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Antall ord *:	17868

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Ja

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Gruppenavn:	(Anonymisert)
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Høgskulen på Vestlandet

MASTEROPPGAVE

Fusjonsenergi: Navigering av fremtidens energi gjennom innovasjon og økonomi

Fusion Power: Navigating the future of energy through innovation and economics

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Master of Science in Business

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28.05.2024

Jeg bekrefter at arbeidet er selvstendig utarbeidet, og at referanser/kildehenvisninger til alle kilder som er brukt i arbeidet er oppgitt, *jf. Forskrift om studium og eksamen ved Høgskulen på Vestlandet, § 12-1.*

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Abstract

This thesis explores how innovations in fusion technology impact economic investments within the field of fusion power, using the ITER project as a central case study. Initial assumptions highlighted the environmental and social benefits of fusion energy and the rising global energy demand. As the research progressed, these assumptions proved complex to verify comprehensively within the available time and resources, necessitating adjustments in the research focus. The study relies primarily on secondary data sources, including official reports, scientific articles, and project documentation, to analyse the technological advancements and economic implications of fusion power.

The findings of this thesis indicate that technological innovations, such as tokamaks and tritium breeding systems, have significantly boosted investor confidence and attracted substantial financial commitments from an international consortium of stakeholders. These advancements showcase the potential of fusion energy, justifying the high initial costs with the promise of long-term, low operating costs and sustainable energy supply. The nature of ITER, involving significant contributions from multiple nations, has facilitated the sharing of financial risks and rewards, enhanced the projects credibility and accelerated the innovative and technological progress.

The reliance, however, is on a limited range of secondary sources, which often reiterate similar information, presents challenges in capturing the most recent developments and diverse perspectives. The static nature of documents and reports may not adequately reflect the evolving nature of the ITER project, potentially leading to an incomplete analysis. Despite these limitations, the research provides valuable insights into the interaction between technological innovation and economic investment in fusion power, underscoring the importance of continued international collaboration and investment in advancing fusion research. The findings suggest that while challenges remain, the overall impact of technological advancements on economic investments in fusion power is both significant and promising, leading the way for fusion energy as a contribution to global energy sustainability.

Abstrakt

Denne masteroppgaven utforsker hvordan innovasjoner innen fusjonsteknologi påvirker økonomiske investeringer innen fusjonskraft, med ITER-prosjektet som en sentral casestudie. Innledende antagelser fremhevet de miljømessige og sosiale fordelene med fusjonsenergi og den økende globale energietterspørselen. Etter hvert som forskningen skred frem, viste det seg at disse antagelsene var komplekse å verifisere grundig innenfor den tilgjengelige tiden og ressursene, noe som nødvendiggjorde justeringer i forskningsfokuset. Studien baserer seg hovedsakelig på sekundære datakilder, inkludert offisielle rapporter, vitenskapelige artikler og prosjektdokumentasjon, for å analysere de teknologiske fremskrittene og de økonomiske implikasjonene av fusjonskraft.

Funnene i denne masteroppgaven indikerer at teknologiske innovasjoner, som tokamak-reaktorer og tritiumavlssystemer, betydelig har økt investortilliten og tiltrukket betydelige

finansielle forpliktelser fra et internasjonalt konsortium av interessenter. Disse fremskrittene viser potensialet til fusjonsenergi, og rettferdiggjør de høye innledende kostnadene med løftet om langsiktige, lave driftskostnader og bærekraftig energiforsyning. ITER-prosjektets natur, med betydelige bidrag fra flere nasjoner, har lagt til rette for deling av økonomiske risikoer og gevinster, økt prosjektets troverdighet og akselerert den innovative og teknologiske utviklingen.

Imidlertid medfører avhengigheten av et begrenset utvalg av sekundære kilder, som ofte gjentar lignende informasjon, utfordringer med å fange opp de nyeste utviklingene og mangfoldige perspektivene. Tilgjengelige kilder og vitenskapelige artikler og rapporter kan derfor potensielt ikke reflektere den stadig utviklende naturen til ITER-prosjektet i tilstrekkelig grad, versus dersom studien inkluderte ekspert intervjuer og direkte observasjoner, noe som potensielt kan føre til en ufullstendig analyse. Til tross for disse begrensningene gir forskningen verdifulle innsikter i samspillet mellom teknologisk innovasjon og økonomiske investeringer i fusjonskraft, og understreker viktigheten av fortsatt internasjonalt samarbeid og investering i å fremme fusjonsforskning. Funnene antyder at selv om utfordringer gjenstår, er den samlede effekten av teknologiske fremskritt på økonomiske investeringer i fusjonskraft både betydelig og lovende, og baner vei for fusjonsenergi som et bidrag til global energibærekraft.

1 Introduction

Traditional energy sources are increasingly viewed as unsustainable due to their environmental impact and finite resources. With global energy demand expected to rise by 34 % from 2022 to 2050, the urgency to develop sustainable and efficient energy solutions has never been greater. Fusion power, the process that drives the sun, emerges as a promising solution, potentially offering an almost limitless, clean energy source capable of meeting global needs sustainably. Fusion produces minimal radioactive waste and has no risk of uncontrollable reactions, making it a highly safe energy process. The primary fuels for fusion, deuterium and tritium, are virtually inexhaustible, as they can be extracted from seawater and lithium.

Despite these potential benefits, achieving practical and sustained nuclear fusion on Earth presents significant technical challenges. The extreme temperatures required to sustain fusion reactions demand advanced materials and sophisticated confinement strategies, such as tokamaks and stellarators. Significant ongoing research in fusion power is dedicated to overcoming these challenges, with projects like ITER leading the way for innovation and technological advancements for a sustainable energy source. ITER, a multinational collaborative project located in France, aims to demonstrate the feasibility of fusion as a large-scale, carbon-free energy source. Using a tokamak design, ITER seeks to achieve a self-sustaining fusion reaction that produces more energy than it consumes.

Research in nuclear fusion has made significant progress in understanding the technical and engineering challenges associated with fusion reactors. Fusion energy represents a revolutionary advancement that could lead to clean and virtually limitless energy. Tokamaks and stellarators, the most promising candidates in fusion technology, use magnetic fields to confine plasma at extremely high temperatures, facilitating the fusion of hydrogen isotopes. This process releases substantial energy, akin to the reactions occurring in the sun. However, there are still significant challenges regarding long-term sustainability, economic feasibility, and the commercialization of fusion energy as a future energy source. While recent scientific advancements have demonstrated the technical feasibility of achieving a successful fusion process with output greater than input, considerable challenges remain in the practical implementation of these technologies.

The motivation behind this research is deeply rooted in the urgent need for sustainable energy sources in response to growing environmental challenges, including climate change and pollution. Traditional energy sources, such as fossil fuels, contribute significantly to greenhouse gas emissions and environmental degradation, exacerbating global warming and its associated impacts. As the world seeks to transition to cleaner energy alternatives, the exploration of innovations in fusion energy due to its immense potential to provide a virtually limitless, clean, and safe energy supply, is a large motivation behind this study. Furthermore, this research is motivated by the need to thoroughly understand the role of technological innovation and economic considerations in advancing fusion energy. Innovation is needed in fusion technology for overcoming the significant technical challenges of fusion power. Moreover, understanding the economic aspects of fusion energy is equally important. The development and deployment of fusion technology require substantial financial investments, both in research and development and in the construction of experimental and commercial reactors. Analysing the economics of fusion energy involves assessing investments, the potential for cost reductions through technological advancements, and the economic benefits that fusion energy can provide.

The purpose of this study is to explore the interplay between technological innovations in fusion energy and their economic implications. Specifically, it aims to investigate how advancements in fusion technology, particularly in tokamak design, influence economic investments within the fusion power sector. By focusing on the ITER project as a central case study, this research will provide a comprehensive understanding of the current state and future prospects of fusion energy. The study aims to highlight the drivers within technological innovations in fusion research and development and analyse how these advancements impact the economical frame of investments from both public and private sectors.

This research will delve into several key areas. It will examine the recent advancements in fusion technology, focusing on tokamaks. This includes improvements in materials science, plasma confinement methods, and reactor design. Understanding these innovations will provide insight into how they address the technical challenges of achieving practical fusion energy. The study will assess the economic feasibility of fusion energy by analysing the costs associated with developing and operating fusion reactors. This includes evaluating the financial investments required for research and development. The research will also touch slightly into exploring the potential of cost reductions brought about by the technological innovations. Additionally, the research will investigate how technological advancements have influenced investment patterns in the fusion power sector. This involves looking into funding sources, both public and private, and understanding the motivations behind these investments. Furthermore, it will explore the commercial prospects of fusion energy by examining the strategies and plans of key players in the field, such as ITER, JET, and NIF. This includes understanding the potential market for fusion energy and the economic benefits of a successful fusion energy industry.

By addressing these areas, the study aims to provide a comprehensive overview of the factors driving fusion energy research and development. Highlighting the connection between technological innovation and economical investment, offering insights into the potential and challenges of making fusion energy a viable and sustainable energy source. This approach allows for a detailed examination of factors influencing the future of fusion energy.

This study aims to answer the research question:

How has innovation in fusion technology affected the economic investments within fusion power?

Delimiting the research to fusion power, the ITER project, tokamaks, and their innovative and economic perspective provide the main framework for this study. Fusion power represents a transformative approach to energy generation, promising significant environmental and economic benefits. The tokamak design, central to the ITER project, exemplifies the most advanced and studied method for achieving controlled fusion reactions. By exploring the technological innovations and economic implications of these developments, this research seeks to provide a comprehensive understanding of the potential and challenges associated with fusion energy. This approach allows for a detailed examination of the factors driving fusion research and development, highlighting the innovation and technical advancement required to make fusion a viable energy source and the economic strategies needed to support its commercialization.

This thesis is structured to have a systematic review of the research process. The thesis begins with an introduction that provides an overview of the purpose of the study, underlying motivation, and the research question this thesis is studying and aiming to answer. This is followed by a comprehensive review of relevant and existing literature to identify insights within fusion power, including scientific papers, technological breakthroughs, and investments within fusion power. The methodology describes the specific of the case study conducted on the ITER project and the analysis applied in the study. The results are presented and evaluated in light of the research question, with a discussion of the implications of the findings. The thesis concludes with the main findings, their significance for both theory and practice, and also suggestions for future research directions.

2 Fusion technology: Literature and insights

According to the institute for Energy Research (n.d.), global energy consumption is expected to increase by 34 % between 2022 and 2050, outpacing advances in energy efficiency.

Fusion power is one of the few options capable of supplying abundant safe baseline energy on a global scale (Carpentieri and Shahzad, 2022). Fusion power has the potential to generate somewhat limitless energy supply but is currently in the experimental stages. Scientists from all around the world have been attempting to replicate the fusion power process since the 1960s (Stallard, 2022). Fusion power is about making an artificial sun on Earth, and this process comes with significant technological challenges. (Chen, 2011). The extreme conditions inside a fusion power plant system like a tokamak which needs extreme temperatures and high magnetic fields necessary to make atoms fuse into a nuclear fusion reaction. This process and intense conditions address several potential problems, that has yet to be overcome (Shahzad and Carpentieri, 2022). Currently, the greatest promise for overcoming these hurdles is lies in the development of tokamak reactors (Chen, 2011).

