

FUSION ENERGY FOR A SUSTAINABLE FUTURE: A REVIEW OF CAPABILITIES AND BARRIERS

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Abstract. Fusion energy has come back into the spotlight, as the demand for electricity is increasing with urbanization, electrification, and new high-energy-intensive industries, but also because fossil fuels are depleted, energy systems also need reliable low-carbon energy. This article considers fusion power as a potentially reliable low-carbon option, using the latest scientific literature and publicly available results from supporting installations, International Thermonuclear Experimental Reactor (ITER), and other international fusion research programs. The study first identifies a high level of aggregation of fusion energy, then summarizes the stated advantages for sustainability and the main obstacles that make it difficult to implement. The analysis shows that the system-wide prospectivity of fusion power is associated with a reliable low-carbon supply, but its near-future commercialization is largely limited by engineering sustainability, resource sustainability, thermal management, and initial cost uncertainty. In conclusion, the article separates the test stages from the requirements of the power plant and concludes that if integrated demonstrations do not quickly eliminate the lack of engineering and costs, fusion power will have more long-term benefits than solutions in the near future.

Keywords: nuclear fusion, low-carbon firm energy, fusion energy, low-carbon electricity, plasma stability, heat exhaust, engineering barriers.

1. Introduction

Nuclear fusion energy is recognised as one of the fastest-advancing energy technologies, which is drawing the attention of an increasing number of people, especially in its early stages. Global private investments have grown by approximately 178% year-over-year, reaching \$2.64 billion in the 12 months leading up to July 2025, which reaffirms the confidence in its significant future potential (Fusion Industry Association, 2025). This surge in interest coincides with pressure on global energy systems from rapidly growing demand for electricity, slow infrastructure development, intensifying climate impacts, and ongoing geopolitical threats affecting energy supply chains. Although wind and solar energy are widely used, the high share of various renewable energy sources poses problems with the reliability and balance of the system. Energy system expansion and large-scale energy storage systems may reduce this variability somewhat, but these processes face serious difficulties related to costs, material acquisition, obtaining permits, and construction time. As a result, in some regions, fossil fuels still constitute a key component of the stable

energy presentation, which contrasts with decarbonization goals and makes energy systems vulnerable to fuel cost fluctuations and geopolitical inconveniences. Nuclear fission, including small modular reactors, is nowadays considered a stable and low-carbon variant, but this technology faces high capital costs, construction risks, waste management, and public acceptance issues (Intergovernmental Panel on Climate Change, 2022; International Energy Agency [IEA], 2023c; World Nuclear Association, 2026). In this context, thermonuclear energy is chosen as a long-term additional energy supply, as it is combined with sustainable energy sources and modern fission technologies. In theory, fusion has a high energy density, consumes a limited amount of fuel, and needs a relatively small area, which, in turn, makes it possible to produce stable, low-carbon energy. Nevertheless, the transition from successful tests to the operation of power plants is still uncertain. On the one hand, the stability of the power plant depends on the performance of the plasma, and on the other hand, it must be resistant to intense neutron radiation. Also, the ability to control extreme heat flows, complete the tritium fuel cycle, and ensure reliable and trouble-free

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operation during the life of the reactor is needed (Mohamed et al., 2024).

This review article explores the basic capabilities of nuclear power and the important scientific, engineering, and system-side barriers that must be overcome before Fusion can take place as a practical source of reliable low-carbon electricity.

2. Methodology

This review article is based on a structured literature survey with a primary focus on recent developments, relying mostly on publications from the last three years (2023–2025) to reflect the current state of fusion energy research, engineering progress, and policy frameworks. Earlier foundational studies were included only where necessary to provide context. The literature review was carried out on the basis of peer-reviewed scientific articles, International Agency accounts, and major publications on the thermonuclear fusion program, with particular emphasis on reactor performance, technical capabilities, and system-level problems. These sources have been identified from academic databases such as Scopus, Web of Science, and Google Scholar, as well as through official publications of organizations such as International Thermonuclear Experimental Reactor, International Atomic Energy Agency, International Energy Agency, U.S. Department of Energy, and the European Commission.

