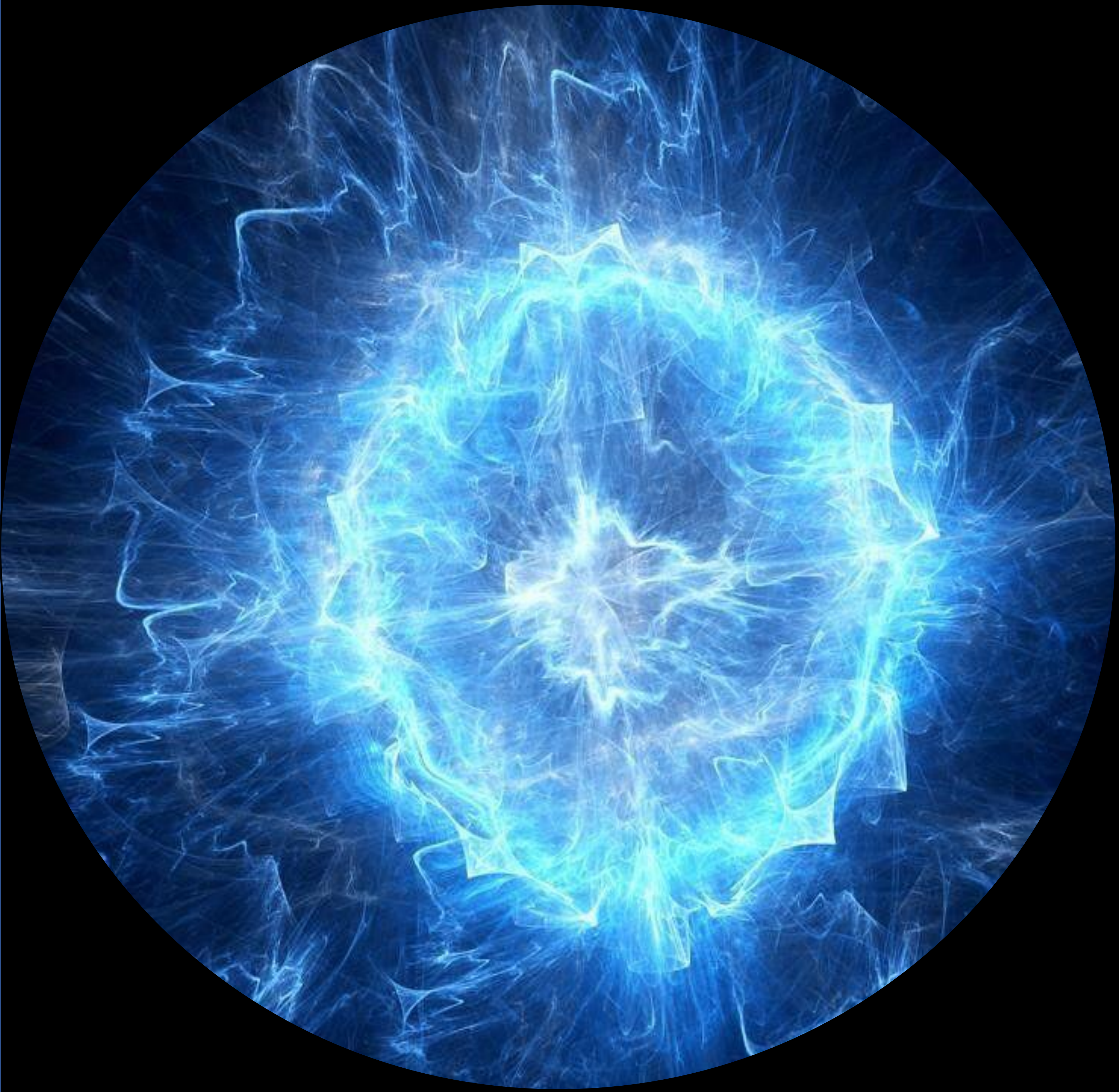
Understanding barriers towards the commercialization of nuclear fusion energy



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Understanding barriers to the commercialization of nuclear fusion energy

Master thesis submitted to Delft University of Technology for the completion of:

Master of Science in

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by

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“I would like nuclear fusion to become a practical power source. It would provide an inexhaustible supply of energy, without pollution or global warming”.

- Author: Stephen Hawking

Acknowledgements

In front of you is the results of six though months of work and dedication. A period in which I … but after many ups and downs I can wholeheartedly express that I am proud to present the result. If it was not for Emile and Pieter, the next 104 pages would have been on a completely different subject, but fortunately you gentlemen agreed to supervise me where the rest of the TPM department was very hesitant about supervising a sci-fi subject like fusion energy. Many thanks' gentlemen! I would like to thank Emile in particular for the constructive criticism and positivity at the moments when I experienced writing the thesis as more complex than nuclear fusion itself. You have a talent for inspiring people and keeping things simple.

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Executive summary

The urgency for decarbonization of the energy grid is ever increasing and fossil energy sources must be replaced by sustainable sources of energy to prevent detrimental levels of global warming. Renewable energy sources wind and solar show potential and contribute to decarbonization but are intermitted and require storage solutions that are exposed to further constrictions and costs. Nuclear fusion is regarded as the most promising new energy source since scientists first learned about it and in theory poses the ideal properties to meet the needs of the world's future energy system. Despite fusion's potential as the ideal energy source for innovating and decarbonizing the energy system, the reality is that 70 years of research and development have not yet resulted in fusion energy on the grid. Overpromises by fusion scientists since the seventies have resulted in scepticism and cynicism towards fusion development with the longstanding quip that "Fusion energy is thirty years away…and always will be". Nevertheless, 2021 saw many important breakthroughs and achievements in fusion research which resulted in it being titled "The best year in the history of fusion development" and led to revived optimism and claims that fusion development is moving from the lab to the grid and commercialization is closer than ever before.

In order to truly understand the process of commercializing fusion energy, the barriers need to be known and understood so that these can be addressed specifically, and the process can be accelerated. Adding to that is, that there are also numerous different technical approaches to fusion, each with their own characteristics. However, currently comprehensive knowledge of these barriers is missing. Information is highly scattered as it is focusses on specific topics of fusion development, mostly the scientific or technical barriers. Adding to that is that most information is on separate technologies or specific experiments. As a result, there is a severe lack of knowledge: it is unknown what all the barriers towards commercialization are, how these barriers differ in severity and how they differ amongst the numerous fusion technologies. In an attempt to tackle this knowledge gap and enable a better understanding of the fusion development, the objective of this research was to develop a comprehensive list of barriers and subsequently study and assess this list for the different approaches to fusion with the intention of increasing the understanding of the pathway for commercialization of fusion energy.

Before starting this endeavour, a conceptual analysis was performed to define the concepts "barrier" and "commercialization". Using these definitions an extensive literature study was performed, alongside 23 semi-structured interviews with almost all the leading fusion institutes and companies. Using predefined selection criteria to deal with the vast amounts of information, a list of fifteen relevant barriers was identified. The barriers described in literature were complemented and extended by empirical experiences and practical examples obtained in the interviews, resulting in a manageable but comprehensive list of fusion barriers towards commercialization, including several barriers that have received very little attention to date.

In an attempt to gain further insight into these barriers and research how these are different for the various approaches to fusion, a methodology was developed to assess the barriers in a standardized way. Based on the principles of the Y-factor method developed by (Chappin et al., 2020), a customized framework was developed for the commercialization of fusion energy technologies. Each barrier was concisely described and subsequently the identified barriers were organized into five categories: Technology, Operation, Cost & Financing, Governance and Engineering. The framework assesses the barriers on a tripartite scale, scoring a value of 0 indicating no barrier, 1; indicating a potential barrier and 2; indicating a significant barrier. For every barrier the scoring criteria were detailed to allow for accurate scoring.

The five most developed and pursued technical approaches to fusion (Tokamak, Spherical Tokamak, Stellarator, Field Reversed Configuration and Inertial Confinement Fusion) were assessed using the designed framework. This was done by three sperate expert interviews. These respondents were selected because they all had high expertise of both fusion energy and experience within the fusion industry and hence contribute to the validity of the research. Analysis of the results lead to numerous interesting findings

- **Barriers generally apply to all technologies**: Although the difference between the fusion technologies were identified and acknowledged by the various respondents, this did not result in notable differences in the scoring of these technologies. Instead, most barriers apply in a similar severity for all technologies.

- **Experts disagree on fundamental barriers**: Two of the respondents disagreed strongly on the scoring of several barriers, such as “Plasma physics”, “Radiation shielding” and “Energy production”. The fact that these respondents both have a PHD in plasma physics, demonstrates the uncertainty of fusion development and underlines the complexity and difficulty of predicting the pathway of fusion technologies. In this particular case the differences mostly originated from the reasoning of the respondents; one argued more from a theoretical point of view while the other purely looked at results to date, exposing that the framework can be interpreted differently by different respondents.

- **Barriers have a strong time element**: The abovementioned disagreements can be partially explained by time. The application of the framework exposed that nearly all barriers are characterized by a strong time dependency and that the barrier value is heavily dependent on the timeframe it is evaluated in. Fusion technology is still under development and while an active effort was made to describe the scoring criteria as closely as possible during the synthesis of the framework, the time dependency and the interpretability that comes with it could not be eliminated

- **Hierarchy within barriers**: The application of the framework also exposed a certain degree of hierarchy within the barriers and found that there was an order of urgency within the barrier categories. A clear and logical pathway could be observed; firstly the “Technology” barriers must be resolved, afterwards the category of “Operation” barriers become most urgent and finally the “Engineering” category. This was substantiated by the scores as these categories received the highest scores. The remaining categories “Governance” and “Cost & Financing” are present throughout the entire innovation pathway.

All in all, the research has three main contributions. The first contribution is the identification of a comprehensive list of fifteen barriers that is validated by experts, can be used to assess all fusion technologies and captures the complete commercialization pathway. Secondly, the developed framework is the first tool that can be used to uniformly assess these barriers and compare them amongst different technologies. Finally, application of the framework increased understanding of the time-dependency and hierarchy of the barriers. Despite the limited value of the quantitative output, the qualitative findings have certainly increased understanding of the barriers and complexity of fusion energy development and showed that the use of the method can enable insightful discussions.

It should be noted that in spite of continuous attempts at safeguarding the validity of the research, there are a number of limitations that should be taken into account when interpreting the research and its results. The development of the scoring criteria is subjective and can be interpreted differently by different respondents, despite the effort to formulate these with a high accuracy and clarity. Simultaneously, because the barrier definitions and scoring criteria are newly designed, these are also constrained by the perception and interpretation of the researcher. Lastly it is important to note that the application of the designed framework was limited to only 3 respondents and the outcomes are therefore based on a small sample size. The overall results of applying and scoring the framework is greatly determined by the individual views and can’t be generalized.

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1. Research introduction

1.1. Introduction

The world is facing the twin challenges of rising energy demand and the threat from catastrophic climate change. In 2014 the Intergovernmental Panel on Climate Change (IPCC) published a concerning study that stated that the world's temperature rise should be limited to 1,5C to prevent a "climate catastrophe" (IPCC, 2014). As a result of this study, 193 countries signed the 2015 Paris Agreement (UNFCC, 2015), pledging to pursue measures to keep global warming to 1.5°C. Green House Gas (GHG) emissions should be drastically reduced to achieve this target and a significant share of these emissions can be contributed to the electricity production sector. In 2019, 40% of GHG emissions were caused by the combustion of fossil fuels for power generation (IEA, 2021). Hence, the transition from fossil fuels to clean and sustainable energy sources can make a significant and necessary impact.

No one energy technology can achieve this change and therefore a broad range of solutions are required. Amongst the most mature clean energy sources today are solar PV, wind and nuclear fission power. Both wind and solar are seeing massive global investment with more growth projected. But both have drawbacks; both are intermittent power sources that cannot be ideally deployed and lack an energy density to meet rising demand. The performance of solar and wind can be improved by applying adaptive and energy storage technologies but there are additional cost and constraints to this (reference). Fission power is a potentially good complement to renewables, but it comes with associated costs, waste concerns, weapons proliferation risk, and public anxiety.

Nuclear fusion, the process that drives the sun's energy production is regarded as the most promising new energy source since scientists first learned about it (Christy, 2021). Theoretically, nuclear fusion power has the ideal properties to meet the needs of the world's future energy system; the fuel is cheap and abundant and has the highest possible energy density, fusion reactions produce little and relatively harmless nuclear waste, and the technology is safe and can provide a stable baseload (Kikuchi et al., 2012). Despite fusion's potential as the ideal energy source for innovating and decarbonizing the energy system, the reality is that 70 years of research and development have not yet resulted in fusion energy on the grid and left many crucial challenges to be solved. Overpromises by fusion scientists since the seventies have resulted in scepticism and cynicism towards fusion development with the longstanding quip that "Fusion energy is thirty years away…and always will be" (Herrera-Velázquez, 2007). The reality is far more complicated, as fusion technology neither is a flawless energy source that can easily be developed, nor is a proven impossible endeavour.

Recent developments in the sector have certainly sparked hope of commercial fusion energy as 2021 was titled "The best year in the history of fusion" during the White House Fusion summit in March 2022. The event was co-organized by the White House Office of Science and Technology Policy (OSTP) and the U.S. Department of Energy (DOE) and was named "Developing a Bold Decadal Vision for Commercial Fusion Energy". It gathered fusion energy leaders from government, industry, academia, and other stakeholder groups to discuss the development of a new decadal strategy to accelerate the realization of commercial fusion energy. An updated strategy is necessary to adjust to changes in the fusion development landscape. The past few years have seen significant scientific breakthroughs that have resulted in an explosive growth of private companies pursuing fusion as the technology has come to a stage where it becomes commercially interesting for private capital to invest. July of this year, the Fusion Industry Association (FIA) published that private companies raised 2.8 billion in the past year and concluded that fusion is transitioning from the lab to commercialization.

1.2. Knowledge gap

Fusion power promises an abundant supply of dispatchable, clean and safe energy with low levels of nuclear waste and even though these benefits of commercially available fusion energy are very clear, many questions regarding how to guide the process towards commercially available fusion are still left unanswered. The difficulties in commercializing fusion energy were first articulated by Rockwood & Willke (1979) to the US department of energy. Their report described the concept of commercialization as "The entire process leading to the first full-scale plant and extends beyond this point to include the diffusion process by which the new product or process spreads from firm to firm within an entire industry" and described a number of barriers and success factors expected to impact this process.

Despite receiving attention more than forty years ago, problems towards fusion energy commercialization have received little attention since. The overwhelming majority of published fusion related literature is highly scientific or technical and mostly describe the results of particular experimental devices. Alternative studies focus specifically on a set of subproblems (financials, public acceptance etc), but are therefore rather one-dimensional. As a result, the information is highly scattered and generally very technology specific. Therefore, it is not possible to capture the complete status of the sector. A more holistic approach was attempted by Harz (2021) and (Pearson, 2020) who applied the PESTEL framework to fusion energy, but both failed to provide argumentations and perform an analysis, therefore the value of their contributions is limited. Additionally, PESTEL is a very general tool and too broad for the nuclear fusion sector that is unique and exceedingly complicated. A higher resolution is required to offer genuine insight.

Therefore, there is a significant knowledge gap; currently no comprehensive overview of the barriers towards commercial fusion energy exists and this results in limited understanding of the challenges on the pathway towards commercial fusion energy. Nor is it possible to compare the different technologies on the complete pathway towards commercialization, instead information is highly scattered and technology specific. Given the increasing urgency for sustainable energy, this is problematic. In order to steer and accelerate the development and realisation of commercial fusion energy a thorough understanding of the barrier is required.

1.3. Research objective and research questions

There is currently no comprehensive overview and understanding of the barriers towards fusion commercialization and the research goal is to fill this gap by providing knowledge on the relevant barriers towards commercial fusion. The objective is to develop a comprehensive list of barriers and subsequently study and assess this list for the different approaches to fusion with the intention of increasing the understanding of the pathway for commercialization of fusion energy.

Main research question:
To what extend does standardized assessment and comparison of the barriers towards commercial fusion energy technologies increase understanding of (how to accelerate) fusion energy development?

To guide the research towards answering this main research question three sub-questions have been drafted:

Sub research questions:
Sub question 1: What are the relevant barriers to commercial nuclear fusion energy?
Sub question 2: How can the identified barriers be uniformly assessed for different fusion technologies in a standardized manner?
Sub question 3: What insights are elicited from assessment of the barriers?

1.4. Trinomics BV

The research in this paper is performed alongside with Trinomics BV as part of one of their larger projects. Trinomics BV is a consultancy firm with a sustainable focus that operates in three branches: Energy, Environment and Climate and almost exclusively works for public institutions, mostly at European and national level. The majority of projects are policy related and the advice are intended for policy making.

This research is part of one of Trinomics' projects for the European Commission and is called: Foresight study on the worldwide developments in advancing fusion energy, including the small-scale private initiatives" intended to map the current state of the fusion industry and building future scenarios with policy advice. This study opens many doors in the fusion industry and offers a unique opportunity to execute the research proposed in this thesis.

1.5. Link to COSEM

The development of commercial nuclear fusion power can potentially shape our future energy system. If the challenges can be overcome and the technology is commercialized this could secure the supply of clean and sustainable energy for the future. The topic is therefore of great societal relevance, while the development contains both societal and technical factors. The objective of the thesis is to reduce complexity and deepen understanding of this innovative technology in a complex socio-technical environment. Hence it aligns very well with the Complex Systems Engineering and Management (CoSEM) master program.

1.6. Report outline

In total this thesis is composed of 7 different chapters that are schematically displayed in **Figure 1.** Report outline. This chapter has explained the reasons for undertaking the study and put forward the research objectives with a set of guiding research questions. Chapter 2 contains a comprehensive research approach and methodology that will be used to execute the research and is aimed at answering the research questions to fulfil the research objective posed in this chapter. Subsequently, Chapter 3 presents information on the different fusion approaches available and provides important information that is helpful in understanding the concepts encountered during the execution of the research. Chapter 4 identifies a detailed and extensive list of barriers, both from literature and interviews. This information is processed and developed into a framework in Chapter 5 and eventually applied in Chapter 6. The final chapter reflects on the obtained results and discusses the observations and usefulness of the study.

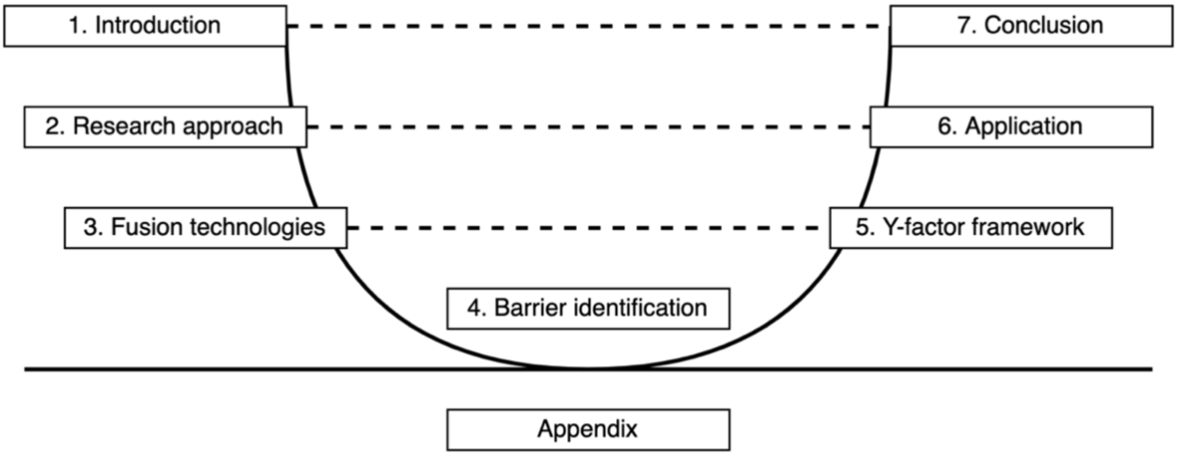


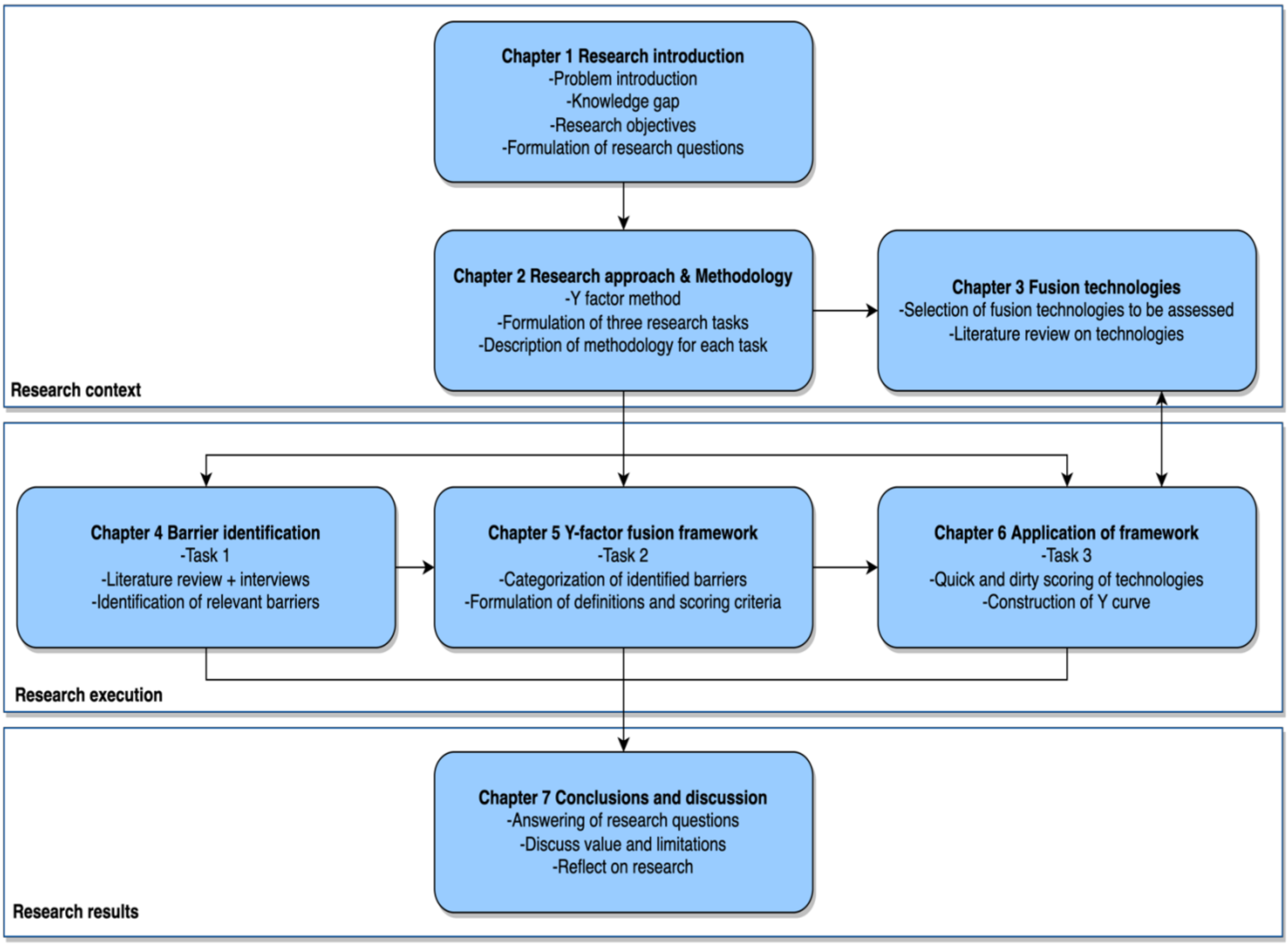
Figure 1. Report outline

1.7. Research Flow Diagram (RFD)

The RFD is complementary to the structure of the report outlined in 1.7. and displays the flow of information within this research. The figure is displayed in **Figure 2.** Research Flow Diagram At the top of the chart is this chapter, Chapter 1, that identifies the knowledge gap and formulates a number of research objectives with corresponding research questions. Indicated by the downward arrow the subsequent chapter is Chapter 2 that details the approach and methodology designed to fulfill the research objective and answer the research questions. Chapter 3 is a necessary information chapter that provided background that is required for the execution of the research and acquiring the results.