The development of fusion energy requires advancements in several critical material systems, including high heat flux components, tritium breeding systems (with neutron multipliers where relevant), plasma diagnostic materials, insulators, blanket coolant systems, vacuum vessels, and superconducting magnet materials. (Bloom, Zinkle, and Wiffen, 2004).

Prominent institutions actively researching fusion technology include ITER, JET and the National Ignition Facility in the USA, Commonwealth Fusion Systems, and TAE Technologies. These institutions are making strides in various fusion reactions and systems, such as deuterium-deuterium (D-D) reaction, magnetic confinement, inertial confinement, and hydrogen-boron fusion.

This thesis primarily focuses on ITER and tokamaks, as they represent the most advanced and comprehensive approaches to achieving large-scale fusion energy. ITER, with its extensive international collaboration and advanced tokamak design, is particularly central to this context. By analysing ITERs technology, goals, and challenges, and comparing them with other tokamak projects like JET, this thesis aims to highlight the current state and future prospects of fusion energy.

This chapter looks into the scientific principles of fusion power, examining the technological innovations in fusion energy, the role of the ITER project, and ongoing research in the field. It explores the specific advancements in Tokamak technology, recent technological breakthroughs, and the economic implications of fusion power. Additionally, the chapter assesses the challenges and opportunities within the fusion energy sector, providing a comprehensive overview of the current state and future prospects of this promising energy source.

2.1 The science of fusion power

Fusion power relies solely on hydrogen, which exists in three forms. Normal hydrogen contains a single proton. Deuterium(D) has one proton and one neutron, also known as heavy water. Tritium(T) is even heavier, containing one proton and two neutrons. The sun generates its energy by converting hydrogen into helium through a series of reactions that we cannot replicate on Earth. Instead, it is converted into deuterium or tritium into helium to achieve significant energy gain (Chen, 2011). For fusion to occur, two hydrogen atoms must get so close to each other that their cores can merge; but these cores carry strong electric charges that hold them apart (McCracken and Stott, 2005). Under the conditions where these electrostatic forces can be overcome, allowing the nuclei to draw very close, the attractive nuclear force which binds protons and neutrons within atomic nuclei will dominate the repulsive forces. This allows the nuclei to fuse. Such conditions are typically achieved by increasing the temperature, which accelerates the ions to velocities sufficient for them to come into close proximity and fuse, thereby releasing energy (Prager, 2019). The nucleus of helium is known as an alpha particle, consisting of two protons and two neutrons. This nucleus is very stable due to its strong binding energy (Chen, 2011).

The fusion reaction between two deuterium nuclei brings together two protons and two neutrons that can rearrange themselves in two alternative ways. One rearrangement produces a nucleus that has two protons and a single neutron. This is the form of helium known as helium-3. There is a neutron left over. The alternative rearrangement produces a nucleus with one proton and two neutrons. This is the form of hydrogen known as tritium, which has roughly three times the mass of ordinary hydrogen. In this case a proton is left over. Energy is released because the sum of the masses of the rearranged nuclei is slightly smaller than the mass of two deuterium nuclei (McCracken and Stott, 2005).

In fusion, hydrogen fuel is heated into a plasma, an electrified state hotter than the sun's interior, and contained using magnetic fields. This process, though challenging, remains a promising path to energy production. Advanced reactions involving helium-3, lithium, or boron could eliminate radioactivity. Plasma-induced fusion relies on heating a hydrogen gas mixture of deuterium and tritium to extremely high temperatures, enabling high-energy collisions that result in fusion. Although the plasma leaks energy, researchers continue working on sustaining this reaction for practical energy production (Chen, 2011).

In the first reaction energy is released, but energy has to be put into the second reaction. The basic fuels for a fusion power plant burning deuterium and tritium will be ordinary water and lithium. Deuterium will be extracted from water, and tritium will be produced from lithium. Both basic fuels are abundant, easily accessible, and relatively cheap. (McCracken and Stott, 2005). Fusion reactions yield about 10 million electron volts (eV) or 10 MeV of energy. The fusion reaction transmuting hydrogen into helium $D + T \rightarrow \alpha + n + 17.6$ MeV (where α represents a helium nucleus and n a neutron) releases 17.6 million electron volts of energy (see Fig. 1). The neutron carries 80 % of the energy and must be captured and converted into heat (Chen, 2011).

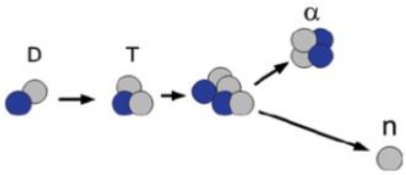

Figure 1. The D-T reaction
Source: Chen, F., 2011. An Indispensable Truth: How Fusion Power Can Save the Planet. Springer.

Tritium does not occur naturally, it has to be bred from lithium in a fusion reactor (Chen, 2011). Tritium is a radioactive form of hydrogen and requires careful handling to minimize environmental release due to its radioactivity. Fusion reactors primarily use metals with high tritium permeability, prompting efforts to develop barrier materials to prevent tritium permeation through structural components. While many barrier materials perform well in laboratory settings, they often fail under radiation conditions typical of fusion environments. Tritium still releases significantly less radiation than fission reactors. The fusion community continues to seek effective solutions to this challenge (Causey and San Marchi, 2012).

One gram of deuterium can generate 300 GJ of electricity. To meet the world's current energy demand, approximately 1000 tons of deuterium would be required annually. Deuterium, which constitutes about 1 part in 6700 of water, can be extracted easily using electrolysis. One gallon of water can yield as much energy as 300 gallons of gasoline. With the vast amounts of water in the oceans, there are over 10^{15} tons of deuterium available, providing an almost limitless energy source. The cost of extracting deuterium is minimal compared to other electricity generation costs (McCracken and Stott, 2005).

2.2 Innovation in fusion energy technology

Innovation involves creating something novel and unprecedented, often pushing the boundaries of current knowledge and capabilities. This process is inherently experimental because it ventures into uncharted territory where established methods and outcomes are not guaranteed. The essence of innovation lies in exploring new ideas, technologies, or methodologies that have not been tried before. To gain knowledge about these new phenomena and determine their potential for success, it is essential to engage in a cycle of experimentation and discovery. This involves designing experiments and conducting trials to observe and analyse the results. Through this process, innovators can gather empirical data, refine their approaches, and develop a deeper understanding of the underlying principles and mechanisms at play (Tidd and Bessant, 2021).

Experimentation is an important methodology to innovation because it allows for practical testing of theoretical concepts, revealing both strengths and weaknesses that may not be apparent in initial planning stages. It provides a framework for learning from both successes and failures, each step bringing valuable insights that contribute to the overall progress of the innovation. It also encourages taking calculated risks and embracing uncertainty, which are fundamental aspects of breakthrough discoveries. By systematically investigating and iterating on ideas, innovators can navigate the complexities of pioneering new ground. The path to innovation is a journey of continuous learning and adaptation. Each experiment adds to the collective knowledge base, paving the way for further advancements and eventually leading to the realization of groundbreaking solutions that can have transformative impacts on society and various industries (Tidd and Bessant, 2021).

2.2.1 ITER

At the 1985 Geneva Summit, Soviet leader Mikhail Gorbachev proposed to US President Ronald Reagan a collaborative next-step tokamak project. The US, Japan, and the European Community agreed, leading to the ITER project (McCracken and Stott, 2005). International Thermonuclear Experimental Reactor (ITER), designed to demonstrate that fusion could be a viable large-scale, carbon-free energy source. ITER, meaning "The Way" in Latin, is one of the most ambitious energy projects in the world today, with 35 nations collaborating to build the world's largest tokamak in France (Prager, 2019).
ITER's primary objective is to investigate and demonstrate burning plasmas where the energy of helium nuclei produced by fusion reactions is sufficient to maintain the plasma's temperature, reducing or eliminating the need for external heating. ITER will also test technologies essential for a fusion reactor, such as superconducting magnets, remote maintenance, and power exhaust systems (ITER, n.d.). The ITER experiment is serving as the flagship facility for global fusion research over the next two decades. Its significance lies in directly linking the progress towards developing a fusion reactor to ITERs physics and technological achievements. This projects success is critical for advancing fusion energy (Freidberg, 2007). The ITER central solenoid will be the largest superconducting magnet ever built. It will produce a field of 13 tesla, equivalent to 280,000 times the Earths magnetic field (The U.S. Department of Energy n.d.).

Between 1988 and 1990, the initial designs for ITER were developed, aiming to show that fusion could produce useful energy. By 1992, the main collaborators, including Canada and Kazakhstan through Euratom and Russia, agreed to continue with the engineering design activities for ITER. In 1998, the ITER Council approved a comprehensive design for a fusion reactor estimated at $6 billion. However, the USA's withdrawal led to a redesign and cost reduction to $3 billion, resulting in the ITER Fusion Energy Advanced Tokamak (ITER-FEAT). This version aimed for a self-sustaining reaction and net energy gain, but not enough for a power plant to demonstrate feasibility (Prager, 2019).

Geopolitical changes by 1998 made ITER challenging to support solely as East-West collaboration. It had to stand on its own merits as a new energy form. Government funding for energy research, including fusion, had decreased, leading to the US withdrawal from ITER. Japan, Europe, and Russia continued their support. The revised 2001 ITER design aimed for 40 MW (megawatt) of heating to generate about 400 MW of fusion power, though not enough for ignition, serving as a significant test bed for fusion power plant technologies (McCracken and Stott, 2005).

USA rejoined the project in 2003, and China also announced its participation. By mid-2005, the six partners agreed to site ITER at Cadarache in southern France. The European Union (EU) and France committed to half of the then-estimated €12.8 billion cost, with Japan, China, South Korea, the USA, and Russia each contributing 10%. Japan would supply high-tech components, host the International Fusion Materials Irradiation Facility (IFMIF), and a subsequent demonstration fusion reactor. India joined the ITER consortium at the end of

2005, becoming the seventh member (Prager, 2019). In November 2006, the seven members: China, India, Japan, Russia, South Korea, the USA, and the EU, signed the ITER implementing agreement. Site preparation at Cadarache began in January 2007, with the first concrete poured in December 2013. Initial experiments, planned for 2018 using hydrogen, have been delayed to 2025, with the first deuterium-tritium (D-T) plasma expected by 2035 (Prager, 2019).

Thousands of engineers and scientists have contributed to the design of ITER. The experimental campaign at ITER is crucial for advancing fusion science and preparing for future fusion power plants. ITER aims to operate with a plasma thermal output of 500 MW for at least 400 seconds continuously with less than 50 MW of heating power input, although it will not generate electricity. An associated facility, at Cadarache, is designed to test components and accelerate their development for ITER, focusing on the divertor structure to remove helium and test tungsten materials. A 2 GW (gigawatt) demonstration power plant, known as DEMO, aims to demonstrate large-scale electrical power production. Initially expected to begin construction around 2024, the timeline has been delayed to 2040 (Prager, 2019).

The European Community launched in 1978 the Joint European Torus (JET) project in the UK, which remains the world's largest operating tokamak. JET produced its first plasma in 1983 and achieved controlled fusion power in 1991, with up to 16 MW of fusion power for one second and 5 MW sustained in D-T plasmas. Numerous experiments have explored different heating schemes, and JET has demonstrated the feasibility of remote handling in a radioactive environment. Significantly upgraded to test ITER plasma physics and engineering systems, JET plans further enhancements to exceed its fusion power record. The Mega Amp Spherical Tokamak (MAST) is also being developed to support ITER (Prager, 2019).