About 200 articles and reports have been selected and evaluated for their relevance. Among the selection criteria, studies on the problems of plasma stability in operating conditions, material degradation, heat dissipation, fuel cycle limitations, accessibility, cost uncertainty, and the readiness of regulators aimed at energy installations are noted. In plasma physics, mere theoretical studies have been excluded that do not present clear results for reactor functionality or system management.

The purpose of this review is not to provide an extensive technical analysis but to summarize the main possibilities and obstacles that determine the practical role of thermonuclear energy in low-carbon power systems in the future. Among the limitations are the lack of detailed cost modeling and the application scenarios of specific technologies remaining for future research.

3. Global development status and future outlook of fusion technology

Fusion is still in the experimental and commercial transition stages, and no fusion power plant currently supplies power to the grid. Current systems are for research purposes and aim to contain the plasma in the reactor environment, ensure material sustainability, implement tritium production, and demonstrate integrated reactor engineering. Demonstration-level reactors (DEMO) are expected to be operational between 2030 and 2040, with

commercial use expected only after ongoing technical and economic evaluation.

Fusion research is being carried out intensively in the United States, Europe, and Asia, with technologically advanced structures being assembled. The European Union is building a large tokamak called ITER in France to demonstrate plasma combustion (Table 1). China is actively pursuing the EAST project for long-term superconducting plasma research.

Table 1. Summarizes the main fusion programs, the type of device used, and the primary objective of each facility (International Atomic Energy Agency [IAEA], 2024a)

Country / Region	Facility	Confinement type	Primary objective
European Union	ITER	Tokamak	Burning plasma demonstration
China	EAST	Tokamak	Long-pulse superconducting plasma
USA	NIF	Inertial confinement	Laser-driven ignition experiments
Germany	Wendelstein 7-X	Stellarator	Steady-state plasma confinement
Japan	JT-60SA	Tokamak	Advanced plasma control research
United Kingdom	STEP	Tokamak (planned)	Pilot power plant development

The United States is conducting both magnetic confinement research and inertial confinement through the National Ignition Facility (NIF). Germany is leading the way in stellarator development with the Wendelstein 7-X, while Japan is contributing with the JT-60SA. The United Kingdom is advancing a pilot plant concept under the STEP program. However, neither of these configurations has yet presented itself as a fully operational commercial reactor.

4. Technical background

Nuclear fusion is a method of energy production in which two light atoms combine to form a heavier nucleus, releasing a large amount of energy in the process. This energy is created from the mass difference between the reactants and the product, which is converted into energy. Fusion is the same mechanism that is responsible for the Sun and other stars shining (Mohamed et al., 2024).

The principle of the deuterium-tritium fusion reaction is illustrated in Figure 1.

To achieve nuclear fusion on Earth, it is necessary to heat the fuel to extremely high temperatures, converting it into a plasma. At such high temperatures, the nuclei of the atoms can overcome their natural repulsive force and come together. To obtain useful energy from nuclear

fusion reactions, the plasma must be maintained for a certain period of time and at a sufficiently high density. The energy generated in nuclear fusion reactors is transferred by the motion of fast particles, which heat the surrounding structures. This heat is then converted into electrical energy using conventional energy generation methods (Wurzel & Hsu, 2022).

