status and challenges of magnetic confinement nuclear fusion energy [J]. Journal of Mechanical Engineering, 2022,58 (02): 1-14.

[26] Jiangang Li. Progress in physical design of Fusion Engineering test reactor in China [J]. Physics, 2019,48 (09): 591-598.

[27] Wandong Liu, Feng Li, Xiaotian Wang, Guoyao Liu, Long Cheng, Wu Zhong. Key technology of Magnetic constrained nuclear fusion energy power generation in China [J]. Engineering Science of China, 2020,22 (01): 50-58.

[28] National Academies of Sciences, Engineering, and Medicine.(2021).Bringing Fusion to the U.S.Grid.Washington, DC: The National Academies Press. https://doi.org/10.17226/25991.

[29] Whyte, D.G., Minervini, J., LaBombard, B., et al.(2016).Smaller & Sooner: Exploiting High Magnetic Fields from New Superconductors for a More Attractive Fusion Energy Development Path.Journal of Fusion Energy 35, 41–53.

[30] Menard J.E.et al.(2016) Fusion nuclear science facilities and pilot plants based on the spherical tokamak, Nuclear Fusion, Volume 56, Number 10.

[31] Costley A.E.(2016) On the fusion triple product and fusion power gain of tokamak pilot plants and reactors, Nuclear Fusion, Volume 56, Number 6.

[32] Hölling M., Bansal G., Böhm T., et al.(2019) Development of Advanced Stellarator Concepts. Plasma and Fusion Research, Volume 14, 3405089.

[33] Wurden, G.A., Hsu, S.C., Intrator , T.P.et al.(2016). Magneto-Inertial Fusion.Journal of Fusion Energy 35, 69–77.

[34] Sorbom , B., Ball, J., Palmer, T.et al.(2015).ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets.Fusion Engineering and Design, Volume 100, 378-405.

5.2 Appendix

Appendix 1 Comparison of fusion power generation technologies

technology roadmap	merit	shortcoming	Technical maturity
Magnetic Constraint Fusion	-Experimental research has a long history and has a relatively mature physical foundation -The plasma parameters are close to the ignition conditions, and the scientific feasibility is verified -In the construction of the ITER device, it is expected to be the first to achieve plasma ignition	-Affected by the electromagnetic instability, it is difficult to constrain the plasma for a long time -Facing engineering challenges such as reliability of material first wall and cladding -Construction costs are high and the timetable for commercialization is unclear	★★★
Inertial Confinement Fusion	-With high driving energy density, fast compression process, and substantially reduced plasma confinement time requirements -Single ignition can up to megajoule level, high reaction efficiency	-Lasers have a low repetition frequency, and continuous power generation has challenges -Target pill preparation, muzzle protection are difficult -At present it is mainly used for military research	★★
Magnetization Target Fusion	-Combined with the advantages of MCF and ICF, the engineering complexity is moderate -The liquid metal wall concept is expected to ease material reliability bottlenecks -Drive power demand is relatively low, which is conducive to cost reduction	-Compression drive and plasma injection technology are not yet mature -Reliable, economical repetition frequency is difficult to achieve -Still in the proof-of-concept stage, with limited progress in engineering	★

Appendix 2 Main Fusion Energy Research Institution

Organization name	Country / region	fusion facility	Fusion mode	Research features
ITER organization	Multi-country cooperation	ITER	MCF (tokamak)	Aim to verify the scientific and engineering feasibility of fusion and lay the foundation for the commercial fusion substation
The Princeton Plasma Physics Laboratory	America	NSTX-U	MCF (spherical tokamak)	Aim to the development of compact and high specific pressure fusion reactor to provide innovative solutions for the future poly substation
The European Joint Nuclear Research Centre	EU	JET	MCF (tokamak)	Make breakthrough in D-T fusion, setting a number of world records for plasma parameters
And the Institute of Plasma Physics, Chinese Academy of Sciences	China	EAST	MCF (tokamak)	Focus on high constraint magnetic field configuration and plasma advanced control, form the brand of "artificial sun"
The Kurchatov Research Institute, Russia	Russia	T-15MD	MCF (tokamak)	It has always been at the forefront in the research and development of superconducting tokamak, leading the fusion research in Eurasia
The Atomic Energy Research Agency of Japan	Japan	JT-60SA	MCF (tokamak)	It promotes cutting-edge research on high-performance plasma and steady-state operation, and is a leading fusion institution in the Asia-Pacific region