The journey of ITER underscores the challenges and the international commitment to developing fusion energy. Despite delays and redesigns, the collaboration continues to strive toward realizing the potential of fusion as a sustainable energy source. The large-scale ITER construction project underway in Saint Paul-lez-Durance, in southern France (ITER, n.d.).

As of September 2023, the nations participating in ITER include the 27 European Union countries, plus China, India, Japan, Korea, the Russian Federation, and the United States. Switzerland, currently a "non-associated third country" in Euratom, and the UK, which has ceased pursuing an association agreement with Euratom, are considered non-participating members in ITER construction, although existing contracts with UK and Swiss citizens and companies are being honoured (ITER, n.d.).

2.2.2 Current fusion research

Magnetic confinement fusion (MCF), magnetic fields are harnessed to confine large volumes of deuterium-tritium (D-T) plasma, often hundreds of cubic meters at a density below a milligram per cubic meter (Prager, 2019). A charged particle in a uniform magnetic field moves freely in the direction parallel to the field, but there is a force in the transverse direction that forces the particle into a circular orbit. The combined motion of the particle is a spiral, or helical, path along the direction of the magnetic field (McCracken and Stott, 2005).

These plasmas are confined at pressures of a few atmospheres and heated to temperatures necessary for fusion to occur. Magnetic fields are particularly suited for this purpose because the charged ions and electrons in the plasma naturally follow the lines of the magnetic field. This containment strategy is critical to prevent the plasma from contacting the reactor walls, which would lead to heat loss and reduced particle velocity, undermining the fusion process (Prager, 2019).

The ideal shape for containing plasma is a toroidal, or doughnut-like, configuration where the magnetic field forms a continuous loop. To successfully confine the plasma within this toroidal field, it is essential to introduce a perpendicular poloidal field. This combination produces a composite magnetic field, where the lines of force follow spiral (helical) trajectories. Such a configuration is crucial for effectively confining and managing the behaviour of the plasma (Prager, 2019). The primary function of the toroidal field is to stabilize the plasma. The most significant instabilities must contend with bending or stretching this magnetic field, which serves a role similar to the steel bars in reinforced concrete. However, unlike concrete, plasma behaves more like jelly, making the magnetic field's structural role critical. Tokamaks benefit from having stronger "reinforcing bars," which significantly enhance their stability (McCracken and Stott, 2005).

There are many conceptual schemes for using reactions to generate fusion power that has been proposed. The tokamak is an experimental machine designed to harness the energy of fusion. Inside a tokamak, the energy produced through the fusion of atoms is absorbed as heat in the walls of the vessel (ITER, n.d.). The tokamak (illustrated in figure 2) is the only design to have produced significant fusion. Moreover, studies of power plants based on the tokamak show that they provide a promising route to commercial fusion power (Smith and Cowley, 2010). The tokamak system is the most well-known type, which employ a series of evenly spaced coils surrounding the torus-shaped reactor to generate the toroidal field (Prager, 2019). The tokamak is a typical magnetic confinement fusion device, which uses a powerful magnetic field to confine plasma in the shape of a torus (Carpentieri and Shahzad, 2022). In addition to horizontal coils outside this toroidal structure generate the poloidal field, a significant electric current is induced in the plasma via a central solenoid, which also enhances the poloidal field (Prager, 2019). As the electric current heats the gas, it turns into a plasma and creates a magnetic field. When this field combines with the external coils, it forms a helical shape that helps keep the plasma away from the chamber walls, providing excellent thermal insulation. However, as the plasma gets hotter, its electrical resistivity drops significantly. The heat from the transformer-induced current can only get the plasma to about one-third of the temperature needed for effective fusion. To reach the higher temperatures required, additional heating power from microwaves or particle beams is needed. The transformer can only sustain the plasma current while the current is increasing in the inner poloidal field. After this point, the plasma current must be maintained by energy from microwaves and beams of energetic neutral atoms, which heat the plasma through collisions. When the plasma reaches around 100 million degrees Celsius, deuterium-tritium (D-T) fusion reactions start. The helium nuclei, or alpha particles, produced from these reactions then heat the plasma even more, continuing the fusion process (Smith and Cowley, 2010).

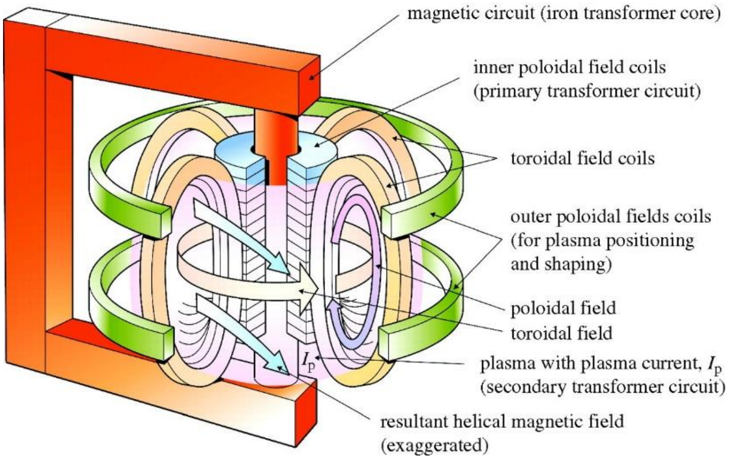

Figure 2. "In a tokamak, the fusion fuel is held in a toroidal chamber surrounded by magnets. A current is induced in the fuel by transformer action and, together with the toroidal field coils, produces a helical magnetic structure that holds the hot fuel away from the wall."
Source: Smith and Cowley, 2010. *The path to fusion power. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 368* (1914), 1091-1108.

Tokamak was first conceptualized in 1951 and remains to this day the most extensively studied and developed fusion devices due to their initially promising design. Despite their propensity for disruptions, these being sudden losses of energy confinement that pose significant thermal and mechanical stress to the reactor structure, the researchers still aim to optimize this operation and mitigate the risks (Prager, 2019). A new laser measurement technology for controlling extreme conditions inside future fusion power plants are being developed. The new laser interferometer system is currently being tested at the Tokamak Energy's Oxford headquarters. It will later this year be installed on the world record breaking fusion machine (White, 2024).

Stellarators provide an alternative to tokamaks by employing a series of coils, often helically shaped, to generate the necessary helical force lines without relying on a toroidal current within the plasma. This design bypasses some of the complexities and instabilities linked to the current in tokamaks, potentially leading to more stable plasma conditions. Although stellarators initially fell out of favor due to difficulties in maintaining stable plasma confinement, advancements in computer modelling have resulted in more precise geometric designs, enhancing stability and allowing for continuous, steady operation (Prager, 2019). Both stellarators and tokamaks feature robust toroidal fields that contribute to stability. However, stellarators differ from tokamaks in that they do not have a plasma current and thus depend on complex external coils to create the poloidal magnetic field. These coils are costly to construct and require precise alignment. Consequently, one reason tokamaks have historically surpassed stellarators in development and application is their simpler and more cost-effective construction (McCracken and Stott, 2005).

Inertial confinement fusion represents a more modern research avenue, utilizing lasers to heat the outer layer of a material. This process triggers an outward explosion, which in turn creates an inward compression, or implosion. As research advances, the field is actively investigating this and other methods with the goal of addressing the complex challenges associated with plasma confinement and advancing towards the realization of practical, sustainable fusion energy (Prager, 2019).

2.2.3 Tokamak

A tokamak is a machine that confines a plasma using magnetic fields in a donut shape that scientists call a torus. Fusion energy scientists believe that tokamaks are the leading plasma confinement concept for future fusion power plants. Tokamaks can sustain plasma currents at the mega-ampere level, which is equivalent to the electric current in the most powerful bolts of lightning (The U.S. Department of Energy n.d.).

"As a function of the tokamak aspect ratio and toroidal field while keeping the triple product, safety factor, and H factor constant. For instance, the values assumed for ITER are illustrated in Figure 3. Figure 3 indicates that moving towards lower aspect ratios (leftward) or higher toroidal fields (upward) results in similar triple products from smaller tokamaks with reduced major radii. This finding is significant because tokamaks of ITER's size can be classified as "megaprojects" (technically, projects over $1 billion; ITER exceeds $20 billion)."(Carpentieri and Shahzad, 2022, p. 59). Historical analyses of megaprojects reveal that cost and time overruns are more common than exceptions. This is largely because megaprojects are often too large for a single company or even a single country to manage efficiently. As the hierarchy between management and workers expands, these projects become increasingly difficult to handle. In contrast, smaller tokamak power plants offer greater agility, allowing for swift adaptation to design optimizations. A significant advancement would be the feasibility of modular construction, which would enable centralized manufacturing away from the construction site. The following sections will delve further into these opportunities. Spherical tokamaks with HTS magnets are among the few viable options for providing safe, abundant energy with a small footprint (Carpentieri and Shahzad, 2022).

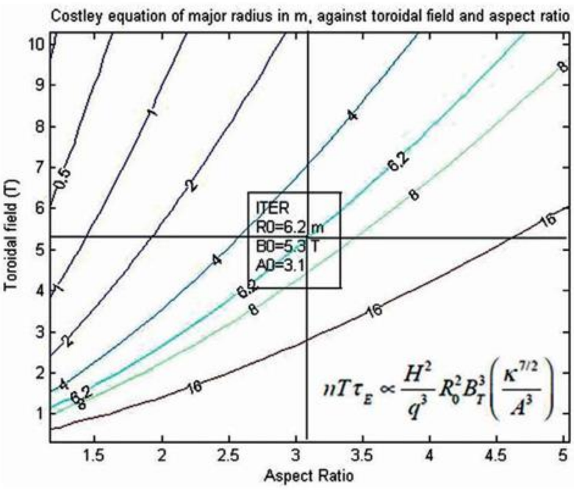

Figure 3. "The reduction in tokamak major radius (lines labeled in meters) which may be given by lower aspect ratios (X-axis) or by higher magnetic toroidal fields (Y-axis). The data are scaled to the ITER operating point at major radius R0 = 6.2 m, toroidal field B0 = 5.3 T, and aspect ratio A = 3.1." Source: Carpentieri and Shahzad, 2022. *Advances in fusion energy research.* IntechOpen.

The tokamak is the leading magnetic configuration for confining fusion plasmas. Creating a fusion plasma in a tokamak involves the following steps: First, a small amount of gas, using hydrogen-deuterium or deuterium and tritium in experiments at JET and actual fusion reactors, injected into the doughnut-shaped vacuum chamber once the magnetic field coils are activated. At the same time, an increasing current is initiated in the inner poloidal field coils.

This process generates an electric current, about 5 megaamperes (MA) in JET and approximately 15 MA in ITER, which flows through the gas via transformer action (Smith and Cowley, 2010). The world record fusion power was achieved in the JET tokamak in England in December 2021. JET produced 59 megajoules of head energy, more than doubling the previous record set in 1997 (The U.S. Department of Energy n.d.).

2.2.4 Technological breakthroughs

December 2022, physicists at the National Ignition Facility in California reported a significant milestone in fusion research. They successfully extracted more energy from a controlled nuclear fusion reaction than the energy used to initiate it, a global first. While this achievement marks a crucial step forward in physics, it remains far from making fusion a viable energy source for practical use (Ball, 2023).