Chapter 2 is very strongly connected to Chapters 4-6 as it specifies the research tasks and methodology for executing these tasks. Chapters 4-6 are also interdependent as the outputs of Task 1 are used as inputs for Task 2. Subsequently Task 3 (Chapter 6) relies on the results of the preceding task and utilizes the information of Chapter 3. Finally, the last chapter (Chapter 7) reflects on the entire research, it answers the research questions formulated in Chapter 1, draws conclusions and reflects on the research process and approach.

Figure 2. Research Flow Diagram



2. Research approach & Methodology

This chapter is dedicated to explaining the research approach and methodology that are used to tackle the formulated research gap and answer the research questions. The explanation is rather comprehensive and extensive. The purpose of this study is to develop a new conceptual framework and therefore the methodology should be carefully explained and understandable.

2.1. Y-factor method

This section is dedicated to the explaining the Y-factor method that the research is based on. Firstly, the principles and original purpose of the method are explained, followed by a conceptual analysis on fusion commercialization that formulates the key definitions needed to adapt this method to be applied for fusion commercialization. The section concludes by positioning the work and formulating a number of design criteria.

2.1.1. Principles of the Y-factor method

The Y-factor method was first introduced by Chappin (2016) and designed to decompose the barriers of the various different climate abatement options to demonstrate 'why' implementation of certain technologies is hampered. The method makes use of twelve socio-technical factors that are evenly divided into four categories. These are: physical embeddedness, behavior, cost & financing and multi-actor complexities. The identified barriers are scored between 0 and 2, representing the degree to which a barrier is present for the technology. After scoring all the factors for each abatement option, the scores are summed and result in the final Y score that can be plotted on a graphical Y factor curve.

This systematic approach analyzes the technologies uniformly and demonstrates how technologies differ in their barriers. After its introduction by Chappin, the Y-factor method has been further researched and applied in a number of studies (Arensman, 2018; Arriaga, 2020; Cheung, 2018; Soana, 2018; Swart, 2019). The beauty of the Y factor is its ability to deepen understanding and compare vastly different technologies in a uniform manner and execution of this method will demonstrate how the total barrier is composed of different categories. Although it was originally developed for CO_2 abatement technologies, this research aims at using the same principles and apply them to the development of nuclear fusion technologies. There are however two inherent differences that should be considered and require the traditional Y-factor method to be transformed.

Firstly, the differences between different nuclear fusion technologies are significantly smaller than those between different CO_2 abatement options, e.g. Air transport and Residential appliances. This allows for more specific barriers Secondly, none of the fusion technologies are commercial yet, whereas the abatement options researched in previous Y factor studies are. The difference between commercialization and implementation seems subtle but is inherent. To adapt the Y method for understanding barriers to fusion energy commercialization requires a deep conceptual analysis.

2.1.2. Conceptual analysis

It is important to define what commercialization is and how this definition translates to the development of fusion energy. Moreover, it is essential to understand what implicit implications this definition imposes and how these implications result in explicit requirements. Once the explicit requirements are defined and formulated it is possible to study what factors form hurdles to the fulfillment of these requirements.

Defining commercialization

There are various different definitions for commercialization available that vary slightly in their focus. The majority of definitions tend to emphasize economic gains to be an important condition tied to commercialization. The Cambridge Dictionary defines commercialization as “the organization of something in a way intended to make a profit” whereas the Oxford Dictionary adds the negative sentiment “especially in a way that other people do not approve of”. These definitions are singular and don’t capture the greater picture. A better and more profound definition is formulated by the University of York. “Process of turning an idea into commercial products or services by commercially developing Intellectual Property (IP) that has been created through research, with the goal of creating successful commercial outcomes which have a positive impact on wider society”. This definition is chosen because besides the commercial gains, it recognizes that commercialization is a process that is based on novel research, and it includes that its outcomes must have a positive impact. Hence it is a more encapsulating definition.

Requirements and barriers

Despite being fairly extensive, the following section is intended to demonstrate the line of reasoning and does not encapsulate all requirements. The main takeaway is how a definition results in a set of subject related requirements and eventually barriers. Applying the aforementioned definition to fusion energy development raises two questions; i) Under what conditions is nuclear fusion energy a commercial product? and ii) when does it have a positive impact on society?

It is implicit that for an energy source to be commercial its production of energy must be profitable
-The energy production process must produce net positive energy. If the process requires more energy than it delivers than the process does not result in a product or service.
-The production cost of the energy must be lower than the price at which the energy can be sold.
-Enough of the product must be sold to recover fixed costs. This implicitly requires that there is enough demand, that the production and sale of the energy is legal and that it is possible to produce the needed quantity.

For an energy source to have a positive impact
-The product must be sold enough to make an impact. This requires fusion energy to be scalable
-The product must offer advantages -> should be cleaner, less intermittent and/or more responsive than the energy sources it replaces and it should be safe

Amongst others, the following requirements can be deducted from these questions.
In order to commercialize nuclear fusion energy technology, it must:
-Produce net positive energy
-Have a lower cost price than the price at which it can be sold (positive economic margin)
-Be legal
-Have the necessary social acceptance
-Adhere to safety standards
-Be possible to produce the needed quantities
-Be cleaner than competing energy sources
-Have better performance than competing energy sources on important energy system operating criteria (e.g., intermittency, availability, dispatchability, quick-response)
-Etcetera

These formulated requirements span across the technical, economic, institutional and social domains but all share the essence of the very definition of a requirement; they are necessary conditions that need to be fulfilled in order for fusion energy to commercialize. The aforementioned requirements are discrete and binary, they are either fulfilled or not. Let me demonstrate this by taking the positive profit margin requirement as an example. This is a discrete requirement. When there is a long-term negative profit margin, producing energy would result in a constant financial loss and therefore the technology would not be pursued or implemented. If the profit margin is positive, there could be other reasons that hamper the commercialization of fusion, but the requirement is fulfilled.

However, there are a number of factors that constitute to the fulfillment of a requirement. These are of a subordinate level to the requirement and are continuous instead of discrete. To exemplify this; the profit margin of fusion energy is composed of a number of determining factors e.g., fuel costs, the production efficiency, electricity price, the amount of subsidy, overhead etc. that are all continuous values and constitute to whether the requirement is fulfilled or not. As the goal is to accelerate the commercialization of fusion, the focus in this research is on identifying the factors that hinder this process. Therefore, the factors that hinder the fulfillment of a requirement are defined as barriers in this research.

Characteristics of a barrier:
1. Continuous value
2. Constitutes, but is subordinate, to requirements
3. Can be difficult to measure (level of governmental support, level of social acceptance)
4. Can change over time
5. Can differ in severity

Formulating a barrier like this means that by definition a barrier has a negative sentiment and is a problem that should be attended. The advantage of this formulation is that it is a conceptual description, and it allows a wide variety of highly different factors to be reviewed and classified as a barrier or not.

2.1.3. Positioning and previous work

This research will explore to what extent the elegant principles of the Y-factor method can be applied for other purposes outside the original intention of the Y-factor method. Thereby pushing the boundaries and potentially freeing the way for novel applications of said method. However, a number of caveats need to be considered in this process.

The Y-factor method was originally designed as an extension for McKinsey's Marginal Abatement Curve (MAC) and is intended for understanding the level of implementation of $C0_2$ abatement options; these technologies are fully developed and commercially available. These exact prerequisites are the challenges that fusion energy currently faces and therefore the original framework and its barrier categories does not apply. Another reason why the Y-factor needs altering is the difference in technologies that will be assessed by the framework. The beauty of the Y-factor is that it allows for the comparison of widely different technologies and given that the fusion development space is comprised of numerous different approaches, this is one of the features why the method was selected. However, the differences between the $C0_2$ abatement options are significantly larger than the difference between fusion approaches and therefore lower-level barriers are required to make the framework useful.

To deal with these implications and explore the possibilities of extending the Y-factor method to new applications, the decision is made to redesign the Y-factor method. This decision sets this research apart from previous research on the Y-factor method that all built on the barrier categories that were originally described by Chappin (2016), therefore deviating from its original research path. The schematic overview in **Figure 3.** Positioning to prior Y factor research displays the position of this research compared to that of previous Y-factor method studies.

Because the Y factor was designed for abatement options and further research has only focused on this original application, the exploration within this study is the first of its kind. Consequentially, no previous experience with- or methodology for altering the Y-factor method exists and this will need to be created.

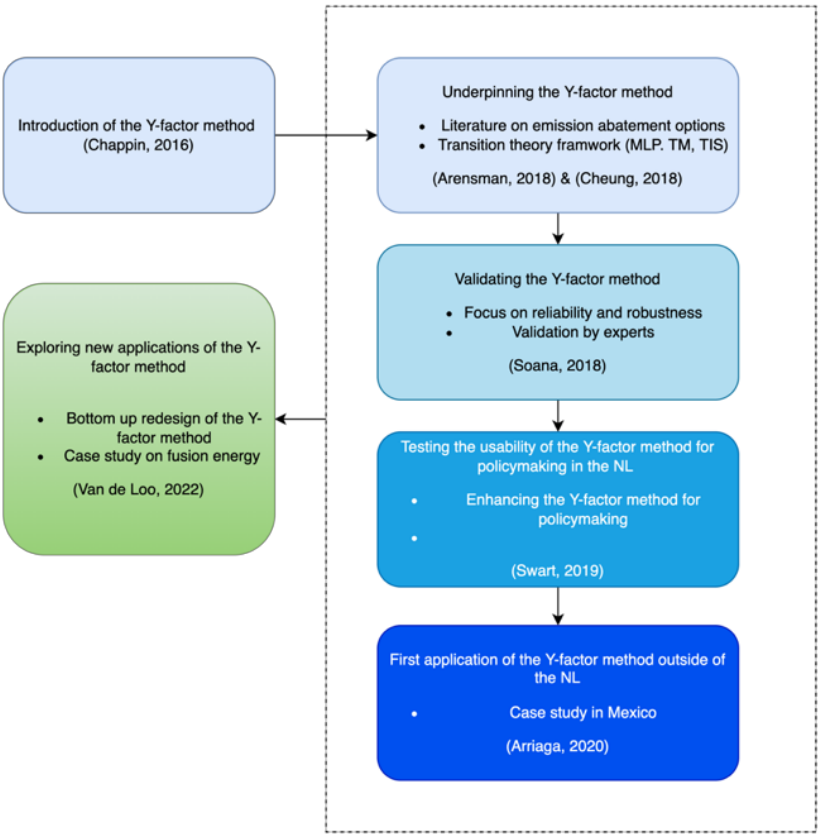


Figure 3. Positioning to prior Y factor research

The refined framework by Chappin et al. (2020) provides guidance for this task and is displayed in **Table 1.** Y-factor framework (Chappin, 2020)One of the findings of the study by Soana (2018) is that interviewed experts made suggestions for additional categories namely Governance, Regulation, and Emotional decision making, thereby implying that the number of categories could be extended if seen fit. The to be developed Y-factor method will contain a similar number of categories but will be kept manageable (max 6).

Category	Factor	Value 0	Value 1	Value 2
Cost and financing	Investment cost required	Absent	Medium	Large
	Expected pay-back time	< 5 years	5-12 years	>12 years
	Difficulty in financing investment	Low	Medium	Large
Multi-actor complexity	Dependence on other actors	None	Few	Many
	Diversity of actors involved	Low	Medium	Large
	Division of roles and responsibilities	Clear	Somewhat unclear	Unclear
Physical interdependences	Physical embeddedness	No	Medium	Strongly
	Disturbs regular operation	No	Slightly	Strongly
	Technology uncertainty	Fully proven	Small	Large
Behavior	Knowledge of actor	High	Low	Lacking
	Frequency of opportunity	Often	Medium	Rarely
	Change in behavior	No	Slight	Severe

Table 1. Y-factor framework (Chappin, 2020)

2.2. Task 1: Barrier identification

This section describes the methodology that is used to answer sub question 1:

What are the barriers to fusion commercialization?

The purpose of this task is to identify barriers for fusion commercialization, as formulated in Section 2.1. The methodology for this is twofold and consists of a literature study and an extensive number of interviews.

2.2.1. Literature selection and analysis

The initial step in this process is mapping the sources that will be used to gather this information. The list of literature to be studied must be of high quality and be relevant to the research. To ensure this, the following search strategy is used.

i) Published preferably after 2015. This is important because the information needs to be up to date and relevant for the state of today. Older articles can be selected if they fit the research objective really well.
ii) Preferably peer reviewed or cited by other papers.
iii) Contain “challenge”, “barrier”, “issues”, “complexity”, “problem” or “hurdle”.
iv) The gathered literature will be scanned and a manageable list of relevant articles is selected.

The subsequent step is extensive reading of the obtained literature to identify what concepts are used that could be classified as a barrier under the definition defined in Section 2.1.2. and develop a table that lists these identified concepts. Not only will these be used independently for the development of he Y-factor framework, these will also serve as inputs for the interviews.

2.2.2. Selection of initiatives to be interviewed

Because there are still a limited number of fusion initiatives around the world, a brief desk analysis of all programs was conducted, and nearly all initiatives were approached to partake in the study as part of the larger Trinomics study for the European Commission. The response rate was very high and the overwhelming majority of the fusion initiatives that were contacted were willing to partake in the study and generally very enthusiastic to discuss the developments in the fusion sector. Only a handful of initiatives did not respond to the invitation, mostly Russian and Chinese initiatives and that can be explained by the current political tensions between these countries and the West. The complete list of participating fusion initiatives is displayed in Appendix B and accumulates to a total of 23 interviews.

2.2.3. Interview format

The decision was made to also do interviews complementary to the literature review as they are expected to add much value. Interviews provide opportunities to ask questions about very specific issues and potentially identify barriers that are not included in literature. Furthermore, interviews may provide a more practical and detailed explanation of barriers experienced by the initiatives, demonstrated by examples.

This thesis was executed alongside Trinomics’ study for the European Commission (EC) called “Foresight study on the worldwide developments in advancing fusion energy”. The purpose of the study is to build future fusion development scenarios and advise the EC on what actions it can take to accelerate the development of fusion energy in Europe. To gather information for this task, a selection of 30 of the most promising public and private fusion initiatives are interviewed on their activities, mission and projections. The duration of these interviews is approximately 45 to 60 minutes, and the format is semi-structured. The full format is attached in Appendix C and varies slightly for public and private initiatives. In addition, ahead of the interviews a desk study was performed on the initiative to conform the interview questions to the progress of the interviewed initiative.

The guiding questions within this interview format that are of particular interest for barrier identification are listed below. It is important to notice that these questions are phrased as challenges, despite the focus of barrier identification. The reason for this is that the interview document had already been prepared in advance of this thesis and last-minute changes were not authorized.

1. Which milestones are being targeted **before 2030**?
2. What are the main challenges that need to be overcome to achieve these milestones?
    a. *What are the financial, technological, scientific, other challenge, and any strategies to overcome them?*
    b. *What is the status/how are you addressing issues around: i) heat shields, ii) power multiplication(Q)/pulse duration, iii) RAMI (reliability, availability, maintainability and inspect ability)? Iv) nuclear safety; v) materials (neutron exposure)*
    c. *How is Deuterium-Tritium self-sufficiency (sourcing, handling, breeding) addressed?*
    d. Could regulatory requirements constitute a bottleneck to your initiative?
    e. Have you already taken into consideration issues around waste, recycling and decommissioning?
3. What does your initiative hope to achieve **after 2030**?
4. What are the main challenges that need to be overcome to achieve these long-term goals?

What are the risks / likely outcomes if they cannot be overcome?

5. To what extend are you dependent on the outputs of other public and private initiatives?

Building up the questions as such opens up the room for the initiatives to first list a number of concepts (challenges/barriers/issues/problems) themselves. Afterwards specific issues (a-e) identified by Trinomics and the EC are addressed and subsequently the long term challenges are addressed

2.2.4 Barrier selection criteria

Once the tasks outlined in 2.2.1, 2.2.2, and 2.2.3 are completed in Chapter 4, a large amount of data is gathered. Selection criteria are needed to lead the analysis and explain how the selections are made in order to extract the important barriers that will eventually be used for the construction of the framework in Chapter 5. It is important to revisit the requirements the barriers must adhere to: Barriers must i) be relevant for the commercialization process and ii) accommodate all types of fusion technologies. The criteria for selecting barriers that adhere to these requirements are nonhierarchically stated and explained below.

Criterium 1. Frequency:

The first criterium that will be used to analyze the encountered concepts and their contextual information is the frequency of the concepts. When a barrier concept is stated by a large number of articles and initiatives it is likely to be relevant. Applying this logic, the other way around is limited, when a barrier is only incidentally encountered during the information gathering task it is not necessarily irrelevant but could be overlooked by the other information sources. Therefore the 2nd criterium is important.

Criterium 2. Severity

The second criterium for determining the relevance of the barriers is the severity of the barrier. In other words, does this barrier really impact the process towards and of commercialization? A good indicator for the severity is the line of argumentation for a barrier that is provided either explicitly in literature or the interviews or can logically be deducted from such statements.

Criterium 3. Information source:
The final criterium for assessing relevance of the barriers is the information source. Literature and interviewees have carefully been selected to ensure validity, but differences in the quality and topicality remain. Developments in the space are quick and may cause literature to lag behind. In case of conflicting claims in the literature, the most recent article is prioritized. Although it is preferred that both literature and interviews confirm the same barrier, the barriers stated by the initiatives during the interviews are considered more relevant in this task because these are encountered in practice. It should be noted that quality differences also exist within these companies; companies are still working on an experimental scale, while the more mature companies are already building pilot plants.

2.3. Task 2: Development of Y-factor fusion framework

This section describes the second research task and the corresponding methodology that is used to execute this task. This activity is guided by the following sub question:

How can the identified barriers be uniformly assessed for different fusion technologies in a standardized manner?

The execution of Task 1 will result in a list of all relevant barriers to fusion energy commercialization, selected using the criteria described in 2.2.4. Now that these barriers have been identified, they can be categorized and developed into a framework that adheres to the principles of the Y-factor method as presented by Chappin (2020). To construct the Y-factor fusion framework three fundamental activities need to be performed

Step 1: Categorization
The first step towards developing the framework is the formation and definition of categories that group similar barriers together. The formation of such categories requires a good line of argumentation to explain the logic behind the formation. Each category preferably holds three barriers as was presented in the original framework by Chappin (2020), but other sizes can also be used when this provides a better fit. This process is visually displayed in **Figure 4**

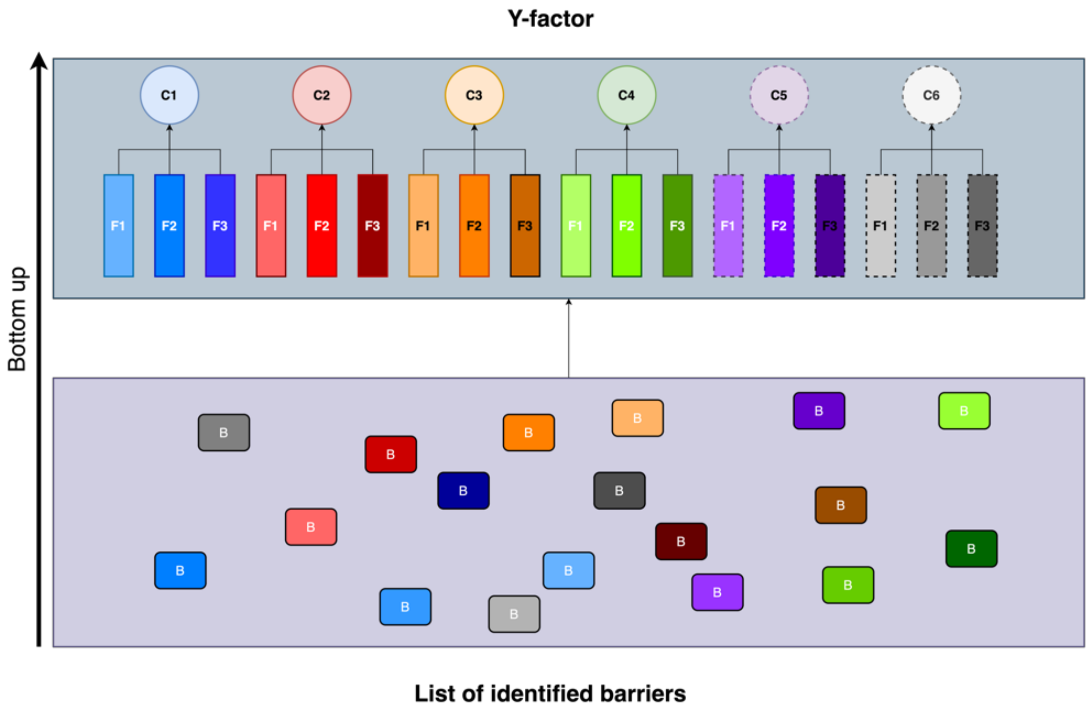


Figure 4 Categorization of barriers

Step 2: Phrasing the definition of the identified barriers
Each barrier in the Y-factor framework needs a concise but precise definition. This definition is extracted from the description in the barrier identification process and must be phrased such that users of the framework understand it easily.

Step 3: Formulation of the scoring criteria
The final step to complete the framework is developing the scoring criteria; each of the barriers should be described by an ad-hoc, tripartite scale that quantifies the severity of the barrier and ranges from a value of 0, 1 to 2. For every barrier identified in step 2, the values 0, 1 and 2 bust be defined, so they can be unambiguously scored.

2.4. Task 3: Application of Y-factor fusion framework

Once the framework has been constructed it will be applied in an exploratory endeavor to test the usefulness and research the insights the framework's application can elicit. To do this, multiple industry experts will be asked to assess and score the barriers for the selected fusion technologies. The respondents will firstly be told about the goal of the research, the theory of the Y-factor methodology and the objective of their participation.