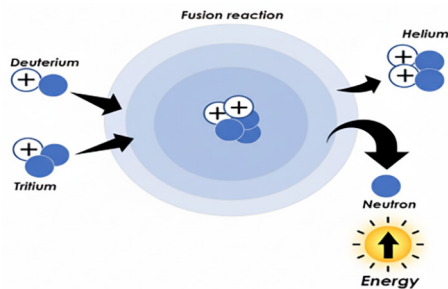


Figure 1. Deuterium–tritium fusion reaction producing helium, a neutron, and energy (Mohamed et al., 2024) (The figure was generated using an AI-based image generation tool)

A mixture of deuterium and tritium, isotopes of hydrogen, is generally used as a fusion fuel. Deuterium is abundant in seawater, but tritium is scarce and must be produced in a reactor from lithium. This particular fuel combination is preferred because it requires a lower temperature compared to other fusion reactions to ensure the sustainability of the reaction (Meschini et al., 2023).

Fusion reactors are primarily categorised by their plasma confinement methods. Tokamaks use intense magnetic fields generated by external coils along with a current flowing through the plasma, which, while providing adequate confinement, leads to stability issues. However, stellarators rely solely on external magnetic coils, offering the potential for continuous operation with improved stability, but they are more challenging to design and build. Inertial confinement reactors use powerful lasers to compress small fuel pellets and initiate the fusion process with brief bursts; this method is fundamentally different from magnetic confinement and is primarily used for research purposes (Beidler et al., 2021).

The main magnetic confinement configurations used in fusion devices are illustrated in Figure 2.



Figure 2. Comparison of magnetic confinement systems in fusion reactors: tokamak with axisymmetric toroidal coils (left) and stellarator with three-dimensional twisted coils (right) (Hambling, 2016)

5. Capabilities of fusion energy for sustainable power systems

5.1. Low-carbon power for the home and grid support

Fusion energy is often presented as a low-carbon energy source because the process does not require combustion and does not produce carbon dioxide during operation. However, as with all energy systems, its carbon intensity must be assessed throughout its entire life cycle, including construction, material production, fuel processing, plant operation, maintenance, and decommissioning. Life Cycle Assessment (LCA) studies show that magnetic confinement fusion is expected to have greenhouse gas emissions similar to nuclear fission and wind power, typically in the range of 5–20 gCO₂-eq/kWh, depending on the material impact and equipment design. These estimates are significantly lower than fossil fuel-based electricity generation, where natural gas has over 400 gCO₂-eq/kWh and coal has over 800 gCO₂-eq/kWh.

The majority of life-cycle emissions in fusion systems do not come from fuel consumption, but rather from the production of structural materials, superconducting magnets, and large concrete containment structures. Tritium processing systems and plant maintenance activities are also additional sources of emissions. Therefore, the low-carbon advantage of fusion energy is related to efficient material selection, plant life, and high operational availability. In the system view, the potential climate benefits of fusion depend not only on the efficiency of plasma physics, but also on engineering optimization and supply chain sustainability (IPCC, 2022).

Fusion energy holds great promise as a way to generate reliable, low-carbon electricity that is not affected by weather conditions and can complement other variable renewable energy sources such as wind and solar. As the use of renewable energy expands, energy systems need greater flexibility to instantly balance supply and demand, as intermittent energy generation can create both shortages and surpluses at different times (European Commission-Eurostat, 2023). If fusion can be implemented as a viable technology on the scale of a power plant, it could provide dispatchable power on demand and reduce the reliance on ageing fossil fuel backup generators by supporting reliability services such as reserve power and frequency regulation. The key point is that this is the value at the overall system level. The benefit of fusion to the electric grid depends on providing high reliability, maintenance capabilities, and predictable operating conditions, which are governed by real engineering constraints (Gorenstein Dedecca et al., 2025; IEA, 2023b).