In August 2023, scientists from the U.S. Department of Energy successfully replicated a nuclear fusion reaction, confirming the net energy gain first reported in December 2022. This confirmation has sparked significant excitement among investors, who are optimistic about the transformative potential and opportunities that nuclear fusion could bring to the energy sector (Duggan, 2023).

In February 2024, a significant milestone in nuclear fusion research was achieved at the UK's JET laboratory, setting a new world record for energy output. The experiment produced 69 megajoules of energy over five seconds, marking a notable advancement in the quest for clean and limitless energy. This achievement is particularly impressive as it was accomplished with just 0.2 milligrams of fuel, highlighting the potential efficiency of fusion power. The record-setting experiment at JET was described by scientists as a "fitting swansong" for the pioneering reactor. This breakthrough demonstrates the power of international collaboration and the potential of fusion energy to provide a sustainable and abundant energy source for the future The success of this experiment provides valuable data and confidence for the development of future fusion reactors, including ITER, which aims to further explore and demonstrate the viability of fusion power on a larger scale (Stallard, 2024).

First Light Fusion is developing an innovative fusion method by using a high-speed projectile to compress a target containing fusion fuel. The key challenge is to launch the projectile accurately and ensure it remains solid upon impact, which is crucial for their power plant design. Recently, First Light successfully extended the 'standoff' distance from 10mm to 10cm in their experiments. Dr. Nick Hawker, Founder & CEO, emphasized the focus on overcoming engineering challenges as they move towards commercializing fusion energy (BBC News, 2024).

Scientists at Lawrence Livermore National Laboratory in California have achieved a significant milestone in replicating the sun's power in a laboratory setting. During an incredibly brief event, lasting less than 100 trillionths of a second, 2.05 megajoules of energy comparable to the energy released by a pound of TNT were directed at a hydrogen pellet. This resulted in a substantial release of neutron particles, products of the fusion process, carrying approximately 3 megajoules of energy, yielding a 1.5-fold energy gain (Chang, 2022).

2.3 Economic perspectives on fusion power

Fusion energy must demonstrate not only its cleanliness, safety, and environmental friendliness but also its cost competitiveness with other energy sources. Projections from various groups in the US, Japan, and Europe suggest that fusion-generated electricity could be cost-competitive by the mid-21st century. However, these long-term estimates carry significant uncertainties, especially when compared with known costs of building and operating current fossil fuel power plants. The future costs of fossil fuels are unpredictable due to fluctuating prices and potential environmental regulations, which could increase operational costs significantly if environmental damage costs are factored in. Currently, electricity from fossil fuels does not account for environmental and public health damages, which are challenging to quantify. Some experts suggest that true coal-generated electricity costs could be up to six times higher if these external costs were included. Advanced technologies might reduce greenhouse gas emissions and pollutants, but they would also raise power plant costs. Similarly, predicting future costs for renewable energy sources like wind, solar, and tidal energy is difficult, as these technologies are generally more expensive than fossil fuels and often require government subsidies. While costs are expected to decrease as these technologies develop, their intermittency necessitates costly energy storage solutions for them to become major energy sources (McCracken and Stott, 2005).

Fusion energy, by contrast, benefits from stable and insignificant fuel costs, with fuel contributing less than 1% to the overall cost due to the high energy yield from small amounts of fuel. The primary costs for fusion energy lie in the initial capital investment for power plant construction and maintenance. Many components of a fusion power plant, such as buildings, turbines, and generators, will have known costs, but the complex plasma confinement systems will be expensive to build and replace. Recent tokamak design studies suggest that an optimal plant size generating around 1000 MW of electricity could be economically competitive to other fuels (McCracken and Stott, 2005).

The efficiency is an important factor influencing the fusion electricity costs. Given the limited future options for energy supply due to finite fossil fuel reserves and environmental concerns, renewable sources like wind and solar will become increasingly important but cannot meet all energy needs. Centralized energy sources like fusion will be essential. An independent European Commission evaluation in 1996 deemed a commercial fusion power plant a demanding yet achievable goal within approximately 30 years. Thus, timely development and construction of prototype fusion plants are critical to ensure fusion energy readiness when needed (McCracken and Stott, 2005).

"Fusion is the ultimate energy source," asserts Phil Larochelle, a partner at Breakthrough Energy Ventures, a venture capital firm investing in fusion companies. He highlights that if fusion can be successfully harnessed, it offers an essentially infinite, free, and universally accessible energy source that is also carbon-free. Recently, billions of dollars from venture capitalists and tech entrepreneurs have poured into the fusion field. Companies like Helion, which secured $500 million in its 2021 fundraising, are striving to build commercial fusion power plants and achieve net energy production in the coming years (Barber, Brumfiel, Carlson, and Ramirez, 2024). The government of the UK has also announced an investment of £200m to deliver electricity from a fusion reactor by 2040. (McGrath, 2019).

The Euratom framework proposal for a co-programmed European partnership (PPP) for fusion innovation establishment during the 2025-2027, which will complement the F4E innovation partnership, focusing on distinct characteristics and funding strategies. The partnership aims for an annual budget of EUR 30-100 million, with smaller initial budgets that will scale up. A recommended 75:25 funding split will allocate 75 % to key enabling technologies for DEMO and 25 % to other fusion approaches, including inertial fusion and magneto-inertial fusion. This allocation supports high-risk, high-potential technologies and offers a route for EU firms to scale. The partnership will bring together academia, businesses, and governments to advance in innovation. This collaboration provides companies with technical and financial support necessary for advancing new or advanced technologies. The aim is to de-risk innovation and remove barriers to commercialization by providing public finance instruments and access to research labs and facilities at both EU and national levels (European Commission, Directorate-General for Energy, Smith, Gérard, & Bene, 2024).

Investing in fusion energy innovation is attractive to EU investors, including angel investors, venture capital firms, and sovereign wealth funds. Understanding how investors perceive risk-sharing and ownership is crucial, as these factors can significantly influence their investment decisions. Investors are motivated by the potential for significant long-term returns and the opportunity to contribute to sustainable energy solutions. They typically adopt a portfolio approach, relying on external experts for due diligence and technical advice. The long timelines for fusion technology commercialization require patience, with venture funds generally having lifetimes of around 14 years. Opportunities to cash in investments may arise before commercialization, such as when venture capital sells to institutional investors as technology nears market readiness (European Commission, Directorate-General for Energy, Smith, Gérard, & Bene, 2024).

To date, investors have primarily focused on fusion start-ups rather than companies in the fusion supply chain. However, there are opportunities for supply chain investments, which has attracted EUR 90 million by focusing on developing key components for the fusion sector (European Commission, Directorate-General for Energy, Smith, Gérard, & Bene, 2024).

The public sector must play a facilitating and enabling role by continuing to fund basic research, supporting early-stage development, creating a favourable regulatory framework, investing in the fusion supply chain, and providing a stable policy framework. PPPs are vital as they allow investors to leverage their investments, access additional financial resources, and reduce investment risk through public sector involvement (European Commission, Directorate-General for Energy, Smith, Gérard, & Bene, 2024).

Investors have significant opportunities in the fusion energy sector through partnerships with government entities, which allow them to leverage their investments and access additional financial resources. By collaborating with established entities in the clean energy sector, investors can utilize state-of-the-art research and development facilities to accelerate technological advancements. Furthermore, these partnerships help reduce investment risks and enhance potential returns by benefiting from the public sector's credibility and independent verification processes, ensuring a more secure and promising investment (European Commission, Directorate-General for Energy, Smith, Gérard, & Bene, 2024).

By partnering with governments and other organizations, investors can help shape the clean energy sector, drive policy changes, and align investments with strategic national priorities. The Fusion Energy Sciences program will receive $763 million for 2023-2024, including significant allocations for ITER. Congress has also allocated $630 million for Inertial Confinement Fusion research, supporting breakthroughs at the National Ignition Facility, totalling $1.4 billion in fusion research funding by the US government (European Commission, Directorate-General for Energy, Smith, Gérard, & Bene, 2024).

Substantial investments from both public and private sectors are driving advancements in fusion technology. These investments aim to develop necessary technologies, infrastructure, and regulatory frameworks, making fusion a viable and sustainable energy source. The proposed Co-Programmed European Partnership for fusion innovation will have a significant role in collaborating with innovation to advance fusion technology (European Commission, Directorate-General for Energy, Smith, Gérard, & Bene, 2024).

2.4 Barriers and opportunities

Entering the ITER Era, the fusion community now focuses on constructing the ITER experiment and achieving its burning plasma mission. The international team is manufacturing and assembling the massive components for the core tokamak device and developing the supporting infrastructure at the Cadarache site in France. Researchers are prototyping plasma control solutions to optimize ITER's performance and maintain a burning plasma for extended periods. Looking beyond ITER, future fusion systems will need to sustain continuous burning plasma operations for months, with only brief maintenance interruptions. For commercial applications, fusion energy must be captured and converted to electricity, and fusion systems must breed sufficient tritium to sustain their fuel supply. New plasma machines are investigating control strategies for long-pulse to steady-state plasma sustainment. Fusion materials research is advancing, focusing on plasma-facing materials that can endure prolonged exposure to intense particle and neutron fluxes, as well as materials for power extraction. The pace of fusion reactor technology development is accelerating. Several modules are being designed in several countries for construction and testing in ITER. Planning is also underway for the next major steps following ITER, such as DEMO machines. These will integrate burning plasma with systems for power extraction and tritium breeding, aiming to demonstrate continuous operation, a closed fuel cycle, and net power generation from a fusion plant. There is no single, unique way to chart the progress in fusion research toward commercial power plants. Experimental machines are nothing more than equipment that researchers use to build the scientific and technical foundations for fusion that will eventually provide society with the knowledge of what is required to obtain net energy from a fusion system safely and economically (Neilson, 2016)

ITER is supported by seven nations representing over half the worlds population. With an estimated cost of $21 billion, located in France and aims to test the sustainability of a continuous fusion reaction, or burn. The project is scheduled for completion by 2019, with an operational period of at least ten years. Concurrently, another large machine will be necessary to address engineering challenges not covered by ITER. The first power-producing fusion reactor, DEMO, is planned for post-2050. The main constraint on progress is financial resources (Chen, 2011). An organization behind a £20 billion fusion power station in Nottinghamshire admits there is no guarantee of its success. The government announced that the advanced facility will be built at the West Burton A plant. Fusion, a potential source of limitless clean energy, is currently experimental (Royce and Jefford, 2022).

The creation of a complete fusion power plant, from ITER to DEMO, necessitates the expertise of large industries experienced in operating large-scale power plants and possessing nuclear expertise. These industries are crucial in the design phase to avoid operational and technological challenges. The fusion supply chain report highlights suppliers' needs, including recognizing fusion's potential, confidence in scaling production, and the perceived risks due to the uncertain commercialization timeline. Suppliers seek clear long-term component needs, financing mechanisms to minimize risk, and continuous commercial opportunities to retain expertise developed through ITER projects. Public funding should create a pipeline of projects to sustain the supply chain. According to Fusion for Energy (n.d.), the construction of ITER and the investment in the development of fusion energy technology which means many business opportunities. Reaping the benefits from the ITER project extends beyond commercial gains. Companies involved in fusion research can access new markets, enhance their skills, and drive innovation. Additionally, they benefit from the transfer of know-how, the creation of new applications, the establishment of international collaborations and commercial partnerships, and the setting of new benchmarks in fusion technology.