The application of the framework is done systematically, for every barrier the definition and formulated scoring criteria are explained, and the respondents will be asked to comment on the barrier in general, identify differences for the different technologies and assign "Quick and dirty" scores. This process is done for all the identified barriers. Once all the respondents have assigned their scores, the results can be plotted on a graphical Y factor curve, an example of such curve is displayed in **Figure 5.** Y factor curve (Chappin, 2020)**.**

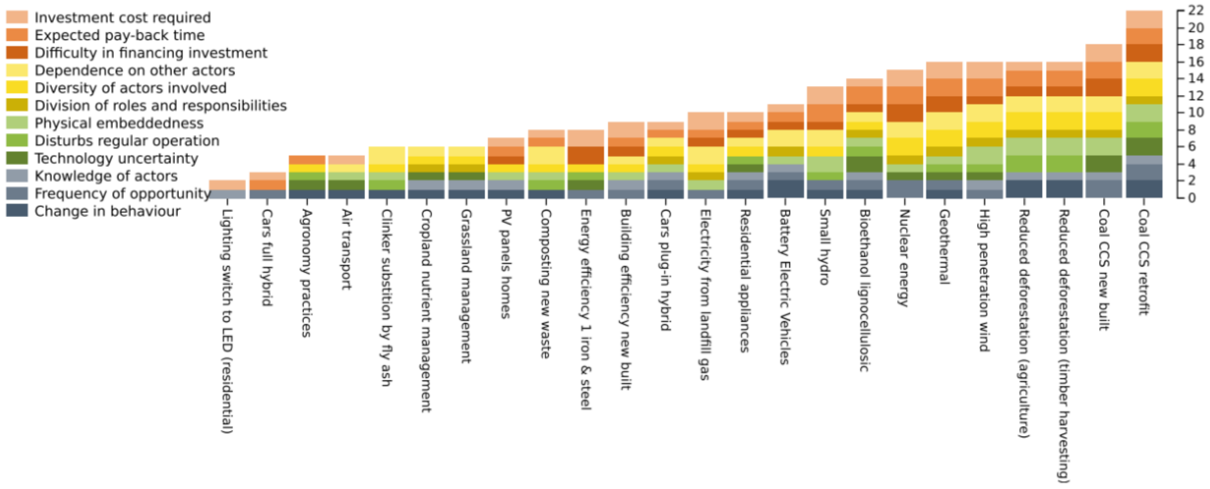


Figure 5. Y factor curve (Chappin, 2020)

While the accuracy of the assigned scores is certainly not negligible, the emphasis in this task is on the argumentation process. The intended value of the framework is to facilitate discussion and increase understanding of the barriers towards commercial fusion and therefore the thought process and views of the respondents will be documented during this task so that these can be analyzed. Upon finishing the scoring, the respondents are asked to comment about the completeness of the framework, the identified barriers and give final remarks in an attempt to increase the validity of the results. Due to time constraints the number of respondents is limited and therefore validation is not within the scope of this research.

3. Nuclear fusion development

This chapter is dedicated to the introduction of core concepts and background information that are necessary to understand the research. Firstly, the basics of nuclear fusion are explained as this is necessary to understand the different approaches to fusion. Secondly, the five most promising fusion concepts are described that will be evaluated later in the research. Lastly, the latest developments in the fusion industry are described, both in public and private fusion initiatives.

3.1. Basics of nuclear fusion

Nuclear fusion is the process where the nuclei of smaller elements fuse together to form one heavier and larger element(Takeda & Pearson, 2018). During this process, a small amount of mass in the form of a neutron is separated and this 'lost' mass is released as kinetic energy according to Einstein's equation $E=m*c^2$. This is the process that powers the heat and light production of stars, including the sun (Burbidge et al., 1957).

For achieving nuclear fusion on earth, multiple different 'fuels' can be used but research is primarily focused on the fusion reaction between two isotopes of hydrogen: Deuterium and Tritium (Nuttall et al., 2020). These elements are the most readily available of the possible alternatives and the Deuterium-Tritium (DT) reaction is regarded as the "easiest" to achieve although extremely high temperatures in excess of 100 million Kelvin are still required (Takeda & Pearson, 2018).This reaction is shown in Figure 6. The amount of energy that is released from the fusion reaction is the product of three factors n, T and τE, the ion density, ion temperature and energy confinement time respectively. (Costley, 2016).

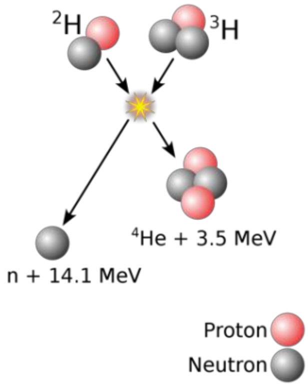


Figure 6. Deuterium-Tritium fusion reaction (Barbarino, 2020)

- **Density:** The hydrogen isotopes are in a state of plasma and are stripped of their electrons which causes them to have a positive charge. To overcome this repulsion force, the nuclei should be brought within 10^{-15}m of each other to allow fusion to happen. Hence, the plasma should be really dense. The hydrogen in the core of stars is condensed by its immense gravitational force, but on earth artificial methods for achieving the desired plasma density are necessary. This is called confinement.

- **Temperature**: The nuclei need to move at sufficiently high speeds to be in the plasma state. This is a high energy state that requires an exceptionally high temperature. At this temperature, Deuterium and Tritium are stripped of their electrons. On earth a temperature exceeding 100m Kelvin (K) is necessary to achieve the desired fusion process.

- **Confinement time**: The confinement time is the duration of the reaction and hence positively correlated with the total amount of energy that is produced during the fusion reaction.

These criteria were described by Lawson (Lawson, 1957) and are highly relevant for the development of fusion technology into an energy source. Generate net positive energy from the fusion reaction requires the reaction to release a greater amount of energy than is required to initiate and maintain the reaction. For a fusion reaction this is the ratio of the energy output from nuclear fusion reactions in the plasma to the energy supplied to sustain the plasma and is known as the fusion energy gain Q (Takeda & Pearson, 2018). Hence, a Q = 1 defines that the energy produced by the plasma equals the energy supplied by the plasma, a phenomenon that is defined as breakeven conditions. In order to extract net energy gain from a fusion reaction, the engineering gain must be greater than 1. This is the energy that can be extracted from the plant compared against the total energy consumption of the fusion plant

Scientists have been exploring how the energy from this nuclear fusion process may be harnessed for energy production ever since it was discovered. For the past 70 years and counting, research has focused on developing a reactor that is capable of holding the conditions that optimize the Lawson criteria for the plasma and can achieve a net power gain. A large number of fusion approaches exist, and a taxonomy is displayed in **Figure 7.**

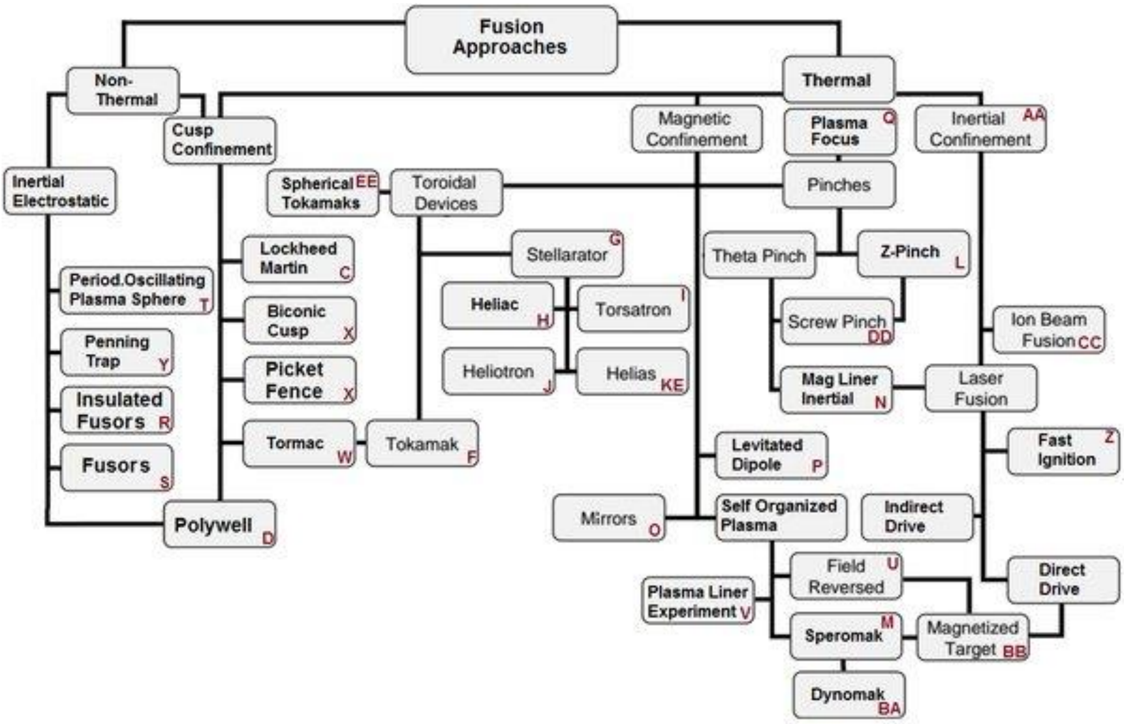


Figure 7. Taxonomy of fusion approaches (Takeda & Pearson, 2018)

Within this taxonomy the two major approaches are magnetic- and inertial confinement. The differentiator being the method for achieving the necessary plasma density criterium. This section will shortly describe the most promising and most pursued approaches to fusion. It should be noted that far more approaches exist and are being pursued, but this section only describes the most common ones.

3.2. Magnetic Confinement Fusion

When the fuel is heated to such extreme conditions it becomes a plasma and the particles become positively charged because they lose their electrons (Gibbon, 2014). In magnetic confinement, the electromagnetic properties of these particles are used to “hold” the plasma along a magnetic field in a reactor vessel. Magnetic confinement fusion has been pursued since the 1950’s and serves two main benefits; firstly, the density of the plasma can be controlled which is necessary to hold the density of the plasma and maintain the reaction (Hinton & Hazeltine, 1976). Secondly, the 100 million Kelvin plasma is kept away from the reactor walls, which is required both to prevent energy losses and because no materials capable of withstanding such great heat have yet been invented. Many different sizes, configurations and fuels are currently experimented wit

3.2.1. Tokamak

The tokamak is the most successful configuration for fusion energy to date and over 200 of these machines have been built, planned, or have already been decommissioned. **Figure 8** Tokamak configuration (Haupt, 2018) Figure 9 Inside of JET reactor (EUROfusion, 2022)schematically displays the general design elements of a tokamak. The plasma is confined in a torus shaped vessel which is completely enclosed by toroidal coils, creating a strong magnetic field in the toroidal direction. This magnetic field confines the plasma and keeps it away from the reactor walls (Costley, 2016). A perpendicular magnetic field is created by coils in the poloidal direction, this drives a current through the plasma and heats it to fusion temperatures. (Kikuchi et al., 2012; Takeda & Pearson, 2018).

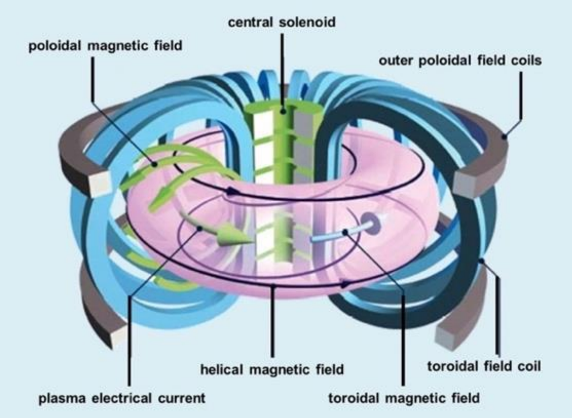


Figure 8 Tokamak configuration (Haupt, 2018)

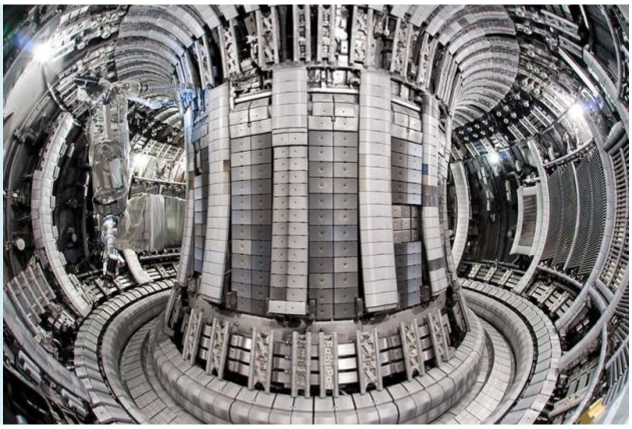


Figure 9 Inside of JET reactor (EUROfusion, 2022)

Tokamaks are well understood and currently the most extensively researched approach to fusion with numerous highly advanced Tokamaks operational today in testing facilities across the world that have demonstrated significant increases in performance. Recently, the Joint European Torus (JET) in the UK, currently, the world's largest and most powerful operational Tokamak. During its last experiment it achieved a pulse that generated a record high 59MJ of energy (reference) at a Q ratio of 0.67 and this is the highest Q ratio that has been recorded to date. The inside of JET is displayed **Figure** 9. Although the pulse was limited to 5 seconds by the time that the copper magnets could function without overheating, this time period was enough to demonstrate that the reaction could be sustained.

Newer generation tokamak devices have upgraded magnets that are made out of superconducting material with near to no resistance which allows for greater magnetic fields and better cooling properties. These magnets are already used in multiple tokamaks and have demonstrated great advantages. Most notably the EAST and K-STAR Tokamaks in China and South-Korea respectively have gradually increased plasma temperature and pulse duration over the past years and continue to do experiments pushing the boundaries of both variables. In November 2021, KSTAR maintained a 30 second pulse with plasma temperature exceeding 100 million degrees. While the EAST reactor achieved a 120 million electron temperature in May 2021 before setting the world record for long-pulse high-parameter plasma operation and achieved a pulse of 1056 seconds in December. Many of these reactors have been specifically designed to test and validate the International Thermonuclear Energy Reactor (ITER). This Tokamak is currently under construction and will be the largest of its kind once completed.

Although tokamaks are the most advanced fusion devices that have been constructed to date, significant technical challenges still are to be solved. High stability of the plasma is crucial for the efficiency of the Tokamak but remains a challenge. Another challenge is maintaining the current in the plasma and extending the length of operation. A challenge faced by all magnetic confinement approaches is the cooling of the magnets. These need to operate near absolute zero temperature but heat up quickly by the powerful electric currents that run them.

3.2.2. Spherical Tokamak

An evaluation of the “conventional” tokamak is the spherical tokamak (ST), a concept that largely utilizes the same principles and design components as the conventional tokamak. The main differentiator is the geometry of the device. The shape of the vessel in which the plasma is contained- the reaction chamber of a ST is similar to a cored apple rather than the conventional doughnut shape **Figure 10 & Figure** 11

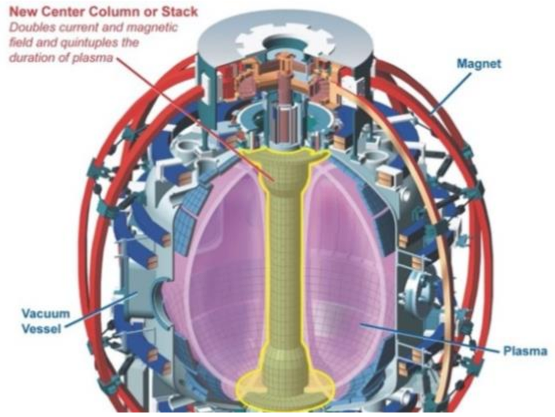


Figure 10 Spherical Tokamak configuration (ITER, 2012

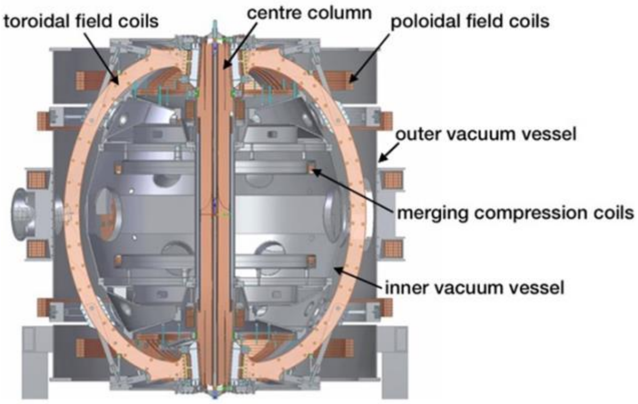


Figure 11 ST40 reactor (Tokamak Energy 2020)

This shape accommodates a different magnet configuration, rather than wiring each magnet coil separately, ST utilizing a single, big wire in the middle and wiring the magnets as half-rings off of this conductor in the central solenoid which significantly lowers the aspect ratio (Ono & Kaita, 2015) and position the toroidal magnets much closer to the plasma. Sykes et al. (2017) describes how this greatly reduces the amount of necessary energy to reach a desired magnetic field, hence the magnetic efficiency of ST’s if higher which make it higher Beta devices. As a result, the device is far more compact, requires smaller magnets and consequently the reactor costs can be reduced. There are also advantages to the spherical configuration in terms of plasma performance. Windridge (2019) states that theoretically, ST’s have a higher stability, more efficient current and lesser disruptions which should all improve the confinement. However, further research is needed to demonstrate this.

Tokamak Energy in the UK built the first spherical tokamak that achieved a plasma temperature in excess of 100 million degrees and simultaneously became the first ever private fusion company to achieve this temperature in a fusion device. The company is currently designing the upgrade and plans to combine the ST design with novel HTS magnets to demonstrate energy gain. An increasing number of initiatives are pursuing this design both in the public and private fusion pathway. In the UK the MAST-U and STEP are under construction while in China ENN is already performing plasma experiments. Most notably is Commonwealth Fusion (CFS), CFS built and tested a near full-scale high temperature superconducting (HTS) magnet that demonstrated a sustained magnetic field in excess of 20 Tesla. The company was able to raise $1.8 billion and is currently constructing the SPARC reactor that will use these magnets and aims at demonstrating net energy gain in 2025.

Despite these successes, further research is required as challenges remain for ST’s too, mostly caused by the geometry. The reconfiguration of the magnets results in limited room for the reactor components, especially in the central solenoid. Particularly shielding this solenoid against the neutrons of the fusion reaction is difficult, but also the engineering and programming of the ST design is more complex. (Gao, 2016)

3.2.3. Stellarator

A stellarator is also a magnetic confinement fusion device that consists of a reactor vessel that is enclosed by magnets. However, the reactor vessel in the stellarator configuration is shaped as a heliacal torus, this is displayed in **Figure 12.** The shape of the torus and the surrounding magnet configuration result in a spiral-shaped magnetic field that confine the plasma in a "twisted" shape. Ongena et al., (2016) describes a number of advantages of stellarators and explains that the advanced configuration of the magnets, no toroidal magnetic field is necessary which makes it conceptually a lot easier to control the plasma. Leading fusion scientist Thomas Klinger once said: "In a stellarator confining the plasma is like holding a broomstick firmly in your fist; in a tokamak, it's like trying to balance the same broomstick on your finger" (Arnoux, 2022) Another highly interesting aspect of stellarators is that this design concept allows for a higher plasma density and longer pulses (Tokitani et al., 2015).

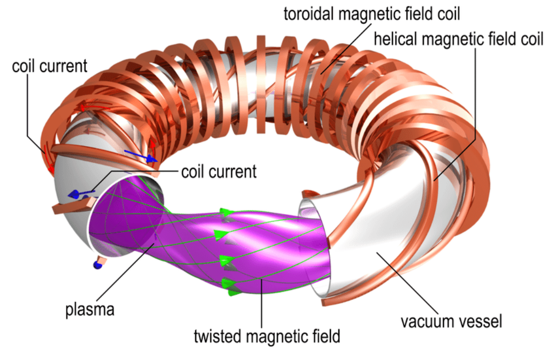


Figure 12 Stellarator configuration (Proll, 2014)

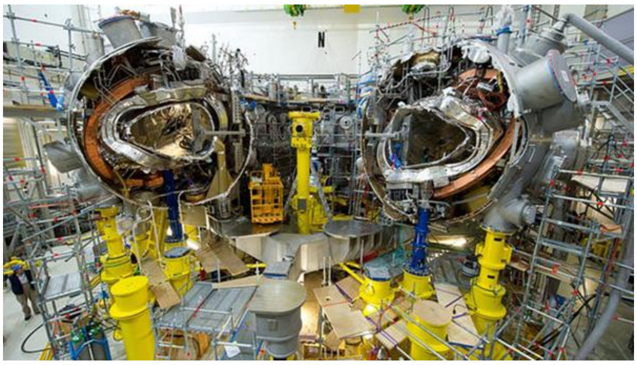


Figure 13 Wendelstein 7-X (Max-planck institute, 2015)

The world's most developed and most advanced public stellarator is operated by the Max-Planck institute for Plasma Physics (IPP) in Germany and is named the Wendelstein 7-X (WX-7). In 2017, WX-7 achieved the world record for stellarator fusion product by demonstrating higher temperatures, densities and pulse durations. The reactor is displayed in **Figure 13.** A series of upgrades were implemented to increase the performance, most prominently the cooling system was improved to enable longer pulses. Eventually Wendelstein aims at demonstrating 30-minute pulses. Breakthroughs in HTS magnets have also sparked interest of initiatives aiming to implement HTS magnets into a stellarator configuration. Type One Energy in the US and Renaissance Fusion in France were founded recently (2020 & 2021 respectively) and are currently working on developing a prototype.

The benefits of the optimized magnetic fields do come at a price; the stellarator design, particularly the magnetic coil system, is more complicated owing to the complex geometry of the machine. The twisted magnetic coils require extreme precision in engineering. Also constructing and integrating the machine is challenging; stellarators are "easy to control but notoriously difficult to build". Also, the modelling and optimizing the machine is more complex and only recently the computational power became available to do advanced plasma simulations.

3.2.4. Field Reversed Configuration

Field Reversed Configuration (RFC) devices are tube shaped fusion reactors consisting of three chambers: formation chambers on either end of the device that are connected by the central fusion chamber. In FRC's the fuel is injected in a gaseous state into the two formation centres and superheated to form plasmas with self-created magnetic fields (Binderbauer et al., 2015). Subsequently, magnetic fields around the formation chambers are used to invert the magnetic field of the plasma to a toroidal field, hence the name "field reversed", and this causes the plasma to form into a doughnut shape and spin in a loop (Gao, 2016). These plasma rings on either side of the device are then shot towards the fusion chamber where they collide and merge to form one hot and dense plasma where the magnetic field surrounding the fusion chamber is rapidly increased to compress the plasma to conditions where fusion can occur. (Kikuchi et al., 2012).

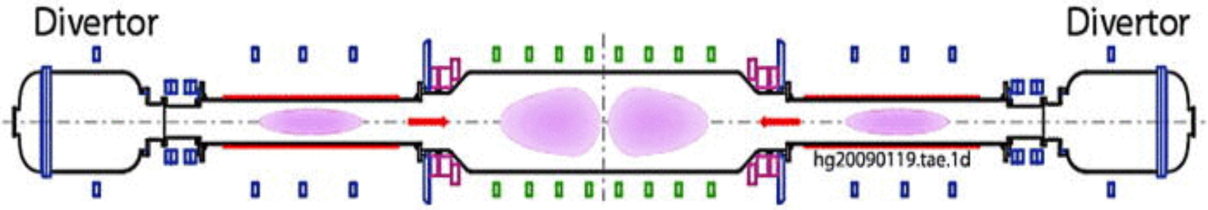


Figure 14 Simplified FRC device (Steinhauer, 2011)

schematically displays a FRC device. The two formation chambers, with plasma rings, are outlined in red and can be seen on both ends of the tube. The red arrows indicate that these rings are shot towards the central chamber, outlined in green, where the rings collide and fusion takes place.

Dewit & Morelli (2019) describe the technical benefits of the FRC concept and identify that FRCs have a simple magnetic topology compared to many MCF approaches, which usually have curved magnetic fields or highly complex coil configurations to shape the plasma. This simple topology results in a high magnetic efficiency: FRCs can more easily achieve high plasma densities and require relatively low magnetic field strengths. Furthermore, (Gao, 2016) states that FRC devices are highly compact and have a simply connected vacuum vessel. However, the most promising feature is the potential of direct energy conversion (Dewit & Morelli, 2019) where ionic flow in plasma changes the magnetic flux of the surrounding magnets and electricity can be generated directly.

To utilize this property different fuels than the ‘traditional’ Deuterium Tritium mix are necessary as this fuel mix releases energy in the form of neutrons. Working around Tritium has many other advantages as it would eliminate radioactivity, the need for neutron shielding and make maintenance easier. The virtue of avoiding these challenges has resulted in significant interest and two of the highest funded private fusion initiatives to date with Helion Energy and TAE Technology recently raising \$2.1 and \$1.25 billion raised respectively. Both companies have been successful and achieved plasma temperatures in excess of 70 million degrees Celsius and planned next experimental devices already to push the performance.