5.2. High energy density by mass

The charm of Fusion is due to the extremely high specific energy, which is, to some extent, compared to the unit mass of the fuel (J/kg). The theoretical specific energy of

Deuterium tritium fuel (D-T) is thought to be approximately 3×10^{14} J/kg, which is millions of times greater than that of conventional chemical fuel (10^7 J/kg), several times higher than that of uranium-235 fission (8.2×10^{13} J/kg) (World Nuclear Association, 2025). This difference is significant because it highlights the reason the fusion process can primarily extract an extremely large amount of energy from a very small mass of fuel, thereby shifting the system's focus from fuel supply issues to engineering problems such as storage, component lifespan, and heat transfer. Figure 3, therefore, clearly demonstrates the difference in scale by comparing the approximate specific energy of U-235 fission and D-T fusion (using the low heat value of gasoline, as a typical chemical fuel, for the residual fuel) (European Commission, 2024; ITER Organization, 2026b).

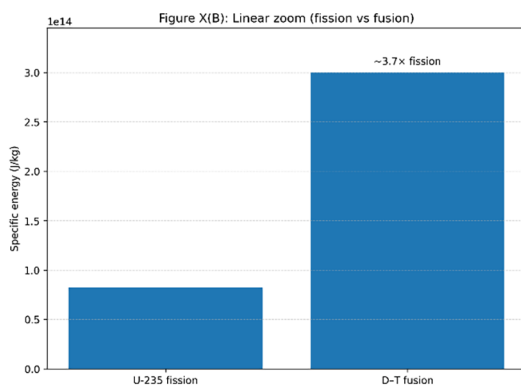


Figure 3. Comparison of specific energy release per unit mass for U-235 fission and deuterium–tritium (D–T) fusion (ITER Organization, 2026b; Mohamed et al., 2024)

5.3. Compact site and reduced land/infrastructure footprint

Fusion energy is often characterized as a sustainable and abundant source of energy, which can be significant for energy systems with constraints such as land use, permitting, and grid expansion (U.S. Department of Energy, 2024). While wind and solar power are geographically distributed and would require the construction of new power lines, a fusion reactor, if technically feasible, could be a centralized site producing high power (IEA, 2025; Keep et al., 2023). This could primarily reduce the amount of land required for energy production and could ease some siting challenges, especially around industrial centers that need reliable power. However, this “small footprint” idea is based on certain conditions: fusion facilities will still require significant support infrastructure, safety and security zones, cooling systems, access for servicing, and connections to the power grid. Thus, the real advantage is not that “fusion is small,” but that the high-power density can provide planning advantages in a single location compared to widely dispersed manufacturing facilities in some cases (UK Government, 2025b).

5.4. Fuel availability and energy security

One of the often-emphasized benefits of fusion is its ability to provide sustainable energy security with regard to its primary fuel resources. Deuterium can be extracted from large quantities of water, and the amount of fuel required is extremely small, which largely reduces sensitivity to fuel price fluctuations and supply disruptions, especially compared to fossil fuels. However, in the near future, most proposed fusion applications are based on the deuterium–tritium (D–T) reaction, and tritium is not abundant in nature (ITER Organization, n.d.-a); it must typically be created and replenished from lithium within the reactor system (IAEA, 2024b; ITER Organization, n.d.-d). This means that fusion’s “fuel access” depends on completing the tritium breeding and processing cycle, the safe management of stockpiles, and ensuring the lithium supply is of the required purity and scale. If these technical and supply chain needs are met, fusion could become a strategically secure source of low-carbon energy, but initially it will likely be closely tied to specialized materials and a complex fuel cycle infrastructure (Strikwerda et al., 2024; U.S. Department of Energy, 2024b).

5.5. Safety and environmental profile

Fusion is generally considered safe because it does not cause a self-sustaining chain reaction, and it is difficult to maintain the ideal state of the plasma; energy production stops rapidly when the basic operating conditions are disrupted (ITER Organization, n.d.-c). From a system operations standpoint, this can reduce the risk of an uncontrolled energy increase, as is the case with conventional nuclear fission reactors. However, fusion is not completely “risk-free.” Many near-term plans involve the use of tritium, a radioactive form of hydrogen, and this material requires strict security, monitoring, and accounting (UK Government, 2025a). Furthermore, High-energy neutrons from the D-T fusion process can activate structural materials, creating radioactive components that must be managed as waste (IAEA, n.d.), although the amount and longevity of the waste may differ from long-lived nuclear fission waste. Therefore, in practice, it is possible to offer some improved safety and waste characteristics compared to nuclear fission, but it also has its own important operational, regulatory, and environmental management needs (Victoria et al., n.d.).