Organization name	Country / region	fusion facility	Fusion mode	Research features
The Lawrence Livermore National Laboratory, USA	America	NIF	ICF	Take the lead in realizing the net energy gain of fusion reaction, and maintain the international leading position in ICF
The British Atomic Energy Agency	UK	Mega Amp Spherical tokamak (MAST)	MCF (spherical tokamak)	Focusing on spherical tokamak route, breeding a large number of innovative fusion start-ups
The MIT Center for Plasma Science and Fusion	America	SPARC	MCF (tokamak)	Develop high temperature superconducting magnet technology, and strive in realizing fusion net power generation
Research Institute of Nuclear Energy and New Energy Technology, Tsinghua University	China	HL-2A 、HL-2M	MCF (tokamak)	Important progress has been made in the steady-state operation of fusion reactor, high-performance plasma physics, and fusion neutrons

Appendix 3. Representative fusion energy start-ups

the name of firm	Location of headquarters	technology roadmap	Amount raised (US $1,000,000)	Main investors
Commonwealth Fusion Systems	Massachusetts, USA	MCF (ARC)	2000	Tiger Global, Google, Temasek
General Fusion	Canada	MTF	200	Amazon founder Jeff Bezos, Tencent

the name of firm	Location of headquarters	technology roadmap	Amount raised (US $1,000,000)	Main investors
TAE Technologies	California, USA	MCF (FRC)	1200	Goldman Sachs, NEA, Tencent,
Tokamak Energy	UK	MCF (spherical tokamak)	200	Legal & General Capital
Helion Energy	Washington, USA	MCF (FRC)	570	Barron Capital, Y Combinator
Zap Energy	Washington, USA	MCF (Z-inch)	200	Chevron, Shell, Lowercarbon
First Light Fusion	UK	ICF	100	And Oxford Science Innovation
Type One Energy	Canada	MTF	-	-
Marvel Fusion	Germany	ICF	50	Earlybird, Primepulse
Renaissance Fusion	France	MCF (Stellarator)	20	The HCVC, the European Investment Fund
Beijing Xiyuan Fusion Technology Co., LTD	Beijing, China	ICF	-	Jun Lian Capital
Shanghai Juyuan Fusion Technology Development Co., LTD	Shanghai, China	MCF (FRC)	-	Lujiazui International Financial Assets Exchange

Appendix 4: The Main Fusion Energy Development Policy

Country / region	The main policy	release time	core content
America	The Road to Commercial Fusion: Strategic Planning for Fusion Energy	2021	It puts forward the strategic target and funding plan for the development of fusion energy in the next 20 years in the United States, and sets the timetable for the realization of commercial fusion power generation by 2040
America	The Energy Act	2020	Developed the first independent provision for fusion energy development, and authorized an estimated $4.5 billion budget for basic research
EU	The EU Fusion Energy Development Roadmap	2021	It forward the grand goal of achieving fusion DEMO and commercial power stations by 2050, and raising the development of fusion energy to the strategic height of Europe's energy transition
UK	Fusion 2040: The Road to the Green Industrial Revolution	2021	It is proposed to vigorously develop the fusion energy industry, promote economic recovery and decarbonization process, and strive to build the first fusion power station in the UK by 2040
China	The White Paper on the Development of Fusion Energy in China	2022	It describes the phased goals of China's fusion energy development, and major projects such as basic research, key technology breakthroughs and engineering test reactor go hand in hand
China	The 14th Five-Year Plan for Energy Development	2022	It stressed the vigorous development of advanced nuclear energy technologies, including fusion energy, to provide policy support for industrial development

Country / region	The main policy	release time	core content
Japan	The sixth basic Plan for Science and Technology Innovation	2021	Fusion energy is listed as a strategic innovation field, and it is proposed to accelerate the application process of engineering through the cooperation between the government, industry, university and research institutes, and promote economic recovery through scientific and technological innovation
Korea	Fusion energy research and development strategy roadmap	2021	It is proposed to commercialize fusion technology nearly by 2040, establish a relatively complete fusion industry chain, and take fusion energy as one of the engines leading the leapfrog development of the economy
France	The French Fusion Development Roadmap	2020	Cleared the construction goals of ITER and the subsequent DEMO and prototype reactor, and fusion energy has been incorporated into the French national low-carbon development strategy
Germany	Fusion Energy Research Program 2019-2024	2019	Focus on the optimization of advanced Wendelstein 7-X and other advanced tokamak devices, and actively participate in DEMO, engineering design, support ITER and subsequent projects