However, avoiding Tritium comes at a cost as it requires significantly higher temperatures and pressures, thereby pushing the technical challenge of energy gain even further. Within the fusion industry there is widespread scepticism towards other fusion fuels as many scientists argue that it can’t be done as D-He3 and pB11 require 4x and 15x higher plasma temperature respectively. Inherently, FRC has its drawbacks too as it is prone to many kinds of plasma instabilities that are extensively described by (Gao, 2016). Severe difficulties remain in understanding the equilibrium conditions and the plasma physics necessary to mitigate instabilities.

3.3. Inertial Confinement Fusion

Inertial confinement fusion is a completely different approach to a fusion reactor and does not make use of magnetic fields to hold and confine the plasma. Instead, it makes use of small pallets which contain a cavity filled with fusion fuel. By compressing these pallets, the cavity with the fuel is compressed to very high temperatures and densities that allow for fusion reactions to take place. In this approach confinement is not achieved by external fields, but by the inertia of the hot fuel that keeps it together for a finite time (hence the name inertial confinement) (Kikuchi et al., 2012)

The compression of the fuel cavity is accomplished by shooting the pallet or "target" with high amounts of energy which causes it to implode and compress the fuel cavity. Various different approaches to ICF exist that differ in the manner of driving energy into the target. All ICF approaches however, are similar in that they operate in batches (targets) and the reaction requires a high repetition rate to be a useful energy source.

3.3.1. Laser driven ICF

The idea of driving ICF with lasers was first published by John Nuckolls in 1972 and currently is the most promising and most pursued approach to ICF (Takeda & Pearson, 2018). The process of ICF magnetic fusion consists of four phases that are displayed in **Figure 15.**

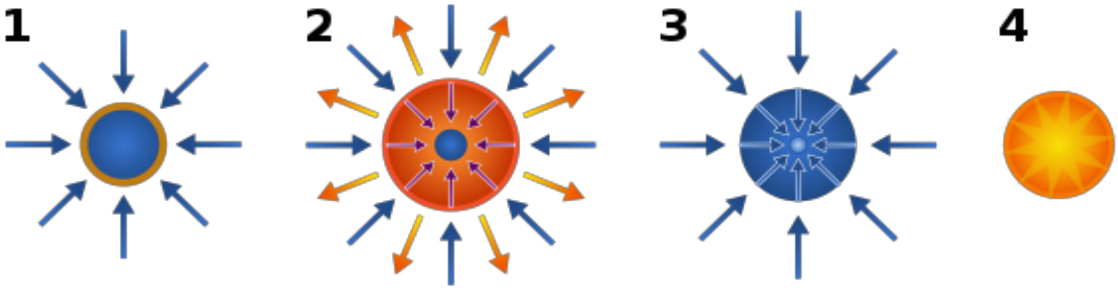


Figure 15. Schematic overview of inertial confinement fusion (Board on Physics and Astronomy, 2013)

Firstly, high energy laser pulses are shot at the surface of a spherical hollow shell target uniformly from all sides. Subsequently, the intense heating of the surface causes the target to implode, which starts the third phase, in which the fuel is compressed to extreme density and temperature initiating fusion reactions. Finally, the holy grail of ICF is the desired fourth phase, namely ignition. Ignition occurs when the energy produced by the fusion reactions is sufficient to heat the remaining fuel to fusion reaction conditions. At that point, no additional external heating source is needed, and the reaction in essence is self-sustaining until the fuel is depleted. (Board on Physics and Astronomy, 2013). However, ignition has not been achieved yet.

Multiple variations within laser ICF exist that differentiate in the way that the laser energy is delivered to the fusion fuel. R.Betti & O.A. Hurricane (2016) have extensively described and compared direct- and indirect-driven ICF. Both approaches are similar, direct drive focuses the energy of the lasers directly on the capsule surface, while indirect drive focuses the laser energy on a highly advanced structure (Hohlraum) that encapsulates the spherical target in which the laser beams form a bath of X-rays that drive the capsule. This approach trades energy efficiency for energy density. The differences are graphically shown in **Figure 16.**

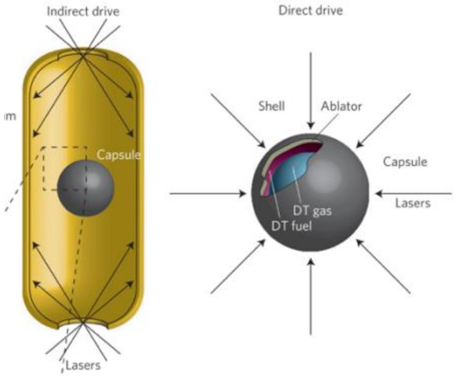


Figure 16. Indirect vs Direct drive (Betti & Hurricane, 2016)

The advantage of direct-drive ICF is that it maximizes the energy that is coupled to the imploding fuel as no energy is lost in the Hohlraum, but only the capsule. This better laser-energy coupling allows for a greater fuel mass. However, the specific technical specifications of direct drive results in greater nonuniformity and less desirable capsule specifications. Direct- and indirect-driven laser are the conventional paths to ICF development, but their development has also sparked interest in alternative inertial fusion approaches that promise either a lower ignition threshold, a more stable implosion, or a higher energy gain needed for industrial applications (Tabak et al., 2014). Amongst others, these approaches include fast ignition and shock ignition.

Fast ignition is the most developed of the alternative approaches and is an extension of conventional ICF. In addition to the laser driven compression, one side of the target is shot with an ultra-short pulse ultra-high-power laser to drive ignition (Zhang et al., 2020). Theoretically this approach is highly promising as it allows for relaxation of the implosion requirements since an additional external driver delivers additional energy, but the required laser beam intensities do not yet exist (Tabak et al., 2014). In addition, the fast ignition method to ICF further complicates the physics and introduces new problems that are not understood. Shock ignition also works with delivering extra power during the process of compressing the target but rather than additional laser energy, a shockwave is sent into the fuel to trigger the desired ignition of the fuel (Zhang). Igniting the fuel through a combination of compression and shock heating in theory increases the efficiency of the process but is relatively unexplored and advanced yet.

3.4. Nuclear fusion sector

This section expands on the aforementioned technologies and offers information on the current state of affairs in the nuclear fusion industry. On the basis of the public and private commitment to nuclear fusion, the most noteworthy initiatives, milestones and general developments will be described to offer context of the industry.

3.4.1. Public fusion research

From an economic perspective, the development of previously described fusion technologies is incredibly time- and capital intense. For instance, in the United States, investments in fusion development have accumulated to over 18 Billion dollar since the 1950's and hasn't resulted in a commercial application yet. In addition, fusion development carries the risk that it will not be economically or technically viable, potentially eliminating the potential to commercialize the technology and yield returns. This investment profile has historically shied away private capital and resulted in fusion development being funded and executed by governments. The International Atomic Energy Agency (IAEA) was set up in 1957 under the umbrella of the United Nations and is an independent intergovernmental organization that amongst other goals, serves to promote and enable cooperation of nuclear technologies such as fusion power. Shortly after it was founded, the Director General, Hubert de Laboulaye stated that: "Complete exchange of information and coordinated research on an international scale appears to be the only means to get things going faster".

Tokamaks

The vision of public fusion development is still characterized by this perspective and epitomized by the development of the International Thermonuclear Energy Reactor (ITER). The agreement to establish ITER was signed in 2007 and involves the collaboration of 35 countries that by joint effort are constructing the largest tokamak to date. The mission of ITER is to demonstrate the technical feasibility of fusion power and it is planned to achieve this by proving net energy gain, operational durability and demonstrate safety (ITER, 2022) ITER is financed for 45.5 percent by Europe, whereas China, India, Japan, Korea, the Russian Federation and the United States contribute approximately 9.1 percent each to the estimated 25-billion-euro construction cost.

ITER was originally projected to be completed in 2020 (ITER, 2022) but has been plagued by delays ever since construction started in 2015. The Covid pandemic, damage to components during transport and a regulatory hold are likely to push back its completion to 2027-2028. Once completed, experiments will be gradually scaled up to DT operation and demonstrate 500MW energy production. The next step in this roadmap is the development and construction of a series of demonstration (DEMO) plants in several of the partaking countries that are projected to deliver net power to the grid by 2050 and serving as a proof of concept for a commercial fusion power plant.

Until ITER is constructed, the Joint European Torus (JET) in the UK is the world's largest and most powerful operational Tokamak and it has constituted greatly to the development and science of ITER. It ran an experiment in December 2021 that achieved a record 5 second pulse, generating 59MJ of energy and proofed to be very valuable for the validation of ITER. However, there are more tokamaks that assist the ITER and DEMO roadmap, particularly in Asia. The EAST and K-STAR Tokamaks in China and South-Korea respectively both use superconducting magnets that allow for high performance. Over the past years both reactors have gradually increased plasma temperature and pulse duration with current experiments pushing the boundaries of both variables. In November 2021, KSTAR maintained a 30 second pulse with a plasma temperature exceeding 100 million degrees. While the EAST reactor achieved a 120 million electron temperature in May 2021 before setting the world record for long-pulse high-parameter plasma operation by achieving a pulse of 1056 seconds in December 2021.

The newest experimental tokamak that is intended to pave the way towards successful ITER experiments is the JT60-SA tokamak in Naka, Japan. The construction and assembly of JT60-SA was completed in 2020, but during commissioning in 2021 the reactor encountered issues with one of the superconducting coils which caused damage. Diagnosis of the cause and repairs have been carried out, indications are that commissioning will be completed after summer 2022. Expected key contributions from JT60-SA operation will be research and experiments for higher tokamak plasma pressures and the testing of a divertor concept.

Spherical Tokamaks

In addition to the numerous tokamaks around the world, there is also public research and development of spherical tokamaks. The UK Atomic Energy Authority (UKAEA) is responsible for the development of fusion energy in the United Kingdom and is currently pursuing two significant spherical tokamaks. It operated the Mega Ampere Spherical Tokamak (MAST) up until 2013 and is currently operating the Upgrade (MAST-U) that has demonstrated longer pulses, increased heating power and a stronger magnetic field (Unknown, 2022). Furthermore, the reactor also experiments an innovative new plasma exhaust system. The planned successor of the MAST-U reactor is the Spherical Tokamak for Energy Production (STEP) reactor which would act as a pilot plant for fusion power from a spherical tokamak approach. The American counterpart of the MAST-U is located at the Princeton Plasma Physics Laboratory (PPPL) and is the National Spherical Torus Experiment-Upgrade (NSTX-U). Scientists at the PPPL recently stated that the reactor could serve as the model for a pilot fusion plant (Nuclear Newswire, 2022)

Other technologies

Public research is developing the tokamak and spherical tokamak along a predefined pathway with multiple reactors. This is unique for these two technologies and does not apply to the remaining approaches to fusion. Although several public institutes are researching the stellarator design, there is only one noteworthy reactor which is the aforementioned Wendelstein 7-X reactor in Germany. Although funding to operate the reactor continues no successor or other stellarator devices have been planned.

This is similar to the state of public ICF research where the National Ignition Facility (NIF) is the only evident public effort. The facility indirectly drives fusion targets with a combined 192 laser beams that deliver up to 1.9 megajoules of energy. In 2021 the NIF facility achieved a burning plasma state in which the plasma is predominantly self-heated by fusion reactions in the plasma. Although burning plasma is short of ignition or energy gain it is a highly significant milestone for fusion research, as studying burning plasmas will elucidate other new physics in this regime. It was revealed that four experiments had been conducted that passed the threshold for a burning plasma and that “several promising avenues for further increases in performance are identified and will be pursued by the US inertial fusion program”. The concrete roadmap and timeline for achievements is undisclosed at this time.

3.4.2. Private fusion research

In July 2022, the Fusion Industry Association (FIA), an international coalition of private fusion companies, published its report on the status and development in the private sector (FIA & UKAEA, 2022) and ascertained that the explosive growth is continuing. In the prior version of the yearly report the FIA displayed **Figure 17** that demonstrates the growth of the private fusion sector and over the past year another eight new fusion companies were founded (**Figure 18)**

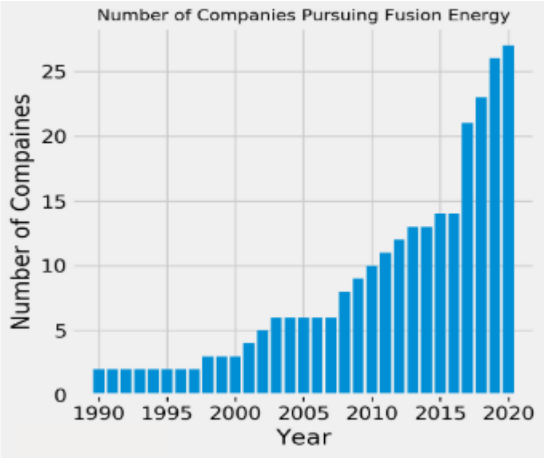


Figure 17 Growth of fusion companies (FIA, 2021)

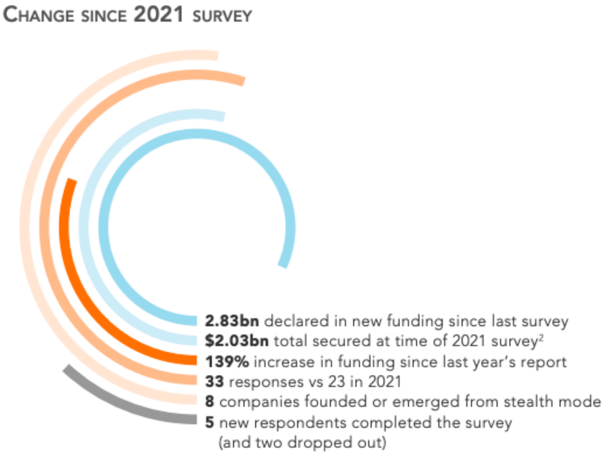


Figure 18 Private sector statistics (FIA, 2022)

Not only has the number of fusion companies skyrocketed over the past year, also the funding of these companies has increased exponentially. The FIA survey reported that in the duration of one-year private fusion companies raised over $2.8 billion in funding, more than doubling the all-time total funding and bringing this to $4.7 billion. Whereas of 2015, only one company had raised over $100 million in funding, currently 8 companies have passed this threshold, with a handful of companies raising upwards of a billion dollars.

The growth pattern can partially be explained by observing developments in the public fusion sector. Public programs have achieved a number of important breakthroughs that have brought the realization of nuclear fusion a lot closer. Not only has this allowed private fusion start-ups to build on proven technology, it has in turn also attracted large funds from private investors that expect the industry to yield profits within a manageable timeframe (Halem, 2018). As the groundworks have now been laid out and certain technological concepts have been proven, investment risks have decreased. While at the same time, delays in the public pathway have increased the upside of novel private companies. This combination has fueled an enormous increase in funding towards private sector fusion development.

The most noteworthy companies and achievements are summarized in **Table 2** Leading fusion companieson the next page and this overview demonstrates that the USA and the UK are the frontrunners in terms of private fusion. Furthermore, within the private fusion space, the FRC companies are amongst the highest funded initiatives while in these are not seriously pursued in the public programs.

Table 2 Leading fusion companies

Approach	Company name	Information	Achievements
Tokamak	Commonwealth Fusion Systems	• Founded in 2018 • Based in X, USA • +$ 2.0 billion raised to date • 300 employees • Tokamak with HTS magnets • Deuterium Tritium	• Built and tested a near full-scale, large-bore high temperature superconducting (HTS) magnet, proving a magnet built at scale that can reach a sustained magnetic field of more than 20 Tesla. • Started construction on pilot plant facility SPARC that is aimed at demonstrating net energy gain by 2025
Spherical Tokamak	Tokamak Energy	• Founded in 2009 • Based in Oxford, UK • $ 200 million raised • 190 employees • Spherical Tokamak • Deuterium Tritium	• 100-million-degree plasma ion temperature in ST40 prototype • First private company to transcend the 100-million-degree mark
Stellarator	Renaissance Fusion	• Founded in 2020 • Based in France • 14 employees but quickly expanding • Stellarator with HTS magnets • Deuterium Tritium	• Currently working on a cylindrical demonstrator that aims to demonstrate their fusion-enabling technologies (superconductors manufacturing technique HTS and liquid metals), without plasma. • This is the first important milestones (horizon of less than 3 years) – needed to be achieved before plasma experiments can be started
ICF	Marvel	• Founded in 2019 • Based in Munich, Germany • $ 60 Million raised to date • 40 employees	• Putting the team together and grow the company. • Published first paper on core concept and demonstrated the approach via extensive simulations. • Done first 4 experiments that proved simulated predictions.
	First Light Fusion	• Founded in 2011 • Based in England • $95 Million raised to date • 70 employees	• Demonstrated the production of neutrons, thereby demonstrating that fusion reactions happen • Optimization of fuel target design
Field Reversed configuration	TAE Technologies	• Founded in 1998 • Based in California, USA • +$ 1.25 billion raised • 400 employees • Hydrogen Boron-11 fuel mx	• Reached 70 million degree plasma temperature • Commercialized spin-off division for revenue • Raised the money for the next testing device that is intended to demonstrate energy gain • Expect to demonstrate energy gain before 2030
	Helion Energy	• Founded in 2013 • Based in Washington, USA • +$2.1 billion raised • 85 employees • Deuterium-Helium 3	• Reached more than 100 million degrees plasma temperature in 2021 • Constructing next experimental device • Plans on demonstrating energy gain in 2024

3.4.3. Current foresights

Whereas public fusion programs are expected to deliver energy to the grid in 2050, provided that everything goes well, almost all private fusion companies claim they can achieve this in a far shorter timeline. ITER is planned to be the first public fusion initiative to demonstrate net energy gain and given the continuous delays this is likely to be after 2035 that was projected while numerous of the more advanced companies state this will can be demonstrated around 2025. This is translated into longer timelines towards actual energy production on the grid. This is clearly depicted in **Figure 19.**

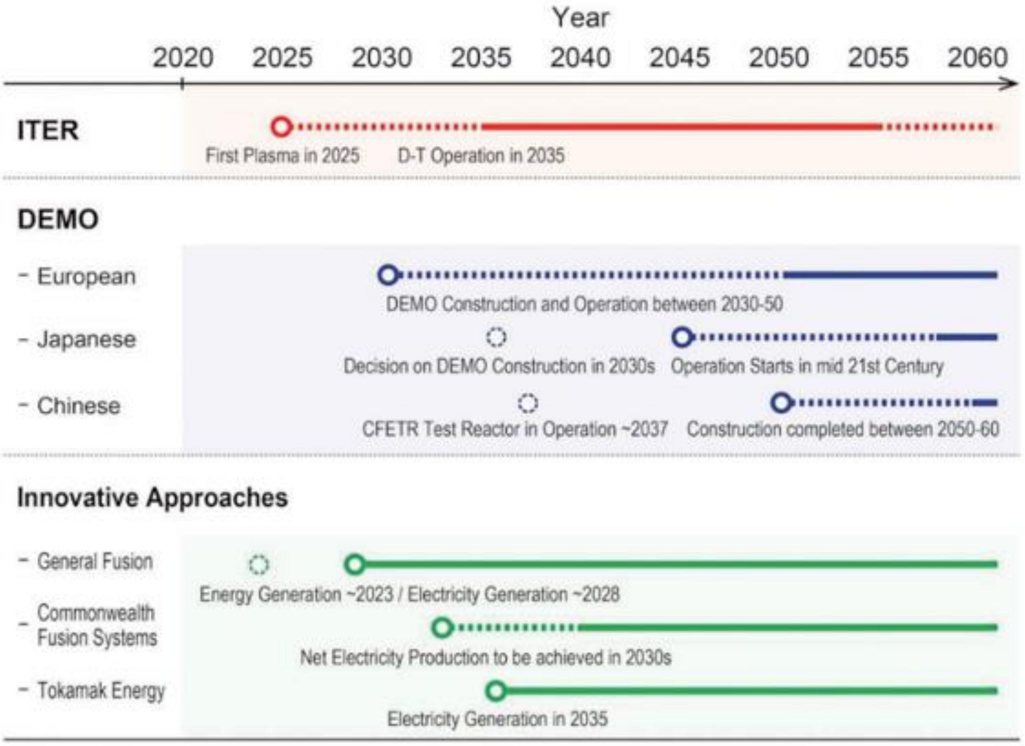


Figure 19. Timelines of public and private fusion initiatives (Halem, 2018)

There is a difference in how these private companies operate compared to public programs. Pearson (2020) describes that private companies are mostly focused on developing core systems and demonstrating technical viability of their inventions. Halem (2018) confirmed this observation after interviewing private companies and investors; the main strategies for private firms are development of intellectual property to be licensed and the design or built of reactors to be sold another party.

Furthermore, the approach to fusion development is far more aggressive than that of traditional public programs. Pressure from investors and more innovative technologies yields quicker innovation cycles, enabling rapid technology development. As such, this opens the possibility of a faster route to fusion.

4. Barrier identification

This chapter is dedicated to the barrier identification task and contains the results of the literature review (4.1.) and the interviews (4.2.) that were performed to eventually develop the Y factor framework in Chapter 5. During this activity the results of literature review and the interviews are displayed in separate tables with a short analysis. Afterwards a more extensive analysis is performed and a finalized list of barriers with definitions is provided.

4.1. Results of literature review

This section briefly describes how the literature review was performed and presents the results of the literature review. Only few initial interesting observations are mentioned in this section as a deeper analysis on all results of the barrier identification phase is performed later in the report.

A total of 17 scientific publications were found using the search approach described in Section 2.1.1. It was purposefully decided to feature articles from various perspectives. **Appendix A**: Selection of literature contains a table that contains the list of literature, as well as the topic of each piece, the fusion approach to which it relates, and a brief description of the content of each article. These selected articles were read and analyzed to identify barrier like concepts, such as issues, problems, challenges, hurdles etc. These concepts were subsequently noted down resulting in approximately 6 or 7 concepts per article.

4.1.1. Table of concepts in literature

The full list of 101 concepts is displayed in **Table 3.** Summarized results of literature review and depicts the author, the fusion approach that is described and the findings of studying the literature. The benefit of documenting the results in this manner is that it makes it simple to trace back concepts and assertions to their original sources during the barrier identification in 4.3. and thereby it enables an easier and better structured analysis later in the process.

Table 3. Summarized results of literature review

Author and date	Technology	Findings
(Gaio et al., 2022)	Tokamak, MCF	- The high active power peaks mainly required for the plasma formation, vertical stabilization and control, due to the high levels of voltages and currents necessary for the Superconducting Coils (SC) coils. - Increasing the power utilization factor in particular for coil power supply - The huge reactive power demand if the classical thyristor converter technology is adopted - The risk of instabilities in the electrical network connected to need of too large RPC systems - Increasing the reliability of fast discharge units for SC coils - The generator capability to operate in compliance with the different solutions of the Primary Heat Transfer System (PHTS) & Power Conversion System (PCS) - Respecting the limits for the interface with the Power Transmission Grid (PTG). - The assurance of required reliability for emergency power supplies (EmPS)
(Buttery et al., 2021)	Compact Tokamak, MCF	- The construction and initial phases of exploitation of ITER, to learn the practical lessons of reactor design and operation, critical to being able to pursue future devices.