5.6. High-temperature heat and industrial decarbonisation options

In addition to electricity, nuclear fusion is sometimes seen as a high-grade heat source that can help reduce carbon emissions in difficult-to-Access Industries. Many industrial processes require continuous thermal energy at high temperatures that are difficult to achieve with renewable energy alone, without the need for large-scale energy storage or major restructuring of technological

processes (IEA, 2023a). If a nuclear fusion reactor can produce continuous heat at the required temperature levels while ensuring reliable and safe operation, it can essentially provide low-carbon process heat and support options such as hydrogen production (via electrolysis by constant energy or thermochemical methods, depending on the temperature achieved) (IEA, 2025). The usual foundation of its feasibility is fundamental: its industrial significance depends not only on the theoretical density of thermonuclear energy, but also on the ability of practical reactor systems to satisfy their thermal and energy needs with high operational readiness, operating time, and affordable prices. From the point of view of the current perspective, the possibilities of nuclear synthesis in the industry are best presented in the near future, not as trust, but as an opportunity that can be achieved through use (Fusion For Energy, 2025; Fusion Industry Association, 2024).

6. Engineering and systemic barriers to fusion power deployment

6.1. Plasma storage and operational stability

The main difficulty is to maintain thermonuclear plasma with high temperature, density, and stability in a manageable and sustainable way. The effectiveness of magnetic restriction systems depends on maintaining the ideal restriction during the suppression of instabilities, since these instabilities can quickly worsen the state of the plasma or stop its activity (IAEA, 2024c). Tokamak must account for off-normal and disruption events that can generate large electromagnetic forces and intense thermal loads on the vacuum vessel, plasma-facing components, and superconducting magnet structures, which represent critical engineering constraints for reactor-scale operation (IAEA, 2001). Although serious problems can be avoided, traffic and boundary instability caused by turbulence can lead to a decrease in density, which leads to an increase in external temperature and a decrease in the possibility of using it for clean energy production (Lehnen et al., 2018). This is important because the power plant is valued not so much for its peak performance in a matter of seconds, but for its ability to produce predictable power with continuous plasma behavior over long periods of time. Therefore, in practice, the problem is a joint issue of physics and management: plasma modes must be stable enough to withstand disturbances, and control systems must maintain stability within real installation constraints, such as component constraints, changing operating conditions, and maintenance-related configuration changes (IAEA, 2024b).

6.2. Material degradation and neutron damage

One of the most serious engineering problems on the way to the realization of future thermonuclear energy is associated with the factors that form high-energy

neutrons: the ability of materials to stay for a long time in conditions of strong radiation. As a result of the bombardment of neutrons, there is a change in the location of atoms and a change in the composition of materials, which leads to sensitization, swelling, sliding, and a decrease in the heat transfer capacity of the materials, as a result of which the stability and heat transfer capacity of the structure are weakened. Parts that come into contact with plasma, together with the influence of strong surface temperatures and particle wear, are more exposed to the harmful effects of neutrons, which speed up the Wear process and make it necessary to replace them periodically. The action of neutrons also activates the surrounding materials, which leads to the fact that the main parts become radioactive, which may require special repair methods, remote-controlled operations, and controlled waste disposal. These factors directly affect the economic efficiency of the unit, since the life of the parts determines the frequency of downtime during the period of operation of the unit, the provision of spare parts, and the amount of energy obtained. As a result, in addition to being part of the final stage, the quality of the materials is important for obtaining reliable design data and requires radiation tests, long-time tested models, and manufacturing processes capable of providing stable characteristics on a production scale (Jimenez & Burroughes, 2019; Pintsuk et al., 2022; UKAEA, 2025).