The potential of nuclear fusion energy is driving significant global investments, led by the EU, China, and the US, due to its promise of a reliable, clean, and limitless energy supply. Despite high initial costs, fusion's long-term economic benefits, such as low operating costs and contributions to decarbonization, make it attractive. The UK is investing in nuclear projects, including Small and Advanced Modular Reactors and the STEP program, to enhance energy security, reduce carbon emissions, and stimulate economic growth. The UK government plans substantial investments to support nuclear fusion R&D, recognizing its role in achieving carbon reduction targets and fostering industry innovation (Elango, 2023).

A future fusion power plant must achieve two essential functions, to extract fusion power for electricity production or industrial applications, such being hydrogen production, and to provide all the tritium needed to sustain the thermonuclear reaction throughout the plants operational lifetime (Neilson, 2016).

Fusion power is still under development and won't be available as quickly as hoped. Early estimates underestimated the scientific challenges of confining plasmas at temperatures exceeding 100 million degrees Celsius. The cost and scale of development were also misjudged, as fusion cannot be achieved on a small scale. However, as demonstrated by the Joint European Torus (JET), achieving fusion plasma conditions is now possible. It also seems feasible to construct viable fusion power stations at a reasonable cost. Nevertheless, significant time is needed to develop the technology to ensure fusion power's reliability and economic viability, including testing materials under power station conditions (Smith and Cowley, 2010).

Achieving high availability, potentially around 75 %, is likely the greatest challenge fusion will face. To reach this goal in relatively future, further development of fusion technology and a system engineering approach, focus on buildability, reliability, operability, and maintainability, leveraging experience from nuclear fission, should be started soon (Smith and Cowley, 2010).

Success in developing fusion as a commercially available power source on Earth is not guaranteed. However, considering the enormous energy challenge and the relatively modest investment needed compared to the approximately $5 trillion annual energy market, accelerating fusion development is fully justified due to its immense potential. With limited alternatives to meet the worlds power needs as fossil fuel availability and willingness to use them decline, we cannot afford to neglect fusion power (Smith and Cowley, 2010).

The main challenge in fusion research has been creating a device capable of heating deuterium-tritium (D-T) fuel to sufficiently high temperatures and confining it long enough to produce more energy than is consumed in initiating the reaction. While current efforts focus on the D-T reaction, which is easier to achieve, the long-term goal is to utilize a deuterium-deuterium (D-D) reaction, which requires much higher temperatures for sustained fusion (Prager, 2020).

3 Research method

This chapter looks into the research method used to examine the ITER project and its implications for the future of fusion energy. The study employs a case study approach, leveraging various data collection techniques to provide a comprehensive analysis of ITER's technological, economic, and strategic aspects. Additionally, this chapter discusses the reliability and validity of the research method and not but least this chapter looks to and acknowledges the limitations in the study.

3.1 Case study

A case study is an empirical inquiry that investigates a contemporary phenomenon in depth within its real-life context, particularly useful when the boundaries between phenomenon and context are not clear (Yin, 2009). It involves formulating a research question, selecting the case, choosing informants, collecting data, and setting criteria for data analysis and interpretation. This method explores situations, events, or organizations deeply to reveal otherwise unnoticed phenomena, offering new insights and developing principles for understanding similar cases (Johannessen, Tufte, and Christoffersen, 2021).

Case studies address the unique challenge of having more variables of interest than data points, relying on multiple evidence sources and benefiting from data triangulation. The development of theoretical propositions guides data collection and analysis, making it a comprehensive method encompassing design logic, data collection techniques, and specific approaches to data analysis (Yin, 2009). Analysing the case within specific contexts, such as physical, social, historical, or economic environments, is common. While qualitative methods like observation or open interviews are frequently used, quantitative data and techniques, such as sensor data, existing statistics, and structured questionnaires, can also be incorporated. Combining different methods is beneficial for obtaining comprehensive and detailed data (Yin, 2018).

In cases with limited samples, alternative techniques are necessary. One option is sorting and systematizing data to find commonalities and differences, often through cross-case analysis. This method focuses on themes within the data, enhancing relevance and transferability to other settings, thus contributing to higher generalizability, and understanding (Johannessen, Tufte, and Christoffersen, 2021).

A single-case design is suitable when the case is critical, extreme, or unique, capable of revealing significant phenomena, events, or situations. This approach allows the researcher to explore a phenomenon from various angles, often leading to detailed descriptions and comprehensive understanding (Johannessen, Tufte, and Christoffersen, 2021).

Yin (2014) identifies five key components for conducting a case study, the research question, theoretical assumptions, units of analysis, the logical link between data and theoretical assumptions, and criteria for interpreting the findings. Research questions in case studies are especially suitable for "how" and "why" questions and exploratory "what" questions.

Theoretical assumptions, arising after posing fundamental questions, direct the researcher's focus. The units of analysis vary, with case selection based on literal versus theoretical replication. Criterion-based selection is the best strategy for choosing cases that meet specific criteria, ensuring the logical link between data and assumptions.

Defining the research questions is the most important step in a research study. Questions have both substance such as, what the study is about, and which form the type of question being asked (Yin, 2009).

Findings in a case study are interpreted in relation to existing theory using methods like explanation building. The goal in case selection is to find the case that provides the most information. Strategic selection is based on suitability rather than representativeness, allowing comparisons and pattern identification. Inductive theory building. Determining when to conclude a case study depends on how much new information is obtained. The final product can be a theoretical framework, hypotheses, or theoretical assumptions, possibly resulting in a mid-level theory presenting variable relationships. In the worst case, the final product may not identify clear patterns in empirical data or merely replicate existing theory (Johannessen, Tufte, and Christoffersen, 2021).

Over-determination concerns the ability to generalize from observations, using inference restricted by existing information. Degrees of freedom, the number of cases minus explanatory variables, minus one, indicate the capacity to generalize. With limited cases, claims about causation are unreliable as they lack information on the spread of the phenomenon (Yin, 2009).

Eisenhardt (1989) suggests that researchers should have between four and ten cases to generalize results. This approach enhances the validity and reliability of the findings, providing a robust framework for understanding complex issues through detailed, context-specific analysis.

The study is formed by several assumptions that shape its scope and approach, particularly regarding the environmental and social benefits of fusion energy, as well as the dynamics of global energy demand. These assumptions are essential for framing the research questions, guiding the methodology, and interpreting the findings.

The assumptions underlying this research emerged even before the study began, and these assumptions were the primary reasons for choosing and conducting this research. These assumptions were that fusion energy will offer substantial environmental benefits. Unlike fossil fuels and or other pollutants that contribute to climate change. Additionally, that fusion is significantly safer compared to nuclear fission. These environmental advantages are assumed to make fusion energy a more sustainable and attractive alternative to conventional energy sources. The study also assumes that global energy demand will continue to rise, driven by economic growth and population increases. The increasing global population will further require energy for transportation, heating, cooling, and various other needs. Given these trends, there is an urgent need for scalable, sustainable, and efficient energy sources.

By navigating under these assumptions, the study aims to provide a comprehensive and realistic analysis of the potential of fusion energy. These assumptions help create a structured framework within which the research can be conducted, allowing for a focused examination of the factors influencing the innovation and economic perspective of fusion energy.

A case study is an empirical inquiry that delves deeply into a contemporary phenomenon within its real-life context. This method is particularly useful when the boundaries between the phenomenon and its context are not distinct. The ITER project, involves various technological, economic, and strategic dimensions, making it an ideal subject for a case study approach. The process begins with formulating a research question, such as exploring the technological advancements and economic implications of the ITER project. Data sources are chosen strategically to provide comprehensive insights about the case study. For ITER, this includes official reports, scientific articles, and relevant documentation from similar projects like JET and NIF. Secondary data sources are predominant in this case study, such as peer-reviewed journals, official reports, and project documentation are analysed. The diverse data collection, even though secondary data, the method ensures a robust analysis, allowing to triangulate data and validate findings through cross-verification.

An element of the case study is its reliance on multiple sources of evidence, enhancing the study and credibility of it. The ITER projects technological challenges and economic impacts can be understood by examining reports, comparing them with similar projects, and validating the findings with scientific literature. The case study uses triangulation analysis, where multiple data points are compared to ensure consistency and reliability. This approach helps to mitigate biases that might arise from relying on few or one single source. Triangulation in the ITER case involves comparing findings from different documents, reports, and scientific articles to ensure that explanation of the ITER case is clear.

A single-case design is particularly appropriate when the case represents a critical, extreme, or unique situation. ITER, being both a unique and highly ambitious project, fits these criteria well. The projects scale, international collaboration, and technological challenges provide data for an in depth analysis, offering insights that can inform future fusion energy projects. Eisenhardt (1989) suggests that having between four and ten cases is ideal for generalizing results. While ITER is a single-case study, it is supported by comparative analysis with other fusion projects like JET and NIF. This comparison helps identify common patterns and unique challenges, creating a basis to still being able to generalize the study.

The methodology also includes a detailed documentation of assumptions and a clear methodological framework, ensuring that other researchers can replicate the study. This transparency enhances the study reliability and validity, making the findings robust and credible. The case study method is an approach that uses data collection techniques and data analysis methods to investigate the complex issues of the ITER case in depth. The use of multiple data sources, triangulation, and a structured framework ensures that the findings are reliable, valid, and applicable to understand the ITER project in depth through the scope of innovation and economics.

3.2 Reliability

A fundamental question in research is the reliability of data, which refers to the dependability and accuracy of the data used. Reliability involves assessing how accurately data is collected, the types of data utilized, and how it is processed (Johannessen, Tufte, and Christoffersen, 2021).

Researchers can enhance reliability by providing a detailed context, often through a case study, and transparently documenting the entire research process. Implementing a review procedure to scrutinize documentation of data, methods, and decisions, including the results, further strengthens reliability. Emphasizing appropriate evaluation criteria also contributes to enhancing reliability and intersects with validity (Johannessen, Tufte, and Christoffersen, 2021). A triangulation strategy can yield a more robust understanding of the research and analysis. This method leverages the strengths of identifying empirical regularities and patterns, while also utilizing the advantages of case studies to reveal the causal mechanisms that produce the outcomes of interest (Moses and Knutsen, 2019).

The reliability of this case study of ITER is supported through a consistent research method across various data sources. By triangulating data from multiple documents, scientific articles, and project reports, the study mitigates potential biases and ensures a comprehensive and stable foundation for the analysis. The study employs a structured approach to document analysis, ensuring that each source is examined using the same criteria and methods, enhancing the reliability of the findings by applying similar procedures across all data points. Using a wide range of secondary data sources, including official ITER reports, scientific literature, and other scientific literature from projects like JET and NIF, the study ensures a broad perspective, which helps in cross-verifying information and reduces the risk of bias when using a few or one single source.

The reliance on well documented and reputable sources, such as peer-reviewed journals and official project documentation, contributes to the reliability of the ITER case study as these sources are generally recognized for their accuracy and thoroughness. Triangulating data from different sources allows for the validation of information through cross-verification, minimizing the influence of anomalies or inconsistencies in individual sources. While the study attempts to cover a comprehensive range of sources, the selection of documents and literature might still introduce bias, as chosen sources may not represent the full spectrum of available information, leading to an incomplete understanding of the complexity of the case.