		- Development of a high performance, high density and β steady state core scenarios and its physics basis (model validation), with high bootstrap fractions at reactor-relevant parameters and sufficient control of transients (instabilities, ELMs) and safe termination - Resolution of an advanced divertor solution capable of reducing erosion and heat flux, - Development and validation of suitable materials, particularly for plasma facing components that are compatible with core performance and the harsh nuclear environment, - Demonstration of effective current drive technologies that can withstand reactor conditions and achieve high efficiency, - Development of high temperature demountable superconductors, - Reactor design and engineering studies, including concepts for tritium breeding
(Turcanu et al., 2020)	Fusion development in general	- Given that fusion is not a hot issue among most publics, it is little known and distant from daily life, properly researching public attitudes towards fusion entails important methodological challenges - Qualitative evidence confirms that nuclear fission does play a key role in the sense making about fusion, as a key device to define fusion was its comparison with fission - The general public has little knowledge about the topic of fusion energy - Confusion between fusion and fission energy is quite frequent among the general public - Fusion engagement activities should be informed by attitudinal analysis of the local and national context in which efforts are made to promote fusion awareness
(Carayannis et al., 2020a)	Fusion development in general	- Private interests in the Oil and Gas industry are still triumphing over new energy technological innovation and implementation - The rapid development of a global fusion economy would likely require an international program of enormous scope and size - The responsible development of fusion reactors is not a given and will likely be determined by three factors that depend on domestic policies and politics as well as international regulation - 1) Technological trajectory of global energy policies (fusion development pathways and timetables). - 2) Management of a peaceful power transition between rising and declining powers (geopolitical conflict management). - 3) Overall acceptance of the nuclear normative order (IAEA regulations). - Geopolitical tensions could hinder fusion development - Because of the high level of technological complexity and secrecy inherent in private-sector fusion IP, the fusion market risks market failure due to information asymmetries - Early technological lock-in (Tokamaks attract most of the funding)
(R. Pearson, 2020)	Fusion development in general	- Materials (Supply chains, environmental impact, carbon footprint, international trade, what are the costs of new materials?) - Tritium Breeding Blankets & Tritium Handling (Blanket lifetime and consequent reactor downtime, maintenance costs, enrichment of lithium-6, scarce materials, tritium supply and use regulations) - Waste & Remote Handling (PR challenge for social acceptance, lead waste, regulations and costs of waste handling, downtimes etc) - Balance of Plant Systems (what are the costs, safety standards and regulations, availability and supply chain of materials)
(El-Guebaly, 2018)	Fusion development in general	- Tritium breeding ratio (it is desired to do tritium breeding in-house to negate the risk of relying on external supplies to provide/control the essential fuel of fusion devices

		- Handling the blanket degradation - Effective shielding strategy differs per fusion configuration (Tokamak, ST and stellarator) - Handling of decay heat - For ST specifically: shieling the central pillar - Handling the amount of Low-Level Waste (LLW) to ensure low environmental impact - Official guidelines and standards to regulate the recycling/clearance processes
(Lindberg, 2018)	Fusion development in general	- Path dependency & Technological lock in (currently Tokamaks) - The case of fusion is characteristic of the early, pre-commercial/pre-market conditions where path dependency in nuclear innovation arises - Unless regulators allow a flexible licensing process and regulatory framework the institutional/legislative path dependencies will create formidable barriers for ‘challenger’ technologies, especially in light of e.g., cost of regulatory approval
(Lopes Cardozo et al., 2016)	Fusion development in general	- High investment costs - Industrial capacity to realize the construction of fusion power plants (manufacturing processes, factories, dedicated machinery, infrastructure, supply chain of materials, mining of raw materials, and—importantly—a trained workforce) - Large financial risks - The cost of fusion electricity - Availability of capital for investments
(Horvath & Rachlew, 2016)	Tokamaks & Stellarators	- Confine large volume plasmas magnetically - Maintain stable plasma at pressure - Achieve high driving currents while avoiding instabilities - Develop low activation materials - Develop tritium breeding technologies - Provide high availability of a complex system using an appropriate remote handling system - Develop system licensing.
(Betti & Hurricane, 2016)	ICF direct and indirect drive	- Target fabrication - The major challenges for fast ignition (FI) are in controlling the energy and the divergence of the fast electrons. - Reducing the energy necessary for ignition - Increasing the energy and precision of shockwaves - Understanding the laser–plasma interactions at specific intensities - Increasing the inertial confinement time - Increasing the quality and/or size of the implosion - Efficient energy coupling - Level of control over the spatial–temporal deposition of laser energy - Amount of testing facilities
(Board on Physics and Astronomy, 2013)	ICF	- Integration of many complex systems - Target fabrication - Target ignition - Heat extraction - Tritium breeding - Reliability of all components to minimize downtime - High availability (high rep rate)
(Neilson et al., 2011)	MCF	- Performance of diagnostics and control systems (fitment, shielding, reliability, precision) - Heating - Reliability and durability of Super Conducting (SC) magnets - Tritium breeding in blanket

		- First wall materials and performance - High availability (maintainability is important for this) - Heat transfer and transport for electricity generation - Regulatory framework and licensing - Electricity generation
(Goodin et al., 2006)	ICF (laser fusion)	- Fabricating the precision fuel-containing capsule - Filling the targets with DT fuel - Cooling fuel to cryogenic temperatures - Layering the DT into a uniform layer - Reaching the volume of targets necessary for large plants
(Kulcinski & Santarius, 1997)	MCF (in the US)	- No perceived need for major new source of electricity production - Major drop in federal funding - Current fusion power plant concepts require very large prototypes - Fusion community does not have an economical power plant concept - Very little private industry money invested - No obvious near-term commercial applications from fusion research
(Rockwood & Willke, 1979)	MCF, but general principles that apply to Fusion in general	- Government regulation - Financial returns and amount of funding - Government involvement - Reliability - Performance and compatibility with the grid - Social compatibility (acceptance) - Speed of market penetration - Correct implementation strategy

4.1.2. Observations literature review

This first activity in the barrier identification process allows for a number of interesting observations. Firstly, the goal of browsing for different perspectives was achieved as the kind of concepts mentioned in the literature differ greatly over the different articles. The distinction between technological challenges can be logically explained by the different approaches to fusion. ICF and MCF utilize inherently different techniques and therefore face different problems. For MCF the development of low activation materials to shield the reactor vessel against high energy neutron damage is particularly important. The other prominent MCF problem is concerned with optimizing the plasma characteristics and mitigating instabilities.

The technical challenges that are often mentioned for ICF on the other hand mostly deal with the efficiency of the lasers, the coupling of energy and the complexity of producing the targets. Interestingly, no highly innovative, novel or hybrid approach that the new wave of private companies is pursuing was mentioned or described in the studied literature, stressing the need for interviews. Further reflection on the technical challenges finds a wide diversity of highly specific technical issues that are expected to be too specific for the framework and probably require attention later in the process.

Articles with a more holistic point of view, focusing on fusion development in general rather than a single technology, emphasized the importance of the government role in this process. Particularly the need for regulating the industry and constructing policy on safety and waste handling. Other frequent themes are the issue of developing technologies for breeding the element Tritium, essential for the DT-fuel that the majority of the fusion industry intends to use (Takeda & Pearson, 2018).

4.2. Results of interviews

The list of selected initiatives (displayed in **Appendix B**: Overview of interviewed fusion initiatives were interviewed guided by the interview format outlined in **2.2.3** to discuss the challenges experienced and foreseen to consequently identify barriers. The names of the initiatives have been anonymized; this was a requirement set by the partaking companies as confidential company information was discussed in the interviews. Because of the limited number of fusion initiatives in the industry, additional information such as the fusion approach have also been excluded. The findings of the interviews are summarized and displayed in
Table 4. Summarized results of interview**.**

Table 4. Summarized results of interview

Number	Barriers identified in interviews
1	- Tritium is scarce and extremely destructive to components, pushing the need for a different fuel. - First reactors will not be economically viable and will require significant subsidies - Utilizing the energy gain and produce electricity - Reaching the necessary temperatures - High and increasing capital costs of fusion plant designs - Attracting staff - Allocation of public funds (so much is going to ITER) - Lack of clarity regarding regulation
2	- Increasing the stability of the implosion - Up the repetition rate whilst maintaining safety standards - Improve shielding against neutrons - Attract more high skilled staff - Increase political will and social acceptance - Tritium breeding and regulation - Quality of supporting and engineering firms
3	- 20% of our design is still low TRL - Speed of institutions accommodate and plan for fusion - Train and increase the workforce - Building a fusion industry - Regulatory framework - Acceptance as a realistic energy source by the government and utilities
4	- Tritium breeding works on paper but needs to be demonstrated within real plant - Development of the suited regulation (role of the government) - Development of timely regulation, private companies move at the speed of innovation and can't stop their activities to wait for regulation - Increasing the frequency of the pulse (repetition rate of the shot)
5	- Understanding of turbulent transport processes work in 3d magnetic configurations - Plasma and turbulence control - Replacing the lining of the vessel with Tungsten - Fast ion confinements - Highly dependent on ITER - Government role (framework for cooperation, funding etc) - Flexible roadmap (what if ITER runs into difficulties) - IP within fusion development needs to be clarified
6	- Demonstrating Tritium breeding - Developing the performance of the blanket - Plasma physics - Development of operating plan to maintain and operate plant - Building the design effectively and efficiently - Costs of fusion energy (related to the availability of the plant) - Involvement of the industry to supply and engineer materials
7	- Development is extremely costly, funding is necessary

	- Supply chain and the availability of resources - Need for materials that don't exist yet - A lot of new people need to be trained to scale the development of fusion - Need for enough testing facilities - Governmental involvement in setting up cooperation and research programs and funding
8	- Plasma confinement - Magnetic field technology - Generating electricity from a net energy fusion reaction - Level of collaboration has significant influence - Tritium breeding - Handling the high energy neutrons
9	- Collaboration between private and public fusion programs. - Tritium breeding to keep the device self-sufficient - Staff can be a challenge, talent is coming in, but it takes time to transfer knowledge - Capital costs of plant are extremely high (billions) - LCOE is dependent on e.g. subsidies
10	- Limited budgets - Demonstrate scaling of the design - Steady state operation - Regulatory uncertainty - Staffing and poaching of staff in the industry - RAMI - Costs of fusion (capital and operating) - Building supply chains and industry
11	- High intensity neutron shielding - Technical elements (magnets, heating, measurement control and diagnostics) - Need for extensive international cooperation - Financial support - Governmental support and recognition
12	- Active cooling capacity - Development of the breeding blanket technology - Tritium breeding and handling - First wall materials - Regulation policy is still uncertain - Efficiency of the current drive - Fulfilling all parameters at the same time - Funding is difficult as plant construction requires enormous investments
13	- Tritium technology needs substantial developments - Material science, need for improving or developing new materials - No uniform regulatory framework yet, UK's approach is good while France's model is not suitable for nuclear fusion - Attracting sufficient funding, current rates should be maintained or increased - Division of funds - Slow timelines and too much focus on single projects
14	- Increasing the power, frequency and efficiency of the lasers - Increase the economics of the laser drive - Manufacturing the nano-targets with precision, high-volume and low cost - Development of a supply chain - High operational costs of ICF - Long term economic viability
15	- Improving access to supply chain and staff - Increasing the magnetic field strength - Tritium breeding - Lowering the capital costs of the machinery

	- Access to funding - Finding and attracting skilled and knowledgeable staff - Lot of uncertainty regarding European fusion regulation - Lithium is subject to price volatility
16	- Regulation is first-of-a-kind but has significant influence - Project management - Supply chain and logistics: many first-of-a-kind components - Funding issues (aligning funding with procurement expenses) - Human competences are key but scarce - Detailing the costs of operation
17	- Divertor design and manufacturing - Increasing pulse duration - Plasma control - RAMI - Material engineering - Need to train and educate skilled staff
18	- Increasing the efficiency of the laser - Improve the current target technology - Mass producing targets at low costs need up to (500k-800k a day) - Reproduce shots consistently and frequently - Difficulties in public/private partnerships - Optimal availability and usage of testing facilities - Regulation of a technology that does not yet exist - Public funding is slow
19	- Lot of uncertainty regarding European fusion energy regulation - Rising costs of lithium - Development of Tritium breeding inside the reactor - HTS need to be further developed (material engineering)
20	- Improve heating (shock heating and adiabatic compression) - Improve the control and mitigation of instabilities - Increase confinement times - Construction of new hardware - Pushing the limits of materials - Collaborations or partnerships with other initiatives - Attracting public funding is very difficult for companies that pursue an alternative approach to ICF and MCF Neutron source scarcity
21	- Increasing plasma pressure and energy confinement time - Upgrading diagnostics and measurement systems (very complicated but necessary to measure plasma density and temperatures) - Controlling the process - Neutron shielding of the central solenoid (trade-off between thickness and efficiency) - Achieve high heat load on the divertor
22	- Old testing facilities - Integration of disciplines (everything should perform together and at the same time) - Availability and capacity of engineering firms that are capable of constructing the highly advanced plants - Risk of expensive fission regulation (capital costs of fusion are higher than fission; equal regulation would make fusion uncompetitive) - Timeframe to market
23	- Further understand block ignition from radiation pressure laser drivers - Increasing laser performance (10PW) and rep rate (>1 shot/minute) - Understanding magnetic fields - Fuel understanding and development (HB11) - Computational modeling

4.3. List of barriers

This section presents the result of the first research task and answers the first research sub-question:

What are the relevant barriers to fusion commercialization?

The literature review of the 18 found relevant academic articles and the execution of 23 semi-structured interviews with fusion initiatives currently pursuing fusion development resulted in an overwhelming amount of information. To process all the material, a thorough analysis was done to extract all the relevant barriers adhering to the selection criteria posed in

The selection of the barriers was done based on i) the frequency of the barrier being mentioned, ii) the severity of the barriers and iii the information source). Furthermore, the selected barriers are required to be formulated in such way that they accommodate for all types of fusion technologies. This analysis resulted in a list of 15 barriers that are briefly elucidated in the following section. The presented list is in alphabetical order and does not contain a hierarchy.

Construction complexity

The construction complexity of (experimental) fusion reactors was not frequently encountered, but the severity of this barrier is really well exemplified by ITER; the project was and still is continuously troubled by delays during its construction. Although this barrier has translated into years of delay of the largest and most prominent fusion project in the world, it was not explicitly mentioned by many of the initiatives. One of them stated that a potential barrier is to build the design effectively and efficiently, whereas others implicitly referred to this barrier by stressing the availability, capacity and quality of engineering firms. This suggests that most initiatives are outscoring the construction and therefore not view it so much as a barrier for their activities currently. However, the complexity of construction was shortly but strongly underlined in literature by Buttery (2021), stating it to be "crucial" that lessons are learned from the construction of ITER. Adding to that was Surrey (2019) that stresses the need for early engagement between the fusion and engineering industry to "ensure that designs are compatible with manufacturing capability". The severity and the example of how construction complexity affects timelines in the development lead to this barrier being selected.

Cooperation between actors

It was identified almost exclusively from conducting the interviews that the behavior of the different initiatives in the sector is an important factor for the development of fusion and that the current level of cooperation between the initiatives in the sector is experienced as a barrier. The argument for cooperation is strong; it allows to leverage the particular skills and expertise of the different initiatives thereby accelerating the speed and efficiency of development. Despite the evident advantages of cooperation, there are currently numerous initiatives that are operating individually and do not interact with each other.

This is especially the case for private initiatives as they are very reluctant to share information. One of the interviewees stated that "We should strive for mutual benefits, but we find that private initiatives only want to profit from public research, and they don't give back". This phenomenon was further exemplified by some of the companies hardly publishing any information about their progress and research while ideally openly exchanging technology and information would help everyone in the field. The selected literature

Cost of energy (COE)

The competitiveness of fusion energy in terms of costs was already used as an example to demonstrate potential barriers in the **Conceptual analysis** and the price competitiveness of fusion was also selected to be a relevant barrier within this research although it was not as frequently encountered in the identification process as some of the other barriers. However, the line of argumentation is strong and logical: if the price of fusion power (accounted for externalities and subsidies) is uncompetitive with other energy sources, there will be no place for it in the market and hence fusion energy will not commercialize. This was already mentioned by Rockwood & Willke in an advice to the Department Of Energy (DOE) of the US. This barrier was further supported in literature. (Halem, 2018; Lopes Cardozo et al., 2016)

The competitiveness of the price was only stressed in a few of the twenty-three interviews. Instead, initiatives had the tendency to mention the specific costs that contribute to the final costs and expressed their worries about the Capex, the OPEX (fuel costs, maintenance and the regulatory expenses). One of the initiatives stressed the importance of the CAPEX and warned that if CAPEX is really high, the plants will not be build; If the plant costs are so large that no institution dares to take on the risk individually, there is no chance that such plant will be constructed. Because all these costs all constitute to the total cost of fusion which will be translated into the COE, these statements further strengthen the selection of this barrier.

Difficulty in raising funding

Attracting the funding for fusion development and the realization of commercially available fusion energy was found to be a prominent barrier during the identification task. The matter was brought up in almost all interviews and marked by 18 out of 19 FIA survey respondents as a major barrier for fusion development towards 2030. It was articulated by several interviewed companies that their current funding does not allow to undertake all research activities they want to and that certain challenges could be solved quicker if they had more funds available. The consensus is that money is to a certain degree a catalyst that can accelerate the development towards commercial fusion, with the same logic a lack of funding poses a significant barrier.

The presence of this barrier was underlined in literature too (Buttery et al., 2021; Carayannis et al., 2020b; R. Pearson, 2020; Surrey, 2019). A study by Halem, (2018) specifically looked into the financing of fusion energy and explained that “The high upfront costs, lengthy delay in payoff, and high risk of commercial success have historically restricted funding interest to a niche set of investors”.

Energy production

It was found that once fusion advances to a level of net energy gain, actually harvesting energy from the reaction is a challenge that remains to be solved and was identified as a barrier towards commercial fusion energy. This barrier is selected as twofold within this research. The first is actually harvesting the energy from the reaction. The energy is released in the form of heat, however, all current efforts at fusion aim at electricity production. Interviewees identified a number of challenges, of which extracting the heat from the reactor is the most important and this was supported in literature by numerous articles. (Buttery et al., 2021; Gaio et al., 2022; R. Pearson, 2020; Surrey, 2019). Heat extraction and subsequent energy conversion technologies are still in the infancy stage for fusion and one interviewee explained that it had not been a priority in past research as first the technology itself has to be proven.

The second predicament regarding energy production are the properties of the technologies as a powerplant and was identified by the more mature private fusion companies. They view fusion technology as a free-market product that will only be successful if its properties conform to the needs of the market. The power capacity, power output durations and continuity were stated as relevant and decisive properties for the success of the technology wants it moves to the commercial domain.

Fuel cycle technology

It was recognized in literature and during the interviews that fuel cycle technologies are of great importance for a successful fusion powerplant concept but are currently still under development. The overwhelming majority of approaches pursue DT fusion and consequently the selected articles focus exclusively on the breeding and fuel cycle of Tritium. El-Guebaly (2018) explains that "Tritium self-sufficiency is among the most important issues that all fusion designers face" and that "it is not a choice but a mandate". Other papers confirmed the relevance of this issue and referred to the mission of a positive Tritium breeding ratio within the reactor to sustain the operation (Buttery et al., 2021; R. J. Pearson et al., 2018)

The importance of developing the fuel cycle technology was also regularly stressed during the interviews which also included a small number of initiatives that pursue fusion with other fuels, hence, the formulation "Fuel cycle", instead of "Tritium cycle". Despite the overwhelming majority of interviewees stressing this barrier, a few very bullish private companies believe it is only a matter of time. One of them stated: "We know it can be done because the science is there, we just need to execute it". Still the barrier is selected given the frequency and the line of argumentation.

Governmental support

The role of the government was highlighted extensively both in literature and during the interviews and the description of this role was found to be multidimensional and include scientific support, subsidies, facilitating cooperation and increasing public acceptance. Historically, governments have been responsible for fusion development and while many private companies are aiming at shortcutting the timelines of the public sector, they still rely on certain gap technologies to be developed publicly and hence this can be a barrier (Carayannis et al., 2020; R. Pearson, 2020). Private company interviewees are somewhat ambiguous on this, while almost all of them recognized a continued need for public research, there are claims that the role of the government has shifted to a more facilitating role.

They state that the government is not doing enough to facilitate cooperation and public-private research programs and this hinders the speed of innovation. The need for government involvement in facilitating cooperation was also pointed out by the interviewees as well as the role of the government to subsidize fusion development. Additionally, a paper by Turcanu et al. (2020) pointed out that public acceptance is also a potential barrier towards commercial fusion and this was confirmed by several interviewees. One of the interviewees summarized this barrier as follows: "The breakthrough of any important technology is inseparable from the recognition and support of the government and the public for the technology, which is what needs to be strengthened at present".

Hardware

The technical components and subsystems that are vital for fusion designs are complex and plentiful and are summarized under the term "Hardware", which was found to be a barrier after frequent identification in interviews and literature. The term encapsulates many technology specific components that were encountered during the identification amongst which were High Temperature Superconducting (HTS) magnets, lasers, targets and divertors. Many of the interviewees formulate desired specification for their components. Hardware that was commonly mentioned by MCF initiatives is the strength and performance and cooling of the magnets, breeding blanket technology and the needed development of a divertor (heat exhaust). Commonly observed hardware components for ICF were the efficiency, power and repetition rate of lasers and the advancements of the fuel containing targets.

These findings are substantiated in many articles in the obtained literature of which an article by the Board on Physics and Astronomy (2013) describes the need for hardware components in ICF and (Buttery et al., 2021; Neilson et al., 2011) describe MCF required hardware of which the latter article gives an example of how upgrading hardware components can benefit the overall design: "Advancements in magnet technology my permit higher magnetic fields and current densities. Such advances would be favorable for reducing machine size". Pearson et al., (2020) performed a case study on a private fusion start up and identified a list of gap hardware specific for that company, amongst which were HTS, divertor and supporting components for fueling and heating. His work provided further context and characterizes the development of fusion hardware as an "expensive and complex" process with "unavoidably high front-end risk"

Investment costs required

The investment costs that are associated with fusion was mainly identified as a barrier during the interview activity as the people that are running these initiatives are responsible for the investments and expenditures of their organization and know from first-hand experience how expensive the endeavor is. Amongst the factors that cause the development of fusion technology to be so capital intensive is that fusion makes use of the state-of-the-art technology, specially designed materials, makes use of highly skilled and expensive employees and many more. Moreover, the required investments costs also affect the speed at which the technology can be deployed once it is developed. It was widely acknowledged during the interviews that as the fusion initiatives move from building experimental devices to pilot plants and then towards complete fusion plants, funding needs will reach new orders of magnitude (i.e., going from tens/hundreds of millions to billions).

The costs of fusion development were also encountered within the selected literature. The paper of (Lopes Cardozo et al., 2016) presents theoretical models on the investment costs required to grow the industry once the technology is available and concluded: "The bottom line is that the development of any new energy source calls for an investment of a few thousand billion dollars before global net energy production reaches a level at which payback starts"

Plasma science

Achieving energy gain from fusion is a very strict requirement for fusion energy to become commercial and it was widely acknowledged in literature and the interviews that plasma science plays a crucial role in solving this puzzle. However, both literature and interviewees agree that advancements in plasma science are needed. One of the initiatives stated: "We don't yet have the level of plasma science that is necessary for our next device", demonstrating that this barrier can seriously hamper the development of fusion and has the potential to be very severe. Many other interviewees pointed out a number of specific plasma science issues of which most deal with plasma confinement such as plasma instabilities, turbulence but also with the heating of plasma. These issues are also described by numerous articles in the obtained literature (El-Guebaly, 2018; Horvath & Rachlew, 2016; Neilson et al., 2011; Surrey, 2019) The idea is that if these issues are better understood, they can be mitigated and the performance of fusion can be increased.