6.3. Heat exhaust and thermal management

Controlling heat flow is considered a major challenge in magnetic nuclear fusion technology, as the reactor must continuously transfer significant amounts of thermal energy from a small area without rapidly failing parts exposed to plasma. The surfaces of the extraction system and the first wall are exposed to high heat and particle fluxes; their durability, on the other hand, is due to factors such as both the properties of the materials and The Shape of the magnetic field, the edge control of the plasma, and the design of the cooling system. The goal is not only to prevent melting or large fissions, but also to control erosion, cracks, and microstructure damage that can occur as a result of thermal changes and neutron radiation. In this context, heat management is not limited to the surface only: heat must be transferred to cooling cycles at high pressure, high temperature, and a strong radiation environment, and then converted into electricity with efficiency. Compromises are required at each stage: high temperatures can increase thermodynamic efficiency, but increase material durability requirements and increase the risk of corrosion, while low temperatures improve durability but reduce system efficiency and economic competitiveness. When heat generation and heat management are not fully implemented, the thermonuclear energy of the reactor under suitable conditions is still closely related to test operating cycles rather

than constant electricity generation (Barucca et al., 2017; Hering et al., 2022; ITER Organization, 2019).

6.4. Engineering complexity, maintainability, and availability

The nuclear fusion power plant should work not just as a physical device, but also as a combined engineering system; the difference between these two aspects poses a significant challenge to commercialization (ITER Organization, 2026a). Concepts related to synthesis include energy-generating magnets, cryogenic technologies, very high vacuum, high temperature, and current equipment, complex diagnostic systems, radioactive fuel monitoring, and simultaneous, often interacting, effective cooling systems. Such complexity intensifies deficiencies and increases the need for maintenance, while neutron activation and pollution issues require remote control and the presence of specialized technical equipment (ITER organization, n.d.-d). The main performance indicator is accessibility: even a slight decrease in the power coefficient can affect the cost of electricity, since fixed costs are high, and equipment replacement requires high costs (UK Atomic Energy Authority, 2024). Sustainability is therefore a design limitation that requires practical planning, which includes modular components, available service ports, reliable remote systems, and conditions beyond ideal. Without proven high accessibility, it will be difficult for synthesized test complexes to switch from demonstration prototypes to a commercially reliable base load or stable power supply (Crofts & Harman, 2014; Surrey, 2019).

6.5. Cost, supply chains, and regulatory

Although difficulties in the physical and engineering fields are slowly disappearing, nuclear fusion still has to overcome barriers to commercialization, such as cost-effectiveness, industrial supply chains, and the need for licensing (Kaiser et al., 2026). Because projects are constantly changing, capital costs still remain uncertain, as many factors affecting costs, including high-voltage superconductors, high-precision manufacturing, extensive vacuum and cryogenic systems, special protection and maintenance equipment, have not yet been standardized for mass production. Operating costs also remain uncertain, especially given the frequent replacement of plasma processing components, the infrastructure needed to recycle tritium, and long interruptions caused by remote maintenance. Going beyond prototypes and scaling up can lead to a shortage of materials and production capabilities, while the need for high-quality assurance standards can limit the number of qualified suppliers. As for the institutional side, licensing systems inherent in nuclear synthesis are still in the process of formation and create uncertainty for sellers and investors in expectations regarding security, regulatory deadlines, and international adaptation. These uncertainties lead to financial

risks: without clearer cost forecasts, proven operational indicators, and predictable ways of obtaining permits, large-scale private investments and the introduction of utilities will be prudent even in the conditions of technological development (Clean Air Task Force, 2025; Fusion Industry Association, 2024).

Global private investment in fusion energy has exceeded approximately US\$7.1 billion, demonstrating growing financial interest but still low compared to developed energy sectors (Fusion Industry Association, 2025).