Appendix 5. Analysis of the fusion energy industry chain

Industrial chain link	Mainly involved in enterprises	Main technology / equipment / service
Upstream (raw material)	Rare earth mining enterprises, non-ferrous metal smelting enterprises, special material manufacturers	Superconducting wire materials, special alloy materials, ceramic matrix composites, etc

Industrial chain link	Mainly involved in enterprises	Main technology / equipment / service
Midstream (equipment manufacturing)	GE, Siemens, Mitsubishi and other heavy equipment manufacturers	Vacuum vessel, cladding, power supply, refrigeration, control system and other fusion reactor host equipment
Midstream (engineering construction)	China National Nuclear Corporation, China General Nuclear Power Corporation, Rosatom and other specialized engineering companies	Fusion engineering design, construction, installation and debugging, etc
Downstream (operational service)	State Grid, China Southern Power Grid and other power companies	Grid connection dispatching, power sales, power station operation and maintenance, etc
Support services	Universities, scientific research institutes, third-party testing institutions, financial investment institutions, etc	Scientific research, personnel training, technical testing, project financing, etc

Appendix 6 Fusion Energy Investment risk assessment

kind of risk	risk factor	risk level	Risk countermeasures
Technical risk	Fusion reactor configuration optimization. Critical components material properties. Fuel cycle self-holding.	★★★★	Multi-technology route combination to disperse research and development risks. Strengthen basic research and break through material bottlenecks. Develop advanced proliferation cladding to realize tritium self-holding.

kind of risk	risk factor	risk level	Risk countermeasures
Engineering risk	System complexity. Engineering design optimization. Construction and installation difficulty.	★★★	Strengthen the multi-disciplinary collaboration and improve the system performance. Introduce advanced digital twin and optimize the design scheme. Apply modular construction to reduce the difficulty of construction.
Operational risk	Fault rate of parts. Fusion fuel supply. Radiation safety protection.	★★	Strengthen preventive maintenance to improve equipment reliability. Improve the storage and transportation system to ensure a stable fuel supply. Strengthen radiation monitoring and establish multiple protective barriers.
market risk	Generating cost. Volatility in electricity demand. Policy support.	★★★	Develop advanced manufacturing and improve cost competitiveness. Expand diversified applications and spread the risk of demand fluctuations. Actively strive for special policy support to obtain early market cultivation.
Policy supervision risks	Financial and tax support. Market access barriers. Missing standard specification.	★★	Participate in the formulation of financial, tax and industrial support policies. Strengthen communication with regulators and eliminate barriers to access. Participate in the formulation of international standards, and lead the improvement of industry rules.

Appendix 7. Measurement of the economic benefit of fusion energy

metric	numeric value	remarks
Construction cost	$50-10 billion / million kW	Refer to ITER, DEMO device estimation
Operating costs	And 2-5 cents / KWH	Mainly including fuel, labor, equipment depreciation, etc
Feed-in tariff	And 5-10 cents / KWH	Consider certain policy support, comparable to nuclear power
Annual generating capacity	7-8 billion KWH	Estimated by the 90% capacity factor
Annual earnings	From $3.5 billion to $8 billion	Estimated by electricity generation and electricity price
Capital pay-off time	20-30 Years	Consider the discount factor estimate
Full-life-cycle benefits	From $50 billion to $100 billion	Estimated by 50-60 years of life
Discounted cash flow rate of return	5%-10%	Estimated by annual revenue and construction cost

Appendix 8 Fusion energy Development SWOT analysis

dimension	content
Strength	-Rich in resources, fuel reserves can meet the use of human for millions years -Intrinsically safe, there is no risk of core meltdown, and less radioactive waste

dimension	content
	-Clean and efficient, with nearly zero emissions of the power generation process, and high energy density
Weakness	-The technology is complex and difficult to break, and it is difficult to achieve commercialization in the short term -High cost, huge upfront investment, and a long investment payback period -Engineering progress is slow, and large-scale application will take time
Opportunity	-The energy revolution is expected to completely solve the human energy problem -Technological innovation to accelerate progress in materials, manufacturing and other fields -Economic growth, creating new industries and job opportunities -International cooperation is conducive to promoting the integration of global innovation resources
Threat	-Technical uncertainty, the breakthrough progress is not as expected -The rapid development of competitive energy challenges the cost advantage -Geopolitical risks and hinder international cooperation -Public acceptance is not high, and the negative cognition is difficult to reverse