The lack of primary data collection, such as direct observations or interviews with experts, limits the depth of insights and the ability to capture nuanced perspectives that scientific documents and reports may not reflect. Such a limitation is partially mitigated by the thorough analysis of secondary sources. While the study relies on the most recent available sources to maintain relevance, the dynamic nature of the ITER project could result in newer developments not being captured. The credibility of the sources used in this study, such as reputable scientific journals, enhances the reliability of the findings due to their rigorous review processes and accuracy that is cross- verified through several scientific papers.

The case study of ITER maintains a high level of reliability through a consistent methodological approach, triangulation of data, and the use of reputable sources.

3.2.1 Replicability

The first step in implementing the replication standard is to create a replication data set. Replication data sets include all information necessary to replicate empirical results. For quantitative researchers, these might include original data, specialized computer programs, sets of computer program recodes, extracts of existing publicly available data (or very clear directions for how to obtain the same ones you used), that describes what is included and explains how to reproduce the numerical results in the article (King, 1995).

Replicability, the ability for another researcher to duplicate the study under similar conditions and achieve comparable results, is crucial for validating research findings. In the context of this case study on the ITER project, several factors contribute to its replicability. The study employs a structured and transparent methodological framework, detailing the steps for data collection and analysis. This includes the systematic review of secondary data sources such as official reports, scientific articles, and project documentation. By outlining these procedures clearly, other researchers can follow the same steps to replicate the study.

The reliance on well-documented and accessible secondary sources enhances replicability. These sources, including peer-reviewed journals and official ITER project reports, are available to other researchers who wish to verify the findings or conduct a similar study. The use of reputable and stable sources ensures that the data used in the study is reliable and can be accessed consistently over time. The study employs consistent data collection procedures across different sources. This uniformity ensures that the data is gathered in a replicable manner, reducing the variability that could arise from using different methods or criteria.

By triangulating data from multiple sources, the study strengthens its findings and enhances replicability. Other researchers can use the same approach to cross-verify information from various documents and studies, ensuring that the conclusions drawn are robust and not dependent on a single source of data. The study clearly documents the assumptions made during the research process. This includes the selection criteria for documents and literature, the rationale behind the chosen methodologies, and the context in which the study was conducted. Providing this level of detail allows other researchers to understand the basis of the study and replicate it with similar assumptions.

By explicitly acknowledging the limitations of the study, such as the reliance on secondary data and the absence of primary data collection, the research provides a transparent account of potential constraints. This openness helps other researchers to account for these limitations in their replication efforts or to address them by incorporating additional data collection methods. The study includes comparative analysis with other fusion projects like JET and NIF, providing a broader context for the findings. This comparative approach can be replicated by future researchers to validate the results or to compare ITER's progress with other projects.

The study recognizes the dynamic nature of fusion technology and the potential for new developments. By specifying the timeframe of the data used, other researchers can replicate the study within the same period or update it with more recent data to see how findings might evolve over time. In summary, the replicability of this case study on the ITER project is supported by a clear and consistent methodological framework, well-documented data sources, and a transparent acknowledgment of limitations. These factors provide a solid foundation for other researchers to duplicate the study and validate its findings.

3.3 Validity

Validity says something about the credibility and relevance of data and is crucial for generalization. Statistical validity assesses if the sample is representative. In survey research, attrition is common, and researchers must address it when presenting results. They need to discuss whether the attrition rate is significant enough to weaken the study's statistical validity. For instance, if only 60 % of the initial sample remains, this threatens statistical validity. Assuming statistical validity is intact, the next question is about the external validity, or how well the results can be generalized across different contexts and times (Johannessen, Tufte, and Christoffersen, 2021).

Transferability or external validity assesses whether the results from one case study can be applied to another. Research should extend beyond simple data collection; the information must be systematized and analysed. This involves taking coded data out of its original context and reconstructing it to generate new, researcher-created insights about a phenomenon. This method results in a simplified yet typical representation of the original reality. Through this process, theories, concepts, and interpretations are developed to illuminate the studied phenomenon or phenomena (Johannessen, Tufte, and Christoffersen, 2021).

External validity refers to generalizability, or the extent to which findings from experiments conducted 'in the laboratory' can be applied to real-world settings. While internal validity is considered the crown jewel of experimentation, external validity is often seen as its Achilles' heel because it is more challenging to ensure that experimental results are applicable outside the controlled environment of the lab (Moses and Knutsen, 2019).

All research aims to extend conclusions beyond the immediate data collected. In representative quantitative studies, it's possible to statistically generalize findings from a sample to a population. For qualitative studies, the focus is on transferring knowledge rather than generalizing, since generalization typically refers to statistical methods used in quantitative research. Transferability applies to both qualitative and quantitative studies. In quantitative research, results can be applied to related phenomena, which is known as generalizability (Johannessen, Tufte, and Christoffersen, 2021).

Confirmability in qualitative research parallels objectivity in quantitative research, ensuring the research remains neutral and unbiased. To enhance confirmability, researchers should meticulously document every decision made throughout the research process, allowing readers to follow and evaluate these decisions. Additionally, confirmability can be further supported if researchers cross-check their interpretations with existing literature, ensuring their findings are consistent with or supported by other sources (Johannessen, Tufte, and Christoffersen, 2021).

Establishing causal relationships in the social sciences is challenging. Generally, it can only identify correlations between variables, infer the likely direction of these relationships, and suggest possible mechanisms linking the phenomena (Johannessen, Tufte, and Christoffersen, 2021).

A claim of causality between two phenomena is always a theoretical interpretation made by a researcher based on observed empirical relationships. Identifying the mechanisms behind the observed correlation is part of this theoretical work. The concept of internal validity refers to the extent to which we can demonstrate causal relationships. High internal validity means an experiment is conducted in a way that allows us to assert that an observed relationship between two variables likely involves a causal link (Johannessen, Tufte, and Christoffersen, 2021).

The validity of the ITER case study is carefully assessed to ensure its credibility and relevance. The study uses a broad range of secondary data sources, such as official reports, scientific articles, and other documentation, enhancing statistical validity by providing a comprehensive view of the project. However, relying solely on secondary data can lead to biases or gaps since it may not include the most recent developments or unpublished insights from ongoing research. External validity, or transferability, is supported through comparisons with other fusion projects like JET and NIF, allowing insights to potentially apply to similar large scale scientific projects like ITER. The international collaboration and advanced tokamak design of ITER may still limit the generalizability of findings to other projects with different operational frameworks, such as TAE Technologies which use a different approach to achieve fusion power, than ITER. Internal validity of the ITER is demonstrating causal relationships and are addressed by linking empirical data with theoretical frameworks. The study uses techniques such as triangulation, pattern matching, and explanation building to establish robust connections between data and broader theoretical propositions. However, the absence of primary data collection, such as direct observations or expert interviews, limits the depth of the case study.

Confirmability, which parallels objectivity in quantitative research, is ensured by meticulously documenting all decisions and processes throughout the research. Cross-checking interpretations with existing literature reinforce the neutrality and unbiased nature of the findings, allowing for transparency and replicability.

The reliance on secondary data might not capture the latest developments or nuanced insights, potentially leading to an incomplete or biased analysis. The unique characteristics of ITER may not be fully applicable to other fusion projects, affecting the generalizability of the case study. Furthermore, external factors like geopolitical and economic changes can influence the projects trajectory, which static documents may not adequately capture.

3.4 Limitations

The thesis study predominantly uses secondary data sources such as official reports, scientific articles, and project documentation, which may not capture the most recent developments or unpublished insights from ongoing research. Secondary data can vary in quality and consistency, potentially leading to biases or gaps in the analysis. The selection of documents and literature might introduce bias, as chosen sources may not represent the full spectrum of available information, resulting in an incomplete understanding of the projects complexities.

The absence of primary data collection, such as direct observations or interviews with experts in the field, limits the depth of insights and the ability to capture nuanced perspectives. Although expert interviews and direct observations could also lead to bias. Documents and reports are static and may not reflect the dynamic and evolving nature of the ITER project, leading to outdated information being used in the analysis. The case study is context-specific, which could make it difficult to generalize findings to other nuclear fusion projects, as the unique characteristics of ITER may not be applicable to different settings.

The timeframe of this thesis may indeed have limited the ability to capture long term developments and outcomes, affecting the comprehensiveness of the analysis. Additionally, external factors such as geopolitical shifts and economic changes can influence the projects trajectory, which may not be adequately captured through static documents and literature reviews. Acknowledging these methodological limitations provides a realistic perspective on the findings and their implications for the future of fusion energy research.

4 Analysis

The drive to harness fusion power, which could potentially provide limitless and clean energy globally, has been a major focus of scientific research since the 1960s. Given the global increase in energy consumption and the urgent need for sustainable energy solutions, understanding how innovations in fusion technology impact economic investments, is the focus of this research. This analysis examines the state of fusion technology, particularly tokamak reactors, and how advancements influence economic investments.

Fusion power, which replicates the suns energy process, offers significant advantages: it uses abundant fuel (hydrogen), produces minimal long-lived radioactive waste, and emits no greenhouse gases. However, achieving and sustaining the extreme conditions necessary for fusion, especially high enough temperatures as well as the magnetic field is technologically challenging. Tokamaks are leading in fusion research due to their potential to achieve these conditions. Tokamaks confine plasma using magnetic fields in a toroidal shape, which has shown the most promise for achieving sustained fusion reactions. ITER is the most ambitious fusion project to date, involving 35 nations and aiming to demonstrate the feasibility of fusion as a large-scale energy source. Key innovations in ITER include superconducting magnets, plasma heating and control, and tritium breeding. ITERs central solenoid will be the largest ever built, producing a magnetic field of 13 tesla, critical for plasma confinement. ITER aims to sustain plasma with a thermal output of 500 MW for at least 400 seconds, with advanced heating methods including microwave and particle beam injection. Developing materials and methods to breed tritium from lithium within the reactor to ensure a sustainable fuel supply is also a crucial innovation.

Analysing the ITER case study requires an in-depth examination of the projects various dimensions, including its scope, technological advancements, challenges, and implications. ITER exemplifies a significant global collaboration to tackle pressing energy challenges. This analysis will go in depth of ITERs research objectives, technological innovations, financial structure, stakeholder involvement, and strategic importance, providing an understanding of the projects role in advancing global fusion energy research and development.

ITER aims to demonstrate the feasibility of nuclear fusion as a large-scale, carbon-free energy source by achieving and sustaining a fusion reaction to generate more output of energy than the input of fuel. This fusion reaction is known as burning plasma. This involves creating conditions where the energy produced by the fusion reactions is sufficient to maintain the plasmas temperature and reducing or eliminating the need for external heating. The fusion process in ITER relies on the deuterium-tritium (D-T) reaction, which is the most efficient fusion reaction for energy production. In this reaction, deuterium and tritium nuclei fuse to form a helium nucleus, known as an alpha particle, and a neutron, releasing a substantial amount of energy. The energy generated from the fusion reaction is primarily carried by the neutron which releases 80 % of its energy. To achieve a sustaining fusion reaction requires maintaining the plasma at extremely high temperatures, exceeding 100 million degrees celsius. This is achieved using a device known as a tokamak, a doughnut-shaped magnetic confinement device. The tokamak design involves several critical components: the toroidal magnetic field, generated by superconducting magnets, confines the plasma in a circular path; the poloidal field, created by external coils and the plasma current itself, stabilizes and shapes the plasma within the vessel. Together, these fields form a helical structure that effectively confines the hot plasma, preventing it from contacting the reactor walls.