As can be seen in Figure 4, capital investment between 2010 and 2024 is highly concentrated in a limited number of Member States, with a significant increase after 2020 (IAEA, 2024a).

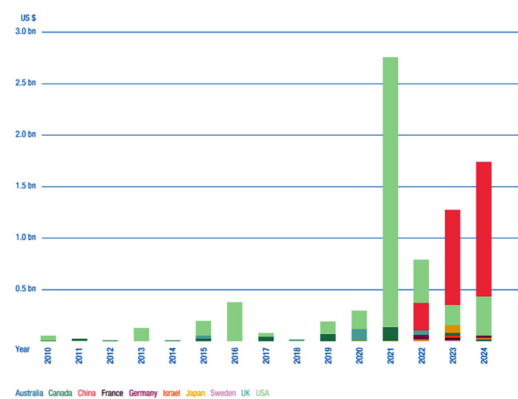


Figure 4. Equity investments to fusion energy companies

7. Discussion

Fusion's potential contribution to a sustainable energy transition is best interpreted at the system level rather than as a narrow plasma-physics achievement. The possibilities discussed in this article – reliable low-carbon power generation, higher specific energy, the possibility of compact placement, fuel safety, safety systems associated with automatic shutdown, and the use of high-quality heating-can only be realized when the operation of the power plant is appropriate. Practical shows that the cost of Fusion depends on its availability, durability, predictable operating conditions, and costs, as modern power systems do not focus on delivering high performance over a short period of time, but rather prefer long-term sustainable, distributable energy, and grid service. Therefore, the main conclusion from the “barriers” section reveals the idea that commercialization responsibility is not just a “breakthrough in physics”, but a technological chain interconnected by plasma stability, wall loads, heat dissipation, and the service life of components. This determines the frequency of maintenance and downtime. In particular, damage and activation of neutrons, coupled with high temperatures and particle fluxes on plasma-oriented surfaces, provide a design environment in which remote maintenance is

not necessary, but structurally determined, and the speed and reliability of maintenance fundamentally determines the operational readiness of the system. As soon as availability becomes the main metric, costs immediately begin to be discussed: fixed capital costs are predicted to be high, component replacement, infrastructures for processing tritium, and long-term downtime can lead to an increase in operating costs, which creates uncertainty in forecasts about level costs. Also, there are supply chains and the same links that explain why regulation is important at an early stage. In an era when the licensing system is still developing, high-quality assurance requirements, special production, and the expansion of limited source bases can create potential compressions, which increases schedule risks and investor uncertainty when transaction data is incomplete. Overall, the review shows that the strengthening of Fusion for clean energy production and industrial decarbonization in the near future, as well as heat dissipation, material service life, repairable architecture and reactor-friendly conditions, are tied to comprehensive demonstrations that address the practical issues of the fuel cycle. Unless these limitations are overcome in accordance with measurable reliability and cost, fusion will be limited to experimental projects and prototype-level advances rather than becoming a commercially viable low-carbon enterprise.

8. Conclusions

Fusion energy remains a promising alternative to low-carbon energy and potentially high-quality industrial thermal energy, but its system cost depends more on power plant performance than on experimental data. This review shows that significant obstacles are caused by technical limitations: the stability of the plasma, the effects of neutrons on the fracture and activation of materials, heat dissipation and temperature control, and, as a result, the requirements for remote maintenance and further service readiness. The implementation of the fuel cycle, particularly tritium production and processing, plays a crucial role in terms of its feasibility in the near future and the state of the supply chain. Cost, increased production, and the development of the regulatory framework are contributing to uncertainties that may affect private investment and the adoption of new technologies, despite ongoing technological progress. In general, the merger should be considered as a strategic long-term choice. This confidence will only increase through comprehensive demonstrations that validate reliability, durability, and practical strategies for reducing reactor operating costs under appropriate conditions.

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