Radiation shielding

Fusion reactions produce radiation that can be harmful and damage the surrounding reactor components and therefore shielding is required to protect against irradiation damage. This was often referred to as Neutron shielding as with the exception of a few fuels, this radiation is in the form of high energy neutrons. In an assessment study, El-Guebaly (2018) presents a list of design requirements with maximum radiation limits for every specific component and explains the challenges to adhering to these limits. All specialized components should provide a shielding function to collectively ensure the integrity of in-vessel components over the course of their operational life, and this should be incorporated during the design of the reactor (Surrey, 2019). Moreover: low-activation materials need to be developed that have the correct properties for shielding against the radiation (El-Guebaly, 2018; Horvath & Rachlew, 2016)

The same points were also raised during the interviews and radiation shielding was also identified as a barrier that is currently faced in practice. One of the interviewees stated that "neutrons literally turn metal into dust" and exemplified the problematic effects by pointing towards the downtimes of JET caused by radiation damage. The relevance of the barrier was further substantiated by the results of the FIA survey.

RAMI

Once energy producing fusion powerplants are up and running, new issues arise that are already identified as potential barriers by a few articles and initiatives and this is referred to as RAMI. Neilson et al. (2011) describes the need for high powerplant availability and argues that this requires reliability and inspectability of components and efficient maintenance plans. This was underlined by El-Guebaly (2018) who referred to this by the common term RAMI[1]. Surrey's article (2019) specifically describes engineering challenges and stresses that RAMI should be accounted for already during the design of the technology.

One of the initiatives explained that ensuring good RAMI performance will be a challenge due to the complexity of the machines. Many high-tech components are closely integrated and moreover can be damaged by the high energy neutrons from the reaction. Although this barrier was identified by a few of the initiatives, it should be noted that it is not seen as one of the urgent barriers currently. This was shown in the complementary FIA survey that shows that the majority of the respondents view this as an issue after 2030.

Regulation

The regulation of fusion was found to be a highly interesting barrier that was frequently encountered in the selected literature with multiple authors stressing the need for and importance of fitting regulation (Carayannis et al., 2020a; Horvath & Rachlew, 2016; R. Pearson, 2020). Rockwood & Willke already described "an urgent need for regulatory stability" back in 1979, stating that "uncertainties in these areas of public policy are perhaps the greatest deterrent to the commercialization of novel energy technologies", concluding the argument by pointing at the burdensome experiences with the regulation of fission. What is so fascinating is that these warnings were described more than four decades ago but are the exact problems that are experienced within the industry today.

Many of the interviewed initiatives confirmed that policy making and regulation is slow and that they experience the regulatory uncertainty that was warned about in literature. As of today, there is no uniform regulatory framework as this differs per country and many specific elements regarding fusion energy are still left undecided. Multiple initiatives expressed concerns about fusion being regulated under the same framework as fission one of the interviewees explained: "the fact is that the capital costs of fusion are higher than those of fission, the same regulatory costs would put fusion out of business even before entering the market"

Staffing

Interestingly staffing was identified to be a barrier towards commercial fusion energy solely based off the information gathered from the interviews. None of the selected articles mentioned the role of staffing but a possible explanation for the absence of this barrier in literature is that staff became a barrier relatively recently. One of the interviewed initiatives explains that the development of fusion energy requires very specifically educated people, preferably with a background in plasma physics. The number of available new workforce is therefore limited by the amount of university graduates from a selective

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[1] RAMI stands for Reliability, Availability, Maintainability and Inspectability. It describes a process whose primary purpose is to make sure that all the systems of a machine will be reliable during the operation phase and maintain their performance under operational conditions with the best possible availability (Romanelli, 2012)

number of studies. This is also referred to as the "talent pool" and this has been steady for a long time, while the number of fusion initiatives has exponentially grown within the private sector. One of the interviewees explained "There is a lot of poaching going on in the industry indicating that staffing is an issue". This development has resulted in many initiatives struggling to attract the highly skilled staff needed to grow and accelerate their R&D activities. Furthermore, besides classical physicists, fusion initiatives require other technical skills too such as programmers, mathematicians and engineers. Interviewees state that it is difficult to attract these people as they are highly desirable by other industries as well.

Supply chains

The International Atomic Energy Agency (IAEA) describes the supply chain as "crucial for building and operating new nuclear power plants" (IAEA, 2022). The LR and interviews affirmed that this also holds for fusion power and established the "Maturity of the supply chain" as a barrier towards commercialization. One of the private initiatives disclosed that the availability of a supply chain was a key factor the decision of which country it would continue its activities and build a new testing facility. Currently initiatives mostly experience supply chain issues as a barrier for the development of their technology. The overall sentiment is that no fusion initiative is capable of developing and producing all its technology in-house and therefore has a dependency on other manufacturers and specialized companies to supply necessary materials, software or components. The article by Surrey (2019) identifies the most crucial materials and technologies that require supply chain development or improvement and states "the length of time this may require should not be underestimated".

5. Y-factor fusion framework

This chapter presents the final framework and will explain the decision that have been made during the categorization of the relevant barriers that were identified in section 4.3. Furthermore, the definition and scoring criteria are formulated for every barrier and the logic for these decisions is shortly explained to allow for a better understanding of the framework and a more accurate application. Thereby this chapter answers the second research sub question:

How can the identified barriers be categorized and scored in a standardized way?

The resulting framework is displayed in **Table 5.** Final Y factor fusion framework and a full-size version of the framework is available in Appendix E. It encompasses the 15 identified barrier spread out over 5 barrier categories that are given the following definitions: **Technology, Operation, Cost & financing, Governance and Engineering**. Unintendedly, but elegantly, every category is composed of three barriers which are given a definition and scoring criteria for the application of the framework.

Table 5. Final Y factor fusion framework

Category	Barrier	Value 0 No barrier	Value 1 Potential barrier	Value 2 Significant barrier	Definition
Technology	Plasma physics	Not	Considerably	Severely	The degree to which plasma physics understanding is lacking
	Fuel cycle technology	Advanced	Medium	Beginner	The level of advancement in fuel cycle technology
	Hardware	High	Medium	Low	The level of hardware advancement
Operation	RAMI	High	Medium	Low	The degree to which RAMI can be implemented in the design
	Radiation shielding	High	Medium	Low	The degree to which the reactor design can be effectively shielded against radiation
	Energy production	Not	Considerably	Severely	The degree to which energy production is problematic
Cost & Financing	Difficulty in raising funding	Low	Medium	High	The degree to which the required investment costs are significant
	Capital costs required	Low	Medium	High	The degree to which raising funding to finance the development is difficult
	Cost Of Electricity	High	Medium	Low	The degree to which the COE are competitive in the market
Governance	Regulation	Not	Considerably	Severely	The degree to which regulation hinders development and deployment of fusion energy
	Cooperation between actors	High	Medium	Low	The level of cooperation between the actors
	Governmental support	High	Medium	Low	The level to which the government supports the development
Engineering	Supply chains	High	Medium	Low	The degree to which supply chains are mature
	Staffing	Not	Considerably	Severely	The degree to which the availability of staffing limits activities
	Construction complexity	Low	Medium	High	The degree to which plant construction is problematic due to its complexity

The particular resolution designed in this framework is higher than the original framework of (Chappin, 2020) as the barriers are more specific and generally lower level, resulting from the fact that it was specifically developed for the fusion development space. The objective and expected benefit of its resolution is that this allows for insightful and detailed discussions on each of the particular barriers that constitute to the commercialization pathway of the different approaches.

The sections 5.1. up until 5.5. chronologically present the barrier categories that are displayed in the framework and every subsection focusses on the definition and scoring criteria of a separate barrier, intended to describe the logic and detail how the framework should be applied.

5.1. Technology barriers

During the barrier identification task, a high number of technical concepts were encountered which was unsurprising given the fact that fusion energy is still a technology in the R&D phase and therefore much of the focus and research activities are centered around the technology itself. To accommodate these highly specific concepts a set of three technical barriers were identified that are presented in the subsections below. These barriers are all centered around making the technology work and even lean somewhat towards the scientific side of fusion.

This category shows significant similarity with "Technology uncertainty" in the original framework that is explained by Chappin (2020) as "The degree to which technological reliability and performance are uncertain". However, Chappin identified this as a sole barrier, while for the fusion industry three barriers that constitute to this were identified that lead to the synthesis of this barrier category.

5.1.1. Plasma physics

Definition: The degree to which plasma physics understanding is lacking
Value 0: Not
Value 1: Somewhat
Value 2: Severely

Plasma physics was found to be a crucial element towards realizing fusion technology as understanding the properties and behavior of the plasma in which fusion takes place is the key to actually realize energy gain from this. Despite the community steadily unraveling and gaining a better understanding of plasma physics, literature and the overwhelming majority of interviewees state that further advancements are needed. Particularly in understanding how plasma can be efficiently heated, confined and how its instabilities and turbulence can be mitigated. The definition for this barrier is formulated as "The degree to which plasma physics understanding is lacking" as the lack of understanding is what poses the barrier. If significant problems are not understood, it is challenging to solve them and this will hinder the progression of fusion technology. To assess this barrier, the state of plasma physics for each technology must be evaluated to establish whether there are gaps in the understanding of its plasma physics.

If none of these are present than plasma physics poses no barrier and can be scored with a value of 0. In the case that a few knowledge gaps exist, there is a risk that these can't be solved. Therefore, this state forms a possible barrier which is scored with a value of 1. When many of these significant knowledge gaps are present this increases the chance that not all of them can be solved and plasma physics is a significant barrier (Value 2).

5.1.2. Fuel cycle

Definition: The level of advancement in fuel cycle technology
Value 0: Advanced
Value 1: Medium
Value 2: Beginner

The fuel cycle was identified as a relevant barrier towards commercial fusion energy as it plays an important role in the self-sufficiency of fusion energy operations. This constitutes to the technical performance of a fusion technology and therefore it was categorized under Technology barriers. The fuel cycle is complementary to the fusion reaction performance, once energy gain is reached, the next step is to maintain this energy producing reaction and this requires fuel cycle technologies.

Nearly all of the interviewed initiatives pursue fusion energy generation using Deuterium-Tritium (DT) fuel mix, as this is scientifically the least challenging fuel towards energy gain performance (Takeda & Pearson, 2018), there are however also a few downsides that will be discussed in 5.2.2 that cause a selected group of private companies to work around DT and pursue different fuel mixes. Therefore, the term fuel cycle is included in the definition instead of Tritium cycle. Differences in the fuel cycle also exist between technologies, particularly between MCF and ICF. This needs to be accounted for in the definition to allow uniform scoring and therefore the definition is formulated as "The level of advancement in fuel cycle technology". The level of advancement enables qualitative scoring

Value 0 indicates that the fuel cycle is not a barrier. This would be the case if a successful fuel cycle is developed, indicated by an advanced level of fuel cycle technology. This definition should be scored a value of 1 if the fuel cycle is a possible barrier, indicated in the scoring with a "Medium" level of advancement. The medium level encompasses technologies with underpinning science that are probable to work within a period of 5 and 10 years. A value 2 indicates a significant barrier and should be attributed to technologies where the fuel cycle is of such complexity that there is a significant uncertainty whether the fuel cycle can be developed at all.

5.1.3. Hardware

Definition: The level of hardware advancement
Value 0: High
Value 1: Medium
Value 2: Low

The final technical barrier to finish this category are the technical components and subsystems that are needed to create the conditions for fusion and identified hardware issues include a wide range of highly specific and technical (synonym for component/parts) wherein a number of key and frequently identified components stood out. This barrier is complementary to "Plasma physics" and "Fuel cycle" as hardware was identified to be a barrier towards the proof of concept of fusion technology. From the rather detailed specifications formulated by the interviewees and literature for various different components can be deducted that there is a necessary performance for fusion hardware and hence the definition is formulated as: "The level of hardware advancement"

To assess technologies on their hardware performance firstly the critical components of the technology must be identified after which the status can be evaluated from the interviewees and literature. When the performance of the hardware forms no barrier to the technical concept of a fusion approach it is found to be of high advancement and is scored with a value 0. A barrier exists when the hardware is limiting the performance of the technology, i.e., the plasma physics are understood but the necessary conditions can't be reached because the hardware doesn't allow for this. When the performance is somewhat limited due to the hardware it is assigned a medium level of advancement (Value 1). In this context it can be reasonably expected that the level of advancement of can be improved. If the performance is severely limited due to "Low" level of hardware advancement, this is considered to be a significant barrier that can't be easily overcome. In this case very significant and plentiful improvement are needed to get the level of advancement up to a desired standard.

5.2. Operational barriers

The second category contains barriers that are also technical but can be distinguished from the first category. The purely technical, almost scientific, barriers are encountered in making the technical principles of fusion energy as a technology work while the operational barriers are encountered during the continuous operation of the technology and generally, they should be viewed in a longer timeframe. They deal with the longer-term operation of the powerplant rather than the proof of concept.

5.2.1. RAMI

Definition: The degree to which RAMI can be implemented in the design
Value 0: High
Value 1: Medium
Value 2: Low

The lifecycle of commercial fusion plants is crucial for the overall cost, success and sustainability of the technology and RAMI was chosen as a good indicator to describe the lifetime as it contains a fourfold of factors that are really important for ensuring a longer lifetime according to the information gathered in Chapter 4. The argument is that as a consequence of low RAMI, downtimes will be lengthy and frequent and will result in complex and costly maintenance. Despite the fact that all factors must be considered, the priority of the interviewees was mostly on ensuring that these machines can be maintained. Assessing RAMI for the selected technologies is complicated as the final commercial designs are still unknown and it requires deep technical knowledge. Furthermore, no reactor has been operating the lengths and frequencies that are comparable with commercial power production. To seek insight into this barrier the complexity of the design can be assessed, when the components are highly integrated and interconnected this generally lowers RAMI performance (Gaio et al., 2022). Another indicator during this point in time in the performance of previous testing facilities in terms of reliability and maintenance issues as well as the expected problems mentioned in the interviews.

The definition to be assessed is "The degree to which RAMI can be implemented in the design". This is not a barrier (Value 0) when RAMI measures are high in the design and reliability and maintainability are strong. RAMI is potentially a barrier when it can't be ensured fully in the design and the performance of the technology is considerably hindered by unexpected maintenance and downtimes. This is scored with a value of 1 when these issues are likely to be resolved or significantly lowered in the next generation of the design. RAMI poses a significant barrier when the technology is continuously plagued with reliability and maintenance issues that significantly hinder the performance and are unlikely to be resolved.

5.2.2. Radiation shielding

Definition: The degree to which the reactor design can be effectively shielded against radiation
Value 0: High
Value 1: Medium
Value 2: Low

The radiation that is released by fusion reactions can cause severe radiation damage to the reactor vessel and components and to prevent this radiation shielding must be implemented in the design to protect the plant and increase its lifetime. It is therefore complementary to RAMI, however where the former looks more at the design holistically, radiation shielding was selected as an independent notion because it was identified as such in the barrier identification task. The importance of radiation shielding was highlighted extensively in interviews and literature and issues encompass the shielding design, geometry of the device and the development of inactive materials that repel the radiation.

The definition of this barrier is formulated as: “The degree to which the reactor design can be effectively shielded against radiation” and to assess this degree of shielding the selected technologies must be reviewed. This includes the amount and type of radiation that the technology produces but also the geometry and design of the technology. More insight into the current state of radiation shielding can be found in the interviews although many initiatives currently work around this by using lower performance fuels that don’t emit harmful levels of radiation. If a technology can be effectively shielded, there is no barrier (Value 0) and this can be because of the type of radiation, the shielding can be done highly advanced or a mixture of the type of radiation and shielding that eliminate this barrier. A value of 1 should be attributed if shielding can be done to a certain degree, but radiation still damages components and requires unforeseen repairs. This score indicates a state where shielding is not good enough yet but shows potential to be improved. Value 2 signifies that the state of shielding technology only allows for low effectivity shielding, hence resulting in severe radiation damage. Furthermore, in this scenario it is dubious whether the needed improvements can be made within one generation of devices.

5.2.3. Energy harvesting

Definition: The degree to which energy harvesting is problematic
Value 0: Not
Value 1: Considerably
Value 2: Severely

Energy harvesting was found to be twofold; firstly, the technical process of actually extraction the heat and subsequent energy conversion was identified as a barrier. Secondly, the powerplant properties in terms of energy output was stated as an important factor to be considered when bringing the technology to market. The logic is clear; if the energy produced within the fusion reactor can’t be extracted, there is no energy output and if the energy output properties are undesirable this affects the adoption of the technology. To accommodate both arguments into one barrier definition, it is formulated as follows: “The degree to which energy harvesting is problematic” that encompasses both the state of the technical process as well as the output properties. As the former is currently a more prominent issue, it receives priority in the scoring.

A value of 0 indicates that energy harvesting is not problematic for a certain technology, indicating that the energy can be extracted with a similar efficiency as other powerplant technologies. Additionally, the power output properties do not cause adoption delays in the market. Energy generation is a possible barrier in the case that the current efficiency is subpar or energy generation not yet possible but anticipated to be solved imminently (Value 1). This barrier is scored as significant (Value 2) when energy extraction is not yet possible and will require significant technical development.

5.3. Cost & Financing Barriers

The third category that was constructed of the selected barriers deals with the costs and financing of fusion power and the name of this category is identical to that of Chappin (2020). The identified barriers it contains show great similarity but are tuned a little bit to accommodate the findings of the research better. The barrier identification phase encountered a list of barriers that are related to the economics of both the development of-, as well as the actual deployment of fusion energy.

5.3.1. Investment costs required

Definition: The degree to which the required investment costs are significant
Value 0: Low
Value 1: Neutral
Value 2: High

The barrier identification task not only confirmed once more that fusion development is incredibly capital intensive (Halem, 2018) but also found that the required investment costs were seen as a barrier by the pursuing fusion initiatives. Moreover, literature and interviews agreed that the costs needed for fusion development will reach new orders of magnitude, but predictions at this point are difficult and exposed to a high degree of uncertainty. This was exemplified during the interview with the Korean Fusion Energy (KFE) program where the cost estimations for the Korean DEMO reactor ranged between 10 and 20 billion dollars. Given that this example demonstrates the cost uncertainty of realizing one single testing project it follows logically that the uncertainty regarding the costs of commercializing a technology is so large that this barrier can't be assessed quantitively.

Therefore, the definition "The degree to which the required investment costs are significant" was formulated which will be assessed on the tripartite scale. It is evident that the required investment costs are incredibly high for all technologies and too uncertain to be quantitatively scored. This has led to the decision being taken to assess the technologies relative to each other. A value of 0 is attributed to the technologies with the lowest expected required investment costs. Technologies with an average expected cost are scored with a value of 1 and the technologies with the highest expected costs are scored a value of 2. To make these cost estimations the roadmaps and associated costs of the various technologies must be analyzed and compared as well as the overall maturity and availability of facilities.

5.3.2. Difficulty in raising funding

Definition: The degree to which raising funding to finance activities is difficult
Value 0: Low
Value 1: Medium
Value 2: Large

The difficulty in raising funding was flagged as an important barrier in the selected literature and this was confirmed by almost all interviewees. This barrier is complementary to the Investment costs required (5.2.1.) for fusion technology as it describes the difficulties that can persist in raising the required investment costs; when the required investment costs are low but it is very difficult to raise money, a barrier towards financing still exists, and vice versa. It was ascertained that the difficulty in raising funding is a relevant barrier towards commercial fusion power and to assess this barrier its definition was formulated as “The degree which raising funding to finance the development is difficult”. This indicates that this barrier is to be assessed qualitatively and this was decision was made due to the meaning of value 0, which describes that no barrier is present. It follows from the uncertainty of 5.2.1. that it is unknown how much funding is necessary and that the amount of required funding is expected to differ between the technologies. Hence it is not possible to

Hence, “The degree to which raising funding to finance the development is difficult” is assessed qualitatively. A value of 0 indicates that there is no barrier which means that the assessed technology experiences a low difficulty and is able to attract enough funding to pursue its planned activities. A value of 1 indicates that a technology experiences difficulties of a medium level and that this is a possible barrier. This applies when funding somewhat limits the activities and speed of development of a specific technology. The value of 2 is attributed to technologies that experience raising funding as a significant barrier; these are strongly limited by their funds and can’t pursue many activities due to lack of capital. To assess this barrier, the funding patterns of the different technologies can be analyzed and compared to evaluate if the availability of funding limits the activities of the different technologies.

5.3.3. Cost Of Electricity (COE)

Definition: The degree to which the COE are competitive in the market
Value 0: High
Value 1: Medium
Value 2: Low

The line of argumentation for identifying “COE competitiveness” as a barrier is strong and logical: the position of fusion electricity in the market is determined by the price and therefore the commercialization success of fusion energy is dependent on how that price compares with the rest of the market. This is translated into its definition which is formulated as “The degree to which the COE are competitive in the market”. This competitiveness depends on the market price and the COE, and this will change over time. Despite some companies already putting forward estimations regarding the LCOE of their envisioned commercial powerplant, this is currently so uncertain that it does not allow for scoring the technologies quantitatively. In addition, both values can change over time and therefore carefully formulating qualitative scoring criteria is more valuable and robust over time.

A value of 0 is assigned to technologies with a high degree of competitiveness meaning that the COE is very close (and preferably lower than) those of other baseload energy sources. The CEO is possible barrier for technologies with a medium competitiveness, this applies to technologies with a higher electricity cost than competing energy sources and this is scored in the framework with a value of 1. The logic is that with further development this gap can be bridged. When the costs are substantially higher than those of competing sources there is a significant barrier and a value of 2 should be attributed to the technology.

5.4. Governance and behavior barriers

The fourth category of barriers is called "Governance" and contains three barriers that deal with the governance of fusion energy and how the actors within this system behave. The identified barriers below occur throughout all stages of the fusion commercialization, currently they affect the research and development of fusion energy, but also influence the eventual deployment and success of fusion energy in the market.

5.4.1 Regulation

Definition: The degree to which regulation hinders development and deployment of fusion energy
Value 0: Not
Value 1: Considerably
Value 2: Severely

Regulation was very frequently encountered during the barrier identification task and despite pleas and for clear and well-defined regulation of fusion energy going back to 1979, almost all interviewed initiatives identified regulation as one of the most severe barriers today. A big part of this is caused by the current unclarity which is a problem as fusion initiatives need to know the legal "framework" they are operating in, preferably in advance to avoid unexpected problems or delays. Not only is there a fear in the industry for being regulated as fission, but they also emphasize the importance of timely and clear regulations that enable them to move at the speed of business and prevent them from being slowed down by long bureaucratic processes such as licensing processes for testing facilities and new powerplants. These can also be very lengthy, taking up to ten years in some cases.

To accommodate this context the definition of this barrier is formulated as "The degree to which regulation hinders development and deployment of fusion energy". This barrier is not present for a technology when there is no hindrance, scored with a value of 0. This signifies that the safety and fuel handling regulations are known and do not pose unreasonable requirements and that the licensing processes are clear and do not lengthen the development time. A value of 1 is attributed when unclarity around aforementioned regulation issues are present and considerably delay the development. Finally, a value of 2 should be attributed in the case that regulation is known and severely slows down or stops the development of fusion energy or if regulation is so unclear that it severely hinders the activities of the initiatives.

5.4.2. Cooperation between actors

Definition: The level of cooperation between the actors
Value 0: High
Value 1: Medium
Value 2: Low

The second barrier within this category is "Cooperation between actors", which was identified to be a barrier because regardless of the evident advantages of cooperation, there are currently numerous initiatives that are operating individually and do not interact with each other. As a result, the particular skills and expertise of the different initiatives are not, or only partially, leveraged and fusion innovation is not going as fast as it could potentially be going. The reluctancy to share information is primarily present between private initiatives that have a financial incentive and intend to gain economically from their activities and logically need to protect their information and technology from competitors.