One of ITERs objectives is to understand the behaviour of burning plasmas. This involves studying how the plasma can maintains its temperature through the energy produced by the fusion reactions. By achieving and sustaining a burning plasma, ITER aims to demonstrate that fusion can be a practical and sustainable energy source. In addition to its primary goal of achieving a burning plasma, ITER aims to test and validate a range of technologies essential for future fusion power plants, such as superconducting magnets. Superconducting magnets are a component of the tokamak design. These magnets generate the strong magnetic fields needed to confine the plasma and maintain its stability. ITER uses advanced superconducting materials that can carry high currents with minimal resistance, allowing for the creation of the necessary magnetic fields. The development and testing of these superconducting magnets are important for the future innovation of the technology that can enable it to ensure the reactors viability and success.

Tritium breeding systems are another essential technology being tested in ITER. Tritium, one of the fuels used in the fusion reaction, is a rare and radioactive isotope of hydrogen that must be produced within the reactor. Tritium breeding systems use lithium to produce tritium through a nuclear reaction with the neutrons generated by the fusion reaction. Remote maintenance systems are also being developed and tested in ITER. These systems enable the safe and efficient upkeep of the reactors components, which are exposed to intense radiation and high temperatures. Remote maintenance technologies include robotic systems and advanced tools that can operate in the harsh environment of the reactor. By developing efficient tritium breeding systems, ITER aims to ensure a sustainable fuel supply for future fusion reactors, while addressing and containing the barrier of the radiation that the tritium carries.

Innovation of the technological challenges of achieving and maintaining a burning plasma, is a significant step towards achieving fusion power. Such innovation could not only ensure the success of the ITER project but also offer essential insights and practical experience for future fusion reactors with other, perhaps even more efficient technology. Through the development and rigorous testing of these innovative technologies, ITER aims to validate fusion as a viable, sustainable energy source. The knowledge gained from ITER will significantly contribute to the global pursuit of efficient and long-lasting fusion energy solutions.

Nuclear fusion occurs when two light atomic nuclei combine to form a heavier nucleus, releasing energy. This requires extremely high temperatures and pressures to overcome the electrostatic repulsion between the positively charged nuclei. In ITER, these conditions are achieved using a tokamak, a doughnut shaped magnetic confinement device. The tokamak design includes several components the toroidal magnetic field, generated by superconducting magnets, confines the plasma in a circular path, the poloidal field, which is created by external coils and the plasma current itself. This stabilizes and shapes the plasma within the vessel. Together, these fields form a helical structure that effectively confines the hot plasma, keeping it away from the reactor walls. Achieving and maintaining these extreme conditions pose significant technological challenges. As already mentioned, the plasma must be heated to temperatures exceeding 100 million degrees celsius. Advances in materials science are important to develop components that can endure these harsh conditions. ITERs technological innovation, such as the use of advanced superconducting magnets are essential for addressing this challenge and ensuring the reactors viability.

The financial aspects of the ITER project requires an understanding of its funding structure and economic implications. The estimated cost of ITER stands at approximately $21 billion, reflecting its status as one of the largest scientific projects globally. This immense financial commitment underscores the global importance placed on developing fusion energy as a sustainable and potentially limitless energy source. The funding for ITER is provided by its seven members: the European Union, China, India, Japan, Russia, South Korea, and the United States. The European Union, as the host of the ITER site in Cadarache, France, contributes 45 % of the total cost. The remaining 55 % is shared equally among the other six members, each contributing approximately 9 %. This funding model exemplifies a significant international collaboration, highlighting the shared commitment to advancing fusion research. Furthermore, the financial contributions cover various aspects of the project, including the construction of the reactor, the development and testing of new technologies, operational costs, and the salaries of thousands of engineers, scientists, and support staff involved in the project. The financial structure ensures a steady flow of resources, enabling continuous progress of technological innovation and addressing the current and future challenges.

A critical aspect of fusion energys future is its cost competitiveness with other energy sources. Projections indicate that fusion-generated electricity could be cost-competitive by the mid-21st century. This potential competitiveness is partly due to the stable and minimal fuel costs of fusion, as small amounts of fusion fuel yield substantial energy outputs. The primary costs for fusion energy are associated with the initial capital investment for building the power plants and the maintenance of complex plasma confinement systems.

Despite these initial costs, the long-term economic benefits of fusion energy are highly compelling. Fusion power promises low operating costs and significant contributions to global decarbonization efforts, making it an attractive investment for the future. The potential for providing a reliable, clean, and virtually limitless energy supply has driven significant global investments from among others; the European Union, China, and the United States. These investments aim to develop the necessary technologies, infrastructure, and regulatory frameworks to make fusion a viable and sustainable energy source.

The potential economic benefits of the innovation that drives ITER and fusion energy on its future path are substantial. Fusion energy promises a potential limitless supply of clean energy, which could significantly reduce dependence on fossil fuels and help mitigate climate change. The economic implications extend beyond energy production to include job creation, technological innovation, and the development of new industries. The innovation and technology developed through ITER could also have the potential to affect other sectors, driving economic growth and enhancing global competitiveness.

Stakeholder involvement in ITER is another critical aspect of its financial analysis. Participating nations provide the necessary funding and political support, while research institutions contribute scientific expertise and technological development. Private investors and companies are increasingly playing a vital role, leveraging PPPs to accelerate technological innovation and commercialization. These partnerships enable the sharing of financial risks and rewards, making fusion research more attractive to private investors. The strategic importance of ITER extends beyond its immediate scientific and technological goals. The project represents a step toward addressing global energy challenges, such as reducing carbon emissions and meeting the future demand for energy which is expected to increase by 34 % by the year 2050. Fusion energy, with its potential for continuous energy production and minimal environmental impact, aligns with global efforts to transition to sustainable energy systems.

Recent technological breakthroughs in fusion research have bolstered economic investments in this field. The JET achieved a significant milestone in February 2024, producing 69 megajoules of energy over five seconds with only 0.2 milligrams of fuel. Such achievements enhance confidence in the feasibility and efficiency of fusion power, encouraging further financial support from both public and private sectors. Achieving high availability and operational efficiency remains a significant challenge for the economic viability of fusion power. Innovations in material science, plasma control, and energy extraction methods are essential for addressing these challenges. Additionally, adopting other systems engineering approaches should be conducted for the successful advancements and deployment of fusion power plants. Despite the promising developments, several barriers must be addressed to realize the full potential of fusion power. High initial costs and long development timelines are significant challenges. The cost of constructing and maintaining fusion reactors is substantial, and the extended period required to achieve commercial viability necessitates sustained funding and investor patience. Geopolitical factors and economic changes can also impact international collaborations and funding commitments. On the other hand, there are significant opportunities within the fusion energy sector.

To conducting a case study approach for an in-depth analysis of the ITER project, various sources have been used to gather comprehensive information about progress and breakthroughs, as well as barriers and opportunities to conduct a case study analysis. Project reports, official documents and scientific research papers is a primary source of the case study. Scientific publications and research papers authored by scientists and engineers working on ITER provide analyses and findings from experimental work and theoretical studies. These peer-reviewed papers give an understanding of the technical challenges and innovations associated with ITER. The scientific publications provide detailed explanations of experiments and results, which contribute to a better understanding of the specific scientific challenges and breakthroughs. Technical documents, including design specifications, gives insight to the technological innovations and engineering solutions implemented in ITER, such as tokamak. Technical documents refer here to the description of the tokamak design, including the functionality of superconducting magnets, tritium breeding systems, and other critical components. It provides insights into the engineering principles and technical challenges that must be addressed to achieve a successful fusion reaction. Triangulation analysis of the data to cross-verifying information from multiple sources assures the reliability and validity of the findings. This process confirms the accuracy and consistency of the collected data, mitigating biases and providing a robust analysis. Triangulating data from different types of sources, such as financial records, project reports, and scientific publications, ensures a comprehensive understanding of the ITER project.

Comparative data from previous case studies of similar projects, such as JET and NIF, inform the analysis and provide a broader context for understanding ITERs contributions. Quantitative data on project costs, funding allocations, and energy output projections support the analysis and help evaluate the projects potential economic benefits. Comparing ITER with other major fusion projects who have had recent technological breakthroughs, like the JET and the NIF, will provide valuable insights into the unique contributions and innovation. The JET, which is in the UK, has been operational since 1983 and is the largest and most powerful tokamak currently in use. It has been instrumental in advancing our understanding of plasma behaviour and testing fusion technologies, such as remote handling and advanced plasma heating techniques. NIF, based in the United States, takes a different approach by using inertial confinement fusion. This method involves compressing a small pellet of fusion fuel using powerful lasers to achieve the conditions necessary for fusion. While NIF has achieved significant milestones, such as the first demonstration of fusion ignition in a laboratory setting, its approach differs fundamentally from the magnetic confinement fusion used in ITER and JET. By building on the knowledge and experience gained from JET and NIF, ITER aims to address the remaining scientific and technical challenges to make fusion a sustainable energy source. The advancements made by these projects have provided a solid foundation for ITER and other fusion projects.

The analysis provides a thorough understanding of ITERs scope, challenges, and implications. Furthermore, the analysis highlights the projects significance in the context of global fusion energy research and development, demonstrating its potential to revolutionize the energy sector and contribute to a sustainable future. The case study of ITER highlights its significant role in global fusion energy research and development. ITER has the potential to contribute to a cleaner and more sustainable future by demonstrating the feasibility of fusion power as a practical and scalable energy source. With increased future funding, ITERs progress could be accelerated, enabling the timely achievement of its goals focusing on innovation and technological advancements. This enhanced financial support would not only mitigate some of the projects current challenges but also facilitate the development of the necessary infrastructure and materials, ultimately ensuring the success of ITER in revolutionizing the global energy sector.

5 Discussion

The thesis began with specific assumptions about innovation and fusion power, aiming to explore the environmental and social benefits of fusion energy alongside the dynamics of global energy demand. The assumptions have been leading the way from the beginning to define the research and approach, as well as developing the research question for the thesis and the methodological approach. The assumptions have also been inductive to the research findings from the beginning.

The first assumption was that fusion energy would provide substantial environmental benefits, distinguishing it from fossil fuels and other pollutants that exacerbate climate change. This assumption was based on the premise that fusion energy could produce potentially limitless of clean energy globally. The second assumption was that fusion energy would be significantly safer compared to nuclear fission, presenting a more sustainable and attractive alternative to conventional energy sources. The last assumption was that global energy demand would continue to rise, driven by economic growth and population increases. The increasing global population necessitates more energy for transportation, heating, cooling, and various other needs, highlighting an urgent need for a sustainable and efficient energy source.

As the research progressed, it became apparent that verifying these assumptions within the available time and resources was more complex than initially anticipated. Addressing these broad assumptions in detail required a more extensive investigation than initially planned. This realization led to several significant adjustments to the research. The focus and research questions were refined and adjusted to align with what was possible given the time constraints, resources, and accessible sources. Given the practical constraints, the research questions and assumptions were slightly modified to focus on more specific and manageable aspects of fusion energy, delineating the theme by a lot. While the broad environmental benefits of fusion energy were initially assumed, the research homed in on specific technological innovations and their economic implications. This shift allowed for a more focused and in-depth examination of the factors influencing the innovation and economic viability of fusion energy, particularly through the case study of the ITER project.