Because both the amount and the quality of collaborations are important, it is very challenging to measure cooperation quantitively. Therefore, the decision is made to assess the level and the barrier is defined as "The level of cooperation between the actors", which will be assessed for the selected technologies. To assign a score for this barrier, the community of each technology should be evaluated and interviews will be very helpful for this task as many initiatives disclosed information about their partnerships. A value of 0 indicates that the barrier is not present and should be assigned if there is a high level of cooperation for the particular technology. This is the case when initiatives are freely sharing technologies and knowledge and work together on solving issues. A value of 1 indicates that some information is shared and cooperation exists on trivial topics or science but that large breakthroughs especially concerning gap technologies are kept private. A significant barrier is indicated with a value of 2 and demonstrates that there is a low level of cooperation where initiatives are not actively working together and hardly share any information.

5.4.3. Governmental support

Definition: The level to which the government supports the development
Value 0: High
Value 1: Medium
Value 2: Low

As pointed out in 4.3. the barrier governmental support is multisided and contains multiple factors; "scientific support, financial support, subsidies, facilitating cooperation and increasing public acceptance" but the most prominent and impactful ones are scientific support and financial support. Historically fusion research is led by governments and still a lot of the work being done in the public sector, however this varies over the different technologies. Additionally, the government does not only decide what public programs to launch and pay for, it was found during the interviews that it also assigns funding to a number of private initiatives. Although the funding is covered in barrier 5.3.2. this is a measure of the government's attitude towards certain technologies. Another important aspect that will greatly determine the commercialization success of fusion energy is the subsidies that will be awarded to the first generation of fusion energy powerplants. Multiple interviewees stressed the need for this and said that this is essential, however this is not expected to be a differentiator across the technologies.
When scoring this barrier, all factors should be considered, but due to the mixed nature, the
The level of support can be considered high for a fusion approach (Value 0) if the government is stimulating the research of that specific technology both by public research and by providing financial support for public private or private initiatives. A medium level of support (Value 1) describes that the government is providing some support in terms of public research programs or funds but is not making a significant contribution that accelerates the development. A low level of support is viewed as a significant barrier and scored with a value 2, meaning that the technology is hardly or not receiving any governmental support either in terms of research or funding.

5.5. Engineering barriers

The last category of barriers is named “Engineering barriers” and can be characterized by a number of factors. First of all, they are non-monetary, they do not deal with the technical fusion process itself or its continued operation. Neither can they be assigned to the governance category as they don’t deal with the choices of actors. Instead, the barriers within this category are combined because they mostly occur during the actual engineering of fusion testing facilities and plants. Although engineering is crucial during the development phase too, these barriers are most likely to affect the deployment and scaling of commercial fusion energy.

5.5.1. Supply chains

Definition: The degree to which supply chains are mature
Value 0: High
Value 1: Medium
Value 2: Low

The development of fusion facilities requires a supply chain for delivering raw materials, semi products and highly advanced components that are needed for the construction of fusion testing and powerplant facilities. It was found in Chapter 4 that the fusion supply chain is not fully developed yet and is stated to be a barrier, especially by more mature initiatives that are currently constructing highly advanced testing facilities or pilot fusion plants and experience difficulties in sourcing everything they need. There are multiple supply chains that are needed; amongst others these include raw materials, fuels such as Deuterium, Tritium and Lithium, and highly specific components. As there are multiple supply chains to be considered and the impact of this barrier can’t be expressed in terms of numbers the following definition was chosen:” The degree to which supply chains are mature”

To score this barrier one should assess the availability of vendors, manufacturers and raw materials that are needed for the development and construction of a certain fusion approach plant. Analyzing the availability of every individual component is not realistic but as a general rule of thumb the most important components for every technology can be identified and researched. There is no barrier present when the supply chain is highly mature and all the needed materials and components are available and of good quality, in this case a value of 0 should be assigned. A value of 1 represents a possible barrier and describes the state of the supply chain where some items are of low quality or they are very difficult or even impossible to obtain at all. However, it should be noted that the industry is just getting started on satisfying the demand and vendors or manufacturers are working on bringing the needed parts to the market. Finally, the supply chain can also pose a significant barrier (value 2), where crucial components or materials can’t be sourced or manufactured and the development is significantly hindered.

5.5.2. Staffing

Definition: The degree to which the availability of staffing limits activities
Value 0: Not
Value 1: Considerably
Value 2: Severely

The interviews fort his research surprisingly uncovered that staffing or more specifically a lack of staffing is seen as a barrier for fusion development. Solving the complexity of fusion requires the world's brightest minds, this argument is evident. However, so is its context as people with such talent are limited and the competition for these people is fierce and spans across different industries. In an attempt to score this barrier, it is formulated as "The degree to which the availability of staffing limits activities". Although this barrier is expected to be highly similar for all technologies, there are a number of information sources that can be used to get more insight and potentially differentiate between the selected technologies. Specialized staff is really expensive and therefore the technologies that have larger wage budgets have a better position of attracting staff, and this is inherently linked to the amount of funding they have available. Furthermore, the size and number of initiatives pursuing a specific technology are also indicators of the cumulative number of staff already working on a specific technology and lastly it can be useful to further study the interviews.

To assess this barrier three scores are available. Staffing is not a barrier when it does not hinder or limit the activities in any way and sufficient people are available or can be hired if needed. This is scored with a Value 0. When a technology does not have enough staff available nor is capable of attracting additional employees a value of 1 is attributed, signifying that the staffing deficit considerably limits the activities that can be undertaken. When this deficit is really large, this will severely limit the research and development activities and pose a significant barrier indicated by a value of 2.

5.5.3. Construction complexity

Definition: The degree to which plant construction is problematic due to its complexity
Value 0: Low
Value 1: Medium
Value 2: High

The complexity of fusion reactors and experimental devices has proven to be precarious during the construction of the planned designs. The continuous delays over the course of ITER's development have illustrated that the construction difficulties should not be underestimated and need to be accounted for in the design. It should be noted that this barrier is difficult to assess as the final designs for commercial energy producing fusion plants do not yet exist or are not made public yet. To seek more insight into this barrier it is useful to analyze the construction processes of prior experimental reactors and evaluate the difficulties that were encountered there and assess what particular stages or components caused delays in these processes. Neither the interviews nor the selected literature focused specifically on what kind of problems were encountered and hence additional information can be sourced with a similar strategy to the original literature review to find insight on this.

The barrier is defined as "The degree to which the construction is problematic due to its complexity" and this barrier is not present (Value 0) when the construction does not pose any problems that cause the construction to have noticeable delays or quality issues. Construction is somewhat problematic (Value 1) if noticeable delays or quality issues arise because of the complexity of the design but of such order that these can reasonably be expected to be mitigated in future projects. If severe problems (are expected) to occur at construction that result in a significant barrier towards the realization of the design a value of 2 should be attributed. This indicates that the construction is highly problematic and that it is not expected that this can be solved in the short-term.

6. Y-factor analysis results

This chapter presents the application of the framework developed in Chapter 5 on the selected fusion technologies in Chapter 3. It firstly presents the results of this chapter graphically in a Y-factor curve that is constructed using the assigned barrier scores for the selected technologies. The five fusion technologies were scored by four people with considerable knowledge and experience with nuclear fusion and the results are displayed and discussed in this chapter.

6.1. Y-factor curves

The results of applying the framework to the selected fusion technologies is graphically displayed in **Figure 20** below. The figure displays the **average** of the assigned scores of the respondents. The barriers are color-coded to display the barrier categories and barriers are displayed in the legend on the right. All the separate scores as well as the average of those scores are displayed in tables in **Appendix F**: Framework application scoring **.**

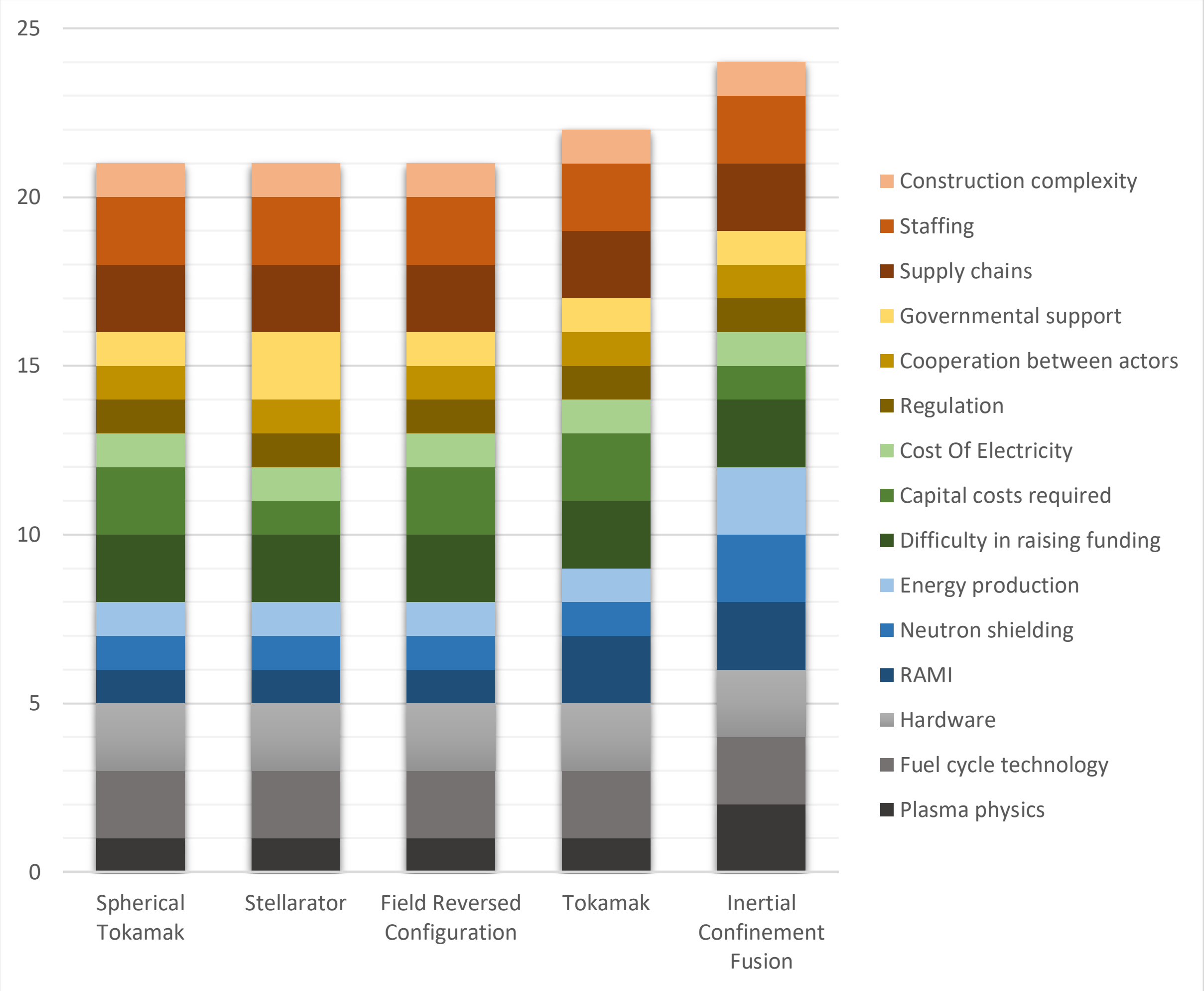

Figure 20 Integer average Y-curve

This figure is constructed using the rounded values of the average scores in order to adhere to the tripartite scale of the Y factor method. Despite the elegance, this loses a lot of information and does not accurately display the results. When the unrounded values are used, the ranking order of the technologies changes significantly and this graph is displayed in **Figure 21.**

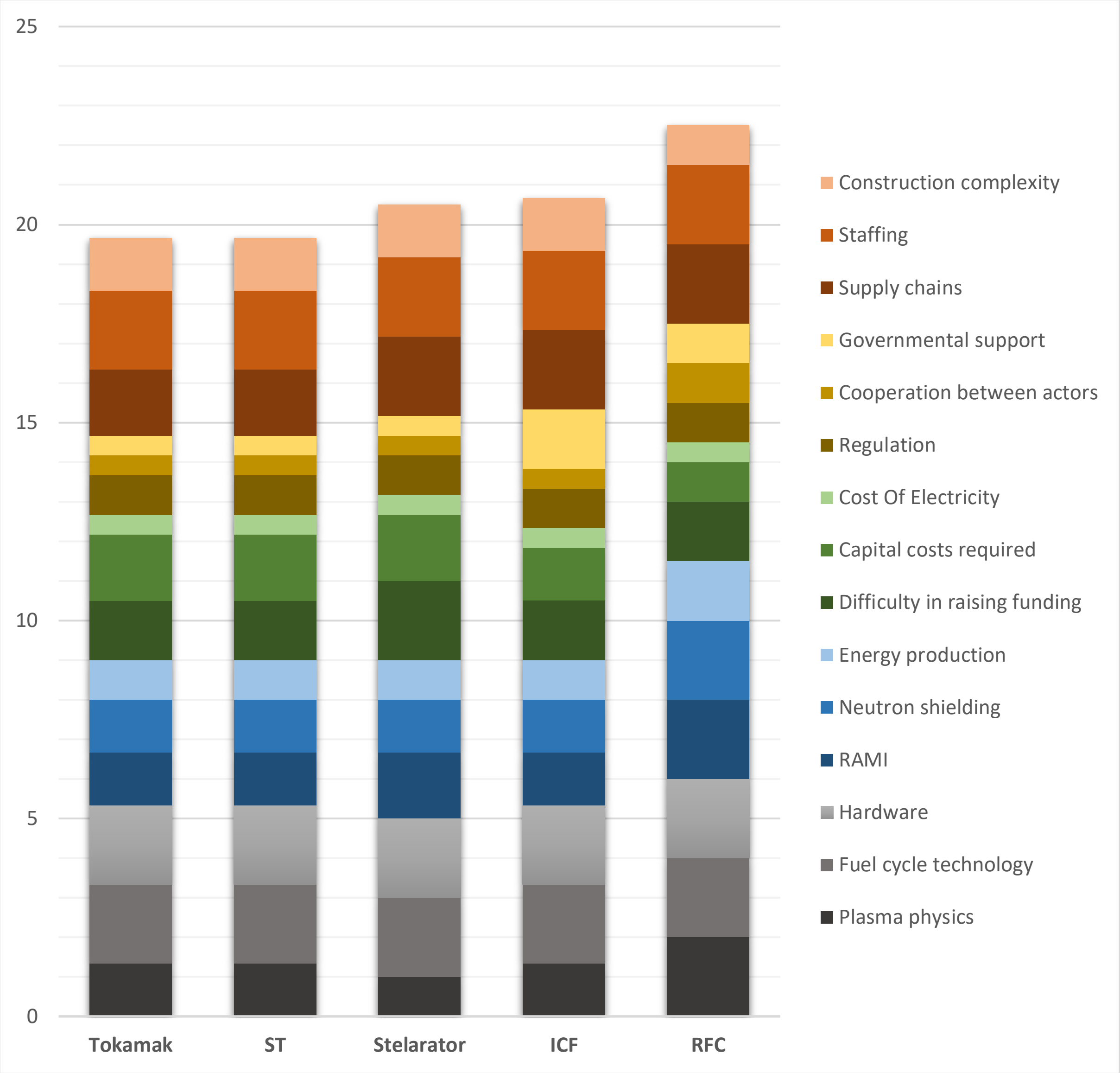

Figure 21 Continuous average scores

The average assigned scoring is hierarchically displayed from the lowest total score on the left to the highest total score on the right. The graph allows for a number of observations:

- It can be observed that all technologies have multiple significant barriers and all technologies result in high Y scores. All barriers score above 18 out of the possible 30.
- Aggregating the total scoring results in the lowest total cumulative barrier score for the Tokamak approach and highest score for FRC, suggesting that the Tokamak has the highest chance of becoming commercializing
- From the graph can be observed that Tokamaks, Spherical Tokamaks and Stellarators have a very similar scoring pattern, which can be explained by the fact that these technologies share many of the same principles. The scores of the FRC and stellarator concept show different scoring patterns as these are vastly different technologies
- Scores for the technical barriers and operational barriers very similar

Although evaluating the found Y-score curves provides some initial information, it must be noted that the awarded scores for certain barriers differed greatly amongst the respondents and a lot of valuable information can be uncovered from the individual scores and the corresponding explanation and argumentation. These are analyzed in the next section.

6.2. Analysis

During the application of the framework, respondents did not only assign scores to each barrier but were also asked to reflect on how they view the barrier, depict differences between the technologies and provide argumentation for the assigned scores. This section analyses and reflects on the most interesting findings of the obtained results. Firstly, the barriers that were unanimously scored as significant are discussed, secondly notable differences between views on barriers are highlighted and lastly the overall framework in general is evaluated.

6.2.1. Significant barriers

The Y-factor analysis revealed that four of the identified barriers are consistently scored as significant for all fusion approaches and these are elucidated below:

Fuel cycle

The level of advancement in fuel cycle technology was seen as a significant barrier for all technologies. It was highlighted by respondent 1 that "tokamaks, spherical tokamaks and stellarators will use practically the same fuel cycle technology as they all intend to use a tritium breeding blanket in a magnetically confined reaction chamber" and this view was shared by the other respondents. Respondent 2 highlighted that scoring this barrier comes down to a Technology Readiness Level (TRL) assessment and that the TRL is very low for all technologies.

It was found that the use of alternative fuels by FRC's offers some theoretical advantages in terms of fuel cycle as it will not use Tritium, but the respondents awarded it a value of 2 because "hardly any research on this has been done". The third respondent indicated that only paper studies have been published on this, but that until an experiment demonstrates this inside a reactor, serious doubts remain and hence it is a significant barrier for all technologies. It was acknowledged by all respondents that ICF has the most difficult fuel cycle as it involves fuel production, target construction and subsequently filling these targets with fuel.

Hardware

The barrier of hardware advancement was regarded as significant by all respondents. Respondent 1 stated that "Currently a handful of fusion companies are very certain they will demonstrate energy gain in the next few years, mostly relying on HTS magnets, however these haven't been demonstrated in a reactor yet so there is significant uncertainty". Respondent 2 argued that none of the critical envisioned components has been exposed to neutrons yet and therefore by terms of TRL it is a significant barrier. He also pointed out that divertors and cooling systems are all in an experimental phase.

Supply chain

It was acknowledged by all interviewees that supply chain constitutes a significant barrier towards commercial fusion energy, but sidenotes about the timeframe of this barrier were made. Respondent 2 stated that: "if you are talking about one or a few functional powerplants, there is not really a prominent barrier present currently, but if you talk about the supply chain for what we need to make an impact, it would score a 7". This score was awarded to all technologies as the respondent indicated that all technologies mostly make use of the same components. Respondent 3 substantiated this claim and explained that only a few components will be largely different, but most of the plant technology will be the same.

Respondent 1 addressed that tokamaks are likely to have a slightly more developed supply chain as more of them had been constructed including the largest fusion project ITER and also noted the supply chain of HTS tape that is used to construct HTS magnets that multiple technologies aim to use. Regarding the time frame the respondent stated that "Of course it'll take time for the supply chain to be built, but at the same time, given the time scale of development, if for the next milestone, we get some reactors working operating, then you will attract the industry engineering companies" indicating that this barrier is dependent on technical breakthroughs.

Staffing

Staffing was not found in the literature but identified as a new barrier by many of the interviewed initiatives and scored to be a significant barrier towards commercial fusion energy. In the barrier identification, initiatives mostly referred to plasma scientists, engineers and STEM trained people, but respondent 3 explained that 10's of millions of people are required to scale fusion to a size that it impacts the energy system. "This includes brilliant plasma scientists to bricklayers and will be an enormous challenge for all technologies". Respondent 2 had similar comments and also mentioned the importance of a scaling the workforce up to millions of people to impact the world's energy system and also spotted no differences in this barrier between the various technologies. Respondent 3 noted that currently more scientists are active for tokamaks but when looking into the future these differences dilute and become irrelevant as the industry scales.

6.2.2. Disagreements

When various respondents applied the framework, it became clear that they had sharp differences and opposing viewpoints on certain barriers, which led them to score them differently. Below these barriers are stated and the disagreements are delineated. For the technical and operational barriers (plasma physics, radiation shielding and energy harvesting) predominantly the views of respondents 2 & 3 are described. These respondents both have a PHD in plasma physics and are more knowledgeable regarding the technical aspects than respondent 1.

Plasma physics

The sharpest difference between the two respondents' views was observed on the first barrier: The degree to which plasma physics understanding is lacking. Respondent 3 felt very strongly about the science of alternative fuels in FRC's and claimed that the use of alternative fuels is absurd from a physics standpoint and as a result he refused to score any of the other barriers for FRC stating: "*If one of the barriers is infinitely high, there is no sense of scoring the other barriers; it is never going to work*". He scored the four other technologies with a value of 0, arguing that the science for these approaches is valid, has been well documented and is well understood. When asked if he believed that the current level of plasma physics understanding is sufficiently high for the development of a net energy producing fusion reactor the response was: "I believe so, the performance is constrained however by other variables such as the hardware".

Respondent 2 presented a very simple but strongly different view:" Nobody *has operated a burning plasma experiment, so nobody knows what the effects of alpha particles is going to be on the behavior of the plasma and the device*", thereby it is a significant barrier. He believes this is uniform for all the technologies with the exception of ICF as the record breaking shot at NIF demonstrated burning plasma for the first time, therefore this is scored as a potential barrier.

Radiation shielding

The two fusion experts also disagreed on the severity of the barrier radiation shielding but were uniform in their scoring across the technologies. Respondent 2 viewed radiation shielding as a significant barrier for all technologies, arguing that nobody had shielded a completely functional fusion device yet and only paper studies exist. He acknowledged that the realization of alternative fuels would eliminate the problem of neutron radiation but still awarded FRC a value of 2 as little to no work on shielding in FRC's has been published.

Respondent 3 stated that radiation shielding technology is well developed and that the knowhow of shielding against radiation is available. Integration in a complex machine might be more difficult, as well as making certain components neutron resilient. However, he believes that shielding technology in itself is not a barrier given the way that the barrier is phrased in the framework.

Energy harvesting
Respondent 2 evaluated energy harvesting from a practical point of view and explained that theoretically it is not extremely difficult but that to date no one has built a closed coolant loop for energy extraction in a functional device. There have been no demonstrations of energy harvested in any of these technologies but research is promising. “FRC’s have the potential for direct energy conversion that would make the process of energy harvesting much easier, but I would be inclined to give it a higher score because less research has been done on it”. In the end he viewed energy harvesting was a potential barrier for all technologies.

Simultaneously, respondent 3 had a very similar logic and reasoned: “Fusion power is generated in the form of heat, by cooling down the reactor using a coolant, the heat can be easily extracted and ran through a steam turbine”. The problem he identified is the type of coolant, as cooling with water would not be efficient in terms of physics but other and more advanced coolants are available and this will likely be no barrier.

6.2.3. Differences between the technologies

One of the research goals was to differentiate between the various approaches to fusion and research whether and how barriers are different for the various technologies. The participants were explicitly asked to delineate any differences between the technologies, however from the Y-curve can be observed that the scores across the different technologies do not differ greatly.

Respondents 2 & 3 scored nearly all technologies the same on each barrier with only two exceptions:

- Both view RAMI as a significant barrier for stellarators and a potential barrier for the other technologies
- Respondent 2 states that governmental support is no present barrier for any of the technologies but ICF and exemplified this with the amount of governmental funding
- Respondent 3 indicates that ICF has a lower barrier in terms of plasma physics due to the burning plasma shot at NIF

Respondent 1 scored with a noticeable higher variation between the technologies and assigned varying scores across the technologies at nearly half (seven) of all barriers and clearly articulate based on what differences the score is differentiated. The differences are listed per technology

- Tokamak
    - Higher capital cost than RFC and ICF as it is a larger and more complex machine. There are multiple examples of multibillion euro tokamaks
    - Lower supply chain barrier as more of them have been built and the development of ITER has further developed the tokamak supply chain

- Spherical tokamak
    - Lower supply chain barrier as the spherical tokamak is closely related to tokamak in terms of components
    - Higher capital cost than RFC and ICF as it is a larger and more complex machine

- Stellarator:
    - Lower barrier regarding plasma physics than the other technologies as they are designed specifically for plasma field optimalization
    - Higher difficulty in raising funding as stellarator initiatives are funded significantly less than the other technologies at the moment

    - Higher capital cost than RFC and ICF as it is a larger and more complex machine

- RFC:
    - Lower capital costs because it is more compact devices and initiatives are able to construct them for far less than MCF devices
    - Higher cooperation barrier as there are no public RFC programs and the known private RFC companies are highly secretive. Also, they use different technology than tokamaks so they don't rely on research from this space.
    - Lower construction complexity

- ICF:
    - Was identified to have a a number of highly different characteristics; far more difficult fuel cycle, more complex energy harvesting due to the pulsed output and a modular design that make it easier to construct and maintain.
    - However, these findings did not result in contrasting scores.