The revisions to the research assumptions did not diminish the core of the studys objective: providing a detailed examination of the potential of fusion energy. The revised assumptions continued to provide a structured framework for the research. For instance, instead of broadly assuming environmental benefits, the study focused on how specific technological advancements, such as tokamaks and the breakthroughs in its field. Despite the need to adapt the assumptions and research questions, the study remained committed to its initial goals. By maintaining a structured framework based on revised assumptions, the research could realistically address the potential of fusion energy within the constraints of available resources. This approach ensured a comprehensive and realistic analysis of the potential of fusion energy, considering the technological innovations and economic investments associated with projects like ITER.

The assumptions underlying this research were the motivation in establishing the foundational perspective of the study. By navigating these assumptions, the study aimed to provide a realistic analysis of fusion energys potential. These assumptions helped to create a structured framework that allowed for a focused examination of the technological advancements and economic investments associated with fusion energy. They also facilitated a clear understanding of how innovations in fusion technology, particularly within projects like ITER, influence economic investments and the future of global energy supply.

The initial assumptions provided a necessary starting point for the thesis, guiding the research direction and shaping the methodology. However, the need to adapt these assumptions to fit within practical constraints led to a more targeted and manageable research focus. This adaptation ensured that the thesis could realistically address the research questions, providing valuable insights into the role of fusion energy innovations in shaping economic investments and future energy solutions. By focusing on specific aspects of fusion technology and their economic implications, the research could offer a detailed and practical analysis, contributing to the broader understanding of fusion energy's potential and challenges.

As the research in the thesis came along, it was evident that to adjust the assumptions of the initial motivation behind the study, a case study on ITER as the research method would offers a comprehensive way to explore the advancements in fusion technology and their economic implications. This method still aligns the overall assumptions the thesis started off with. This approach was good to understand the complex nature of large-scale scientific projects like ITER. The complex nature of ITER gave the insight into fusion power as the motivation initially also was for the thesis. The case study allowed for going in depth of the ITER, providing a deep understanding of the subject. ITER, being the most ambitious and advanced fusion project to date, serves as an ideal case to explore the intricate technological, economic, and collaborative aspects of fusion energy development. The case study method is particularly effective for studying contemporary phenomena within their real life contexts. ITER involves cutting edge technology, international collaboration, and substantial economic investments, making it a rich context for examining the impact of technological innovations on economic investments. The method is suitable for exploring complex interactions between multiple variables. ITERs development involves technological innovations, financial commitments, international politics, and scientific research, all interacting in intricate ways that a case study can effectively unravel.

The case study focuses on technological advancements within ITER, mainly the tokamak, but also studies other technological advancements, such as a tritium breeding system. These innovations are very important for achieving and sustaining fusion reactions and are central to understanding the project's potential and challenges. By examining ITERs funding structure, costs, and financial contributions from participating nations, the case study sheds light on the economic investments required for fusion research. This analysis includes exploring how technological breakthroughs can attract further investment and reduce long-term costs. Furthermore, this thesis investigates the roles of various stakeholders, including governments, research institutions, and private investors. Understanding these roles to see how collaborative efforts and financial commitments drive the project forward. Comparing ITER with other major fusion projects, such as JET and NIF, provides valuable insights into the unique contributions and innovations of each project.

The case study draws on various sources of data, including project reports, official documents, scientific publications, and financial records. This multi-source approach ensures a comprehensive understanding of ITERs progress, technological breakthroughs, and economic implications. To enhance the reliability and validity of the findings, the study employs triangulation by cross-verifying information from multiple sources. This process mitigates biases and provides a robust analysis, ensuring that the conclusions drawn are well-supported by evidence.

The case study incorporates both qualitative and quantitative data. Qualitative data, such as insights from scientific publications, provide in-depth understanding, while quantitative data, such as project costs and energy output projections, support the analysis with some indirect concrete figures to think about. Given the long-term nature of ITER and fusion research, the case study adopts a perspective to examine how technological and economic aspects evolve over time. This approach gained insight to understand the projects ongoing developments and most important, the future potential of ITER and fusion power.

Initially, the study faced challenges due to the broad scope and complexity of verifying all assumptions within the available time and resources. To address this, the research focus was narrowed to specific technological innovations and their economic implications, making the study more manageable. The evolving nature of scientific research and technological development means that new data and findings continuously as this thesis clearly prove by highlighting recent breakthroughs and recently published scientific papers on fusion power. The case study method allowed for some flexibility, accommodating new information and adjusting the analysis as the thesis progressed.

6 Conclusion

The research undertaken in this thesis aimed to address the question: How has innovation in fusion technology affected the economic investments within fusion power? Through an in-depth case study of the ITER project and an examination of secondary data sources, it is evident that technological innovations in fusion have significantly influenced economic investments in several profound ways.

The advancements in fusion technology, particularly those demonstrated by ITER, have substantially boosted investor confidence. Innovations such as superconducting magnets, advanced plasma heating methods, and tritium breeding systems have showcased the practical feasibility and potential of fusion energy. These technological breakthroughs have attracted substantial financial commitments from an international consortium of stakeholders, including governments, research institutions, and private investors. The demonstration of sustained plasma confinement and the development of materials capable of withstanding extreme conditions have shown tangible progress, making fusion power a more credible and attractive investment opportunity.

The high initial costs associated with fusion projects like ITER have been justified by the long-term promise of low operating costs and a sustainable energy supply. The economic rationale behind these investments is driven by the expectation that fusion energy, once operational, will offer a reliable and abundant source of energy with minimal environmental impact. This promise of a sustainable and cost-effective energy solution has prompted significant funding despite the substantial financial and temporal investments required upfront. Investors are motivated by the potential for a significant return on investment in the form of a stable, clean energy source that can meet the growing global demand. Furthermore, the international collaboration embodied by ITER has facilitated the sharing of financial risks and rewards, making fusion research a more attractive investment. The involvement of multiple countries and diverse stakeholders has not only spread the financial burden but also enriched the project with a variety of expertise and resources, accelerating technological progress and enhancing the project's credibility. This collaborative approach has enabled the pooling of knowledge and technological advancements from different parts of the world, creating a robust and diversified foundation for the project.

The case study of ITER reveals that the project's funding structure, involving significant contributions from the European Union, China, India, Japan, Russia, South Korea, and the United States, reflects a shared commitment to advancing fusion technology. The European Union, as the host of the ITER site, contributes 45 % of the total cost, while the remaining 55 % is shared equally among the other six members. This funding model not only underscores the global importance placed on developing fusion energy but also highlights the strategic economic investments made by these nations in pursuit of a common goal. Looking beyond ITER, future fusion systems will need to sustain continuous burning plasma operations for extended periods, efficiently convert fusion energy to electricity, and produce sufficient tritium to maintain its fuel supply. These advancements would be essential for developing practical and economically viable fusion power plants. The financial investments in ITER are laying the groundwork for these future systems, driving the innovation of the necessary technologies and infrastructure.

It is important to acknowledge the limitations highlighted by the research. The reliance of secondary sources, many of which reiterated the same information, poses challenges in capturing the most recent developments and diverse perspectives. This limitation suggests a need for ongoing research that incorporates a broader array of data, including primary sources, to fully understand the dynamic and evolving nature of fusion technology and its economic implications. The static nature of documents and reports may not adequately reflect the latest breakthroughs or shifts in research focus, potentially leading to an incomplete analysis.

In addition, the absence of primary data collection, such as direct observations or interviews with experts in the field, limits the depth of insights and the ability to capture nuanced perspectives. Expert interviews and direct observations could provide real-time insights and updates that are not available in published reports. Although primary data collection methods can also introduce bias, they offer a level of detail that secondary documentation cannot provide.

The specific nature of the ITER case study also presents challenges in generalizing the findings to other nuclear fusion projects. Each fusion project operates under different conditions, with varying levels of funding, technological approaches, and political support. Therefore, conclusions drawn from the ITER case study may not hold for other projects, limiting the broader applicability of the research.

In conclusion, innovations in fusion technology have played a pivotal role in shaping economic investments within fusion power. These technological advancements have not only demonstrated the potential of fusion energy but have also driven substantial financial commitments by promising a sustainable and cost-effective energy future. The collaborative and international nature of projects like ITER further underscores the global importance placed on advancing fusion research, making it a key area of focus for future energy solutions. While challenges remain, particularly in capturing the latest developments and diverse viewpoints, the overall impact of technological innovation on economic investments in fusion power is both significant and promising. The continued advancement of fusion technology and the ongoing international collaboration and investment in projects like ITER are crucial for realizing the full potential of fusion energy as a cornerstone of global energy sustainability.

7 Recommendations

Originating from the claims of 'cold fusion,' research at the nanotechnology level continues to explore low-energy nuclear reactions (LENR). These reactions appear to utilize weak nuclear interactions, as opposed to the strong force used in nuclear fission or fusion, to produce low-energy neutrons. These neutrons are then captured, resulting in isotopic change or transmutation without the emission of strong prompt radiation. LENR experiments typically involve the permeation of hydrogen or deuterium through a catalytic layer and its reaction with a metal. Researchers have reported energy release, but on any reproducible basis, the output is only slightly more than the input. A notable practical example is the reaction between hydrogen and nickel powder, which generates more heat than can be explained by chemical reactions alone. The Japanese government is sponsoring LENR research, a nano-metal hydrogen energy project, through its New Energy and Industrial Technology Development Organization. Mitsubishi is also actively involved in this research (Prager, 2019). Furthermore, it is claimed that there is already developed 10 different methods to produce cold fusion reactions over the past 30 years of research (Mizuno and Rothwell, 2020).

Cold fusion remains an area of ongoing research. While this study does not involve this particular innovation, it is recommended for future research due to its potential promise. Cold fusion, if proven viable, could revolutionize energy production by offering a clean, abundant, and low-cost energy source. Exploring this field further could yield significant advancements and breakthroughs in fusion energy technology.

Another recommendation to future research is the hydrogen-boron reaction. Boron is an element that holds significant promise as a fuel for fusion power. It is non-radioactive and cannot be weaponized, making it an ideal candidate for global energy applications. Unlike uranium or plutonium used in nuclear fission, or tritium used in fusion (the D-T reaction), boron poses no risks. Laser boron fusion, specifically the fusion of hydrogen and boron can produce energy that is a million times denser than that derived from oil. The high energy density of boron fusion means that relatively small amounts of fuel can produce vast amounts of energy, which is a significant advantage for meeting the growing global energy demand (HB11 Energy n.d.).

Unlike other fusion reactions that produce a significant number of neutrons (which can activate surrounding materials and create radioactive waste), the hydrogen-boron fusion reaction produces virtually no neutrons. This characteristic dramatically reduces the production of long-lived radioactive waste, resulting in a much smaller environmental footprint compared to other energy sources such as gas, nuclear fission, solar, wind, or coal. The nature of hydrogen-boron fusion means that the primary reaction products are helium nuclei (alpha particles) and energy. Helium is a benign gas that does not pose any environmental hazards. This clean reaction minimizes the handling and disposal issues associated with radioactive waste, making hydrogen-boron fusion a more environmentally friendly option. Moreover, the reduced radioactive waste and absence of neutron radiation also simplify the reactor design and reduce the cost and complexity of shielding and safety systems (HB11 Energy n.d.).

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