6.3. Framework

Beside assigning scores to the barriers and delineating corresponding arguments and comments, the application of the framework also resulted in more insight in the usefulness of the framework itself. As was delineated in sections **Conceptual analysis** and **Positioning and previous work**, the differences between the deployment of an available and proven technologies and the commercialization of an unproven novel technologies has inherent differences and required a specifically designed Y-factor framework for fusion energy to allow for a Y-factor analysis. The aforementioned scoring was the first application of the newly designed framework and resulted in a number of interesting findings.

Element of time

One of the complications with the adjusted framework is the strong time element that is present in defining and scoring the barriers. The inherent difference between the original framework and this newly designed adaptation is that many of the barriers were found to be dependent on future developments and the duration of time. Although during the synthesis of the framework this was observed and attempted to be limited by setting a timeframe, the element of time was found to be a limitation during the scoring process.

A good example of this was encountered during the scoring of "supply chains" and "staffing", barriers that were very clearly defined for the current situation to allow for a clear scoring scheme. It was found however that although the current situation can be scored, this is not the actual barrier. It was argued that these barriers are not present towards "a" or "a few" commercial powerplants but become highly significant once regarded on the scale of commercialization that is needed for an impact. Hence, the barrier score is influenced by the timeframe in which it is evaluated. A similar argumentation can be made regarding to the technical challenges, which are significant in the short term, but are more likely to disappear when assessed in a longer timeframe.

Because many of the barriers and their scores are characterized by a time element, they contain a high degree of uncertainty as predictions have to made to evaluate them. This is the inherent difference with the original Y-factor framework where the evaluated technologies are developed and can be scored in real time as all the factors can be assessed and don't require looking into the future.

Contingencies and hierarchy

During the scoring it was also highlighted that crucial interdependencies between barriers exist. Most prominently between the difficulty in raising funding and the technical and operational barrier category. Respondent 1 explicitly stated that funding is not long term and contingent on whether the promised results are achieved and therefore is difficult to predict. The barrier can be scored based on current and short-term funding, but that the severity of the barrier is “heavily dependent on the timescale” The third respondent even argued that with perfect information, the difficulty in raising funding would actually reflect the total barrier score of a technology arguing that it should not be treated as a separate barrier. Dependencies and interrelations can also be observed between many other barriers, and can be logically delineated., for instance: the capital costs and the construction complexity are correlated and both dependent on the technical design of the fusion approach.

A strong argument can be made that these interdependencies result in a degree of barrier hierarchy; certain barriers are more important than others. This is graphically displayed in **Figure 22.** Firstly, the technical barriers must be overcome to have an energy producing concept, then operational barriers become the most prominent issue as must be ensured that the technology functions well and sustainably. Once the technology is functional and can be operated, then the engineering barriers become prominent as these plants will need to be constructed and scaled. The barriers related to governance and cost & financing are disentangled from this sequence and can be barriers throughout the entire process.

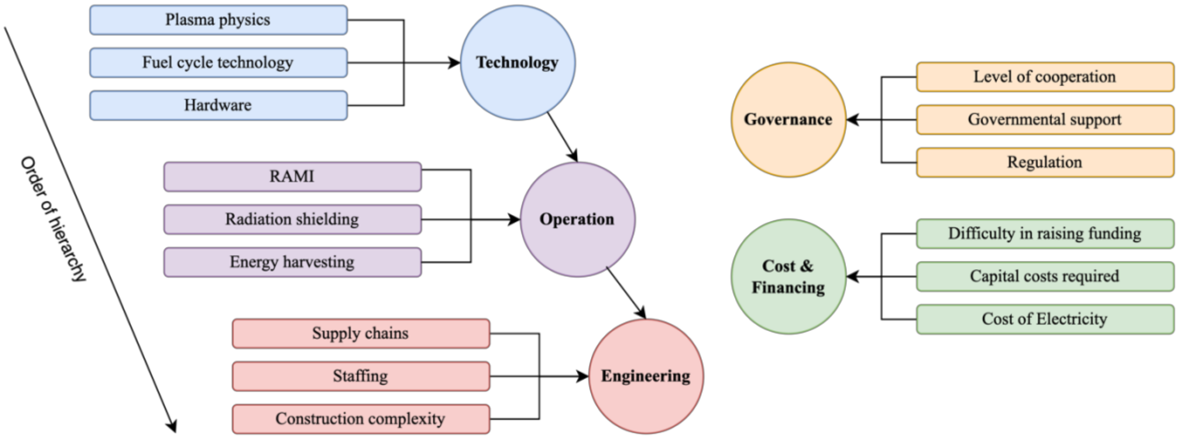

Figure 22 Hierarchy of barriers

Barrier phrasing and completeness

During the application of the framework most of the barriers were well understood by the respondents, however a few comments about the phrasing and definition of some of the barriers were made. Respondent 2 placed a sidenote at “construction complexity” and made an argument that he would personally rephrase it as “construction duration” or “the speed of deployment”. Originally labelled energy harvesting in the framework, respondent 3 corrected this to be phrased “energy extraction.

After completing the scoring of the framework, the respondents were also asked to comment on the completeness of the framework and express if there were barriers they would add to or remove from the framework. Respondent 1 felt that the framework itself was complete but commented on the scoring scale, describing that the tripartite scale is very limited and doesn’t allow for subtle differences in scores. Respondent 3 felt that FRC with alternative fuels should be excluded from the framework and suggested that tokamaks could be split into traditional (low field) tokamaks and high field tokamaks. Besides his comments on the “difficulty in raising funding” barrier he viewed the list of barriers as complete and comprehensive. Respondent 2 stated that some of the technical barriers were listed on a fairly high level and could be further specified but concluded the framework to be comprehensive and even found it to be highly similar to his methodology that he uses to evaluate fusion companies for fusion investors.

Scoring system

The respondents stated that the tripartite scale was really constrained and during the scoring they often hesitated between assigning one of two values. Several times they expressed that the "actual" score was between two values, or that a certain barrier was actually a far higher value than 2. On the one hand the tripartite scoring scale absorbs small differences and information as these are not displayed in the quantitative output of the framework. However, on the other hand the constrained scoring system caused the respondents to want to elaborate on their choice. A sidenote was frequently posted stating that a barrier was challenging to score or was still very uncertain because future developments heavily influenced it. Although the scores themselves are relevant outcomes, the justifications and observations are significant because they offer more understanding.

7.Conclusion and discussion

This chapter concludes the research by answering the research question and discussing the value and limitations of the research. Three research tasks were outlined in the **Research Flow Diagram (RFD)**Figure 2. Research Flow Diagram and formulated to systematically answer the corresponding sub-questions. These are described below and the outcomes are used to synthesize the answer to the main research question and conclude the research. This described in section 7.1. Subsequently, section 7.2 will discuss the limitations that were encountered during the research and discuss possible directions for future research.

7.1. Conclusions

This section is aimed at answering the research questions and concluding on the findings of the research. Firstly, the separate answers to the sub-questions are discussed and afterwards these will be consolidated to conclude on the main research question and finalize the research.

7.1.1. Answers to the sub-questions

The research was structured according to three research tasks with corresponding sub-questions. The first research task was to identify barriers for commercial fusion energy and was guided by the following sub-question:

- ***Sub-question 1: "What are relevant barriers towards the commercialization of commercial fusion energy technologies (Tokamak, Spherical Tokamak, Stellarator, Reversed Field Configuration and Inertial Confinement Fusion)?"***

Before starting the identification process, a conceptual analysis was performed to formulate definitions for the terms "commercialization" and "barrier". Commercialization was defined as "*Process of turning an idea into commercial products or services by commercially developing Intellectual Property (IP) that has been created through research, with the goal of creating successful commercial outcomes which have a positive impact on wider society*".

Using this definition, numerous requirements for fusion technology to become a commercial product could be inferred and a barrier was described as "a factor that hinder the fulfillment of such requirement". Using these definitions, an extensive literature review and twenty-three interviews with fusion initiatives were performed to gather an enormous amount of information. Using a set of selection criteria, a comprehensive list of fifteen barriers was identified. For every barrier, the logic for the selecting it was presented as well as an explanation of how it hindered the commercialization of fusion technology. These are listed alphabetically below and concludes the first research task.

Capital costs required
Construction complexity
Cooperation between actors
Cost of Electricity
Difficulty in raising funding
Energy production
Fuel cycle technology
Governmental support
Hardware
Plasma physics
Radiation shielding
RAMI
Regulation
Staffing
Supply chains

After having identified the list of relevant barriers towards commercial fusion energy, the next research task was to design a framework specifically for assessing the identified barriers and gaining insight into these barriers. This research task was guided by the second research sub-question:

- ***Sub-question 2: How can the identified barriers be uniformly assessed for different fusion technologies in a standardized manner?***

The decision was made to explore the Y-factor method for this purpose and the development of the Y factor framework required a number of steps. The identified barriers needed to be categorized and clear definitions and scoring criteria had to be defined that allow users of the framework to score the barriers in a standardized manner. It was found that the fifteen identified barriers could be elegantly arranged in five categories: Technology, Operation, Cost & Financing, Governance and Engineering. Each category houses three barriers that are related via function

- **Technology**: These are highly technical, almost scientific, barriers towards the performance of the technology and the achievement of net energy gain
- **Operation:** Operational barriers deal with the functionality of the fusion technology a
- **Cost & Financing:** This barrier category was found to be highly similar to the original framework by Chappin (2020) and encompasses the
- **Governance:** These barriers deal with external factors and actor behavior
- **Engineering**: Barriers classified in this category are barriers towards the realization of the physical plants

For each of the barriers a definition was formulated along with scoring criteria to evaluate each barrier on a tripartite scale. This process is comprehensively described in **Chapter 5** each of the individual barriers. The Y-factor fusion framework is the final result of this research task and is depicted below.

Figure 23 Y-factor fusion framework

Category	Barrier	Value 0 No barrier	Value 1 Potential barrier	Value 2 Significant barrier	Definition
Technology	Plasma physics	Not	Considerably	Severely	The degree to which plasma physics understanding is lacking
	Fuel cycle technology	Advanced	Medium	Beginner	The level of advancement in fuel cycle technology
	Hardware	High	Medium	Low	The level of hardware advancement
Operation	RAMI	High	Medium	Low	The degree to which RAMI can be implemented in the design
	Radiation shielding	High	Medium	Low	The degree to which the reactor design can be effectively shielded against radiation
	Energy harvesting	Not	Considerably	Severely	The degree to which energy harvesting is problematic
Cost & Financing	Difficulty in raising funding	Low	Medium	High	The degree to which the required investment costs are significant
	Capital costs required	Low	Medium	High	The degree to which raising funding to finance the development is difficult
	Cost Of Electricity	High	Medium	Low	The degree to which the COE are competitive in the market
Governance	Regulation	Not	Considerably	Severely	The degree to which regulation hinders development and deployment of fusion energy
	Cooperation between actors	High	Medium	Low	The level of cooperation between the actors
	Governmental support	High	Medium	Low	The level to which the government supports the development
Engineering	Supply chains	High	Medium	Low	The degree to which supply chains are mature
	Staffing	Not	Considerably	Severely	The degree to which the availability of staffing limits activities
	Construction complexity	Low	Medium	High	The degree to which plant construction is problematic due to its complexity

The final research task was applying the newly developed framework to score the barriers of the five selected fusion approaches described in Chapter 3; Tokamak, Spherical Tokamak, Stellarator, Reversed Field Configuration and Inertial Confinement Fusion. Besides investigating whether and how these technologies differ in terms of scoring, this research task was also focused on testing the usefulness of the framework. The task was centered around answering the third sub-question:

- ***Sub question 3: What insights are elicited from assessment of the barriers?***

To answer this research question, the Y-factor fusion framework was independently applied by three carefully selected respondents which all possess considerable knowledge on fusion technology and the fusion industry. The process of scoring and discussing the framework with the respondent resulted in five main conclusions:

- **List of identified barrier is comprehensive**: The respondents had minor reservation regarding the phrasing and level of a few barriers, but generally verified the identified list of barriers and regarded it as comprehensive.

- **Barriers generally apply to all technologies**: Although the difference between the fusion technologies were identified and acknowledged by the various respondents, this did not result in notable differences in the scoring of these technologies. Instead, most barriers apply in a similar severity for all technologies. It should also be noted that all technologies “Fuel cycle technology”, “Hardware”, “Supply chains” and “Staffing” were found to be significant barriers for all technologies according to the three respondents of which the latter two only started to receive attention recently.

- **Experts disagree on fundamental barriers**: Two of the respondents disagreed strongly on the scoring of several barriers, such as “Plasma physics”, “Radiation shielding” and “Energy production”. The fact that these respondents both have a PHD in plasma physics, demonstrates the uncertainty of fusion development and underlines the complexity and difficulty of predicting the pathway of fusion technologies. In this particular case the differences mostly originated from the reasoning of the respondents; one argued more from a theoretical point of view while the other purely looked at results to date, exposing that the framework can be interpreted differently by different respondents.

- **Barriers have a strong time element**: The abovementioned disagreements can be partially explained by time. The application of the framework exposed that nearly all barriers are characterized by a strong time dependency and that the barrier value is heavily dependent on the timeframe it is evaluated in. Fusion technology is still under development and while an active effort was made to describe the scoring criteria as closely as possible during the synthesis of the framework, the time dependency and the interpretability that comes with it could not be eliminated

- **Hierarchy within barriers**: The application of the framework also exposed a certain degree of hierarchy within the barriers and found that there was an order of urgency within the barrier categories. A clear and logical pathway could be observed; firstly the “Technology” barriers must be resolved, afterwards the category of “Operation” barriers become most urgent and finally the “Engineering” category. This was substantiated by the scores as these categories received the highest scores. The remaining categories “Governance” and “Cost & Financing” are present throughout the entire innovation pathway.

7.1.2. Answer to the main research question

The objective of the research was to increase understanding of the barriers towards commercial fusion energy by exploring whether these barriers could be identified and assessed. Whereas the sub-questions are more targeted, the main research question to guide the research was more open ended and formulated as follows:

- ***Main research question: To what extend does standardized assessment and comparison of the barriers towards commercial fusion energy technologies increase understanding of fusion energy development?***

The answer to this main research question is mostly a consolidation of the previously described sub-question answers and considerable information was gained throughout the different tasks in the research. The identification task has deepened understanding of the barriers towards fusion energy, as it bridged the academic knowledge with empirical experiences and practical examples. This has not only resulted in more profound barriers, but also identified a new barrier that has only recently became relevant: staffing. This list is new and the first comprehensive overview of barriers towards fusion development, moreover, it is the first overview of barriers that apply to all fusion technologies.

In this research, an attempt was made to assess these barriers by customizing the Y-factor framework and this required categorization of the barriers and the development of scoring criteria. Both had never been done before but exposed that the barriers towards commercial fusion could be grouped into five categories: Technology, Operation, Cost & Financing, Governance and Engineering. The formation of scoring criteria was the first attempt at quantifying the seriousness of the issues to be solved and the concise description for every barrier has increased understanding.

Application of the Y-factor framework, thus, scoring the barriers resulted in further understanding of the barriers as multiple experts expressed their view and rating. It was found that the framework enabled insightful discussions and exposed that most of the barriers are equal for all approaches to fusion, although differences between the technologies exist and were depicted. Besides bringing to light how time dependent the barriers are, a pattern in hierarchy was also identified in the barriers that increase understanding of the pathway from the current state of fusion research. All in all, it can be concluded that the quantitative contribution of assessing the barriers was limited, however the qualitative findings have certainly increased understanding of the barriers and complexity of fusion energy development.

7.2. Discussion

After concluding on the findings, this section is intended to reflect on the research and discuss the value of its outcomes. This is done by reflecting on the academic and societal contributions of the results, placing critical notes at the validity and limitations of the research and finally by identifying the possibilities for future research.

7.2.1. Contributions

The academic value of this research can be decomposed into three main contributions which are listed below:

- **List of barriers:** The first contribution is the identification of a comprehensive list of barriers towards the commercialization of commercial fusion energy. This is the first research that has identified a complete and comprehensive list of barriers; the identified barriers transcend different domains and apply to all fusion technologies. Hence, it allows for a more complete picture of the fusion industry and allows to compare different technologies on a consistent and systematic basis.

- **Barrier insights:** The development of the Y-factor framework and its application have revealed a few insights into the identified barriers that apply specifically to fusion but potentially also transcend to other technologies. Firstly, it was found that the total Y scores do not differ greatly over the different technologies, although differences between the technologies were uncovered. Applying the framework has demonstrated that all technologies face significant barriers. Moreover, testing the framework has shown that experts can have widely different views on barriers, something that underlines the difficulty in predicting whether fusion energy will succeed and perhaps indicates that this is something that is impossible to predict at all.

- **Y-factor:** This research has also contributed to the Y-factor in several ways as it has explored the usefulness of the methodology for other applications as well as its customizability. The development of the framework for fusion was the first research in which the original framework was altered for a different purpose: commercialization of developing technologies instead of deployment of developed technologies. It was found that the simple principles of the Y-method allowed for the customization of the framework and the result was a highly specific and high-resolution framework. However, the application of the framework demonstrated that scoring the barriers for a developing technology is based on very high uncertainties and therefore the scoring was prone to high uncertainties. Still, the application of the framework was useful as it resulted in insightful discussions.

Despite the hopes for more groundbreaking contributions at the start of the research, these academic contributions do have a degree of societal relevance as the findings enable a better understanding of the barriers towards fusion energy development. The framework is well defined and enables people with limited knowledge to quickly grasp the status of fusion energy today, while policymakers and investors can use the framework for more targeted actions in an attempt to accelerate the development.

7.2.2. Validity

As one of the major contributions of this research is the identification of relevant barriers towards commercial fusion, an active and intentional effort was made to maximize completeness and correctness in this regard. To minimize the possibility of missing or overlooking relevant information, an extensive literature review was performed alongside with a substantial number of interviews. This allowed to identify barriers both from an academic and an empirical perspective and made it possible to cross check and validate. Additionally, the sheer number of research institutes and fusion companies that have been interviewed increase the validity of the barrier identification. There is however an inherent risk of researcher bias that alter the researcher's interpretation, it was tried to mitigate the possibility of bias and researcher error as much as possible by using interview formats, discussing findings with experts and developing selection criteria. However, the selection and formulation of barriers is subject to a degree of subjectivity that can't be mitigated.

The development of the framework has a higher degree of subjectivity as this was developed from the list of identified barriers. The formulation of the barrier definitions and the scoring criteria are limited by the researcher's understanding of the barrier but to minimize this and maximize the validity, all respondents were briefed identically before starting the framework application. The definition of each barrier was explained, along with a description of the scoring criteria as described in Chapter 5 to maximize the understanding and ensure that all respondents receive the same treatment and understanding of the barrier at discussion, such that their views can be compared and are based on the same understanding.

The selection of respondents contained different specializations that all contribute to the validity of the research. Two senior energy consultants scored the framework together, one of the respondents is a professor in plasma physics and fusion energy while the last respondent is a former fusion scientist that is now highly involved in consulting private fusion companies and fusion investors. Therefore, all respondents can be considered as knowledgeable and valid users of the framework.

7.2.3. Limitations

It should be noted that this research is subject to several limitations which are delineated and explained in this section. Awareness of the limitations should help to interpret the findings better and understand the validity of the research better.

Firstly, the barriers and scoring criteria are subjective and can be interpreted differently by different respondents, despite the effort to formulate these with a high accuracy and clarity. As a result, the respondents to the framework could have different interpretations. Simultaneously, because the barrier definitions and scoring criteria are newly designed, these are also constrained by the perception and interpretation of the researcher.

The second limitation is that the validation and testing of the designed framework was limited to only 3 respondents and the outcomes are therefore based on a very small sample size. The overall results of applying and scoring the framework is greatly determined by the individual views and can't be generalized. Moreover, one of the respondents refused to score one of the technologies and did not manage to score all the barriers because of time constraints, reducing the sample size even more for these specific barriers. Furthermore, one of the respondents were actually two consultants scoring the framework together, potentially influencing each other's opinions.

Thirdly, the research was performed by one researcher with no prior experience in fusion technology and given the high complexity and difficulty of the subject, it is likely that certain aspects were not completely grasped by the researcher due to the lack of experience. Additionally, the singularity of the researcher also means that the analysis and results are described from one perspective, while these may result in different insights if viewed by someone else.

7.2.4. Future research

Based on the findings and limitations, there are multiple routes for future research that could extend the work performed in this thesis. It was found that the list of identified barriers was complete as this was confirmed by multiple fusion energy experts. However, the Y-factor methodology did not fulfill all research goals as numerous barriers are highly dependent on time, interdepend with other barriers and are exposed to a high degree of uncertainty. As a result, the scoring of such barriers is difficult and up for discussion. This discovery of these limitations also provides a number of further research opportunities of which the most relevant options are delineated.

Firstly, the barriers and the barrier categories in the presented framework were "good", but the current state of fusion does not lend itself well for scoring. Instead of consulting fusion experts to score the designed framework on the tripartite scale, their knowledge could also be used to develop a more suitable evaluation method for the barriers that could offer additional insight.

Secondly, given the time dependencies present in the identified barriers, it would be highly interesting to perform an in dept analysis of the factors and events that influence how the barrier evolves over time. A deeper understanding of barrier "drivers" would allow for the development of highly detailed fusion development scenarios that could potentially offer numerous new insights. For instance, on how the success of fusion development can be predicted, accelerated and how risk can be assessed. In conclusion, given the unmeasurable societal relevance and positive impact of achieving commercial fusion energy, every bit of knowledge on guiding this process helps the mission.

7.2.5. Personal outlook on fusion energy

Before starting my thesis, I had hardly ever heard about nuclear fusion and it was something I had never considered to be a viable energy source that could contribute to decarbonization of the energy system, nor had it ever been mentioned in the CoSEM study program, despite the enormous potential. Don't get me wrong, it is completely understandable why nuclear fusion power doesn't resonate with most people; the idea of operating a machine that contains a plasma that is hotter than the center of the earth sounds like science fiction. Also, the unachievable promises in the past don't help to take away skepticism.

Nevertheless, after spending six months researching the barriers towards the realization of nuclear fusion energy on the grid, where I specifically focused on the challenges and difficulties, I am hopeful, if not almost certain, that we will see fusion energy on the grid within 20 years. During the research I was fortunate to be given the opportunity to speak to many of the CEO's and chairs of the most advanced fusion companies and research institutes in the world, many of which are true visionaries that have dedicated their lifetime to the mission of fusion energy. The advancement that are booked, the many upgrades and new testing facilities that are under construction or in the pipeline- all in combination with extreme budgets give many reasons to be excited about the future.

At the same time, this thesis has underlined that significant issues remain in the grand scheme of things, and that not all problems are solved once net energy production is achieved. Given that the industry is convinced that net energy will be demonstrated within 3 years, I would say: on to the next challenge!

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Appendices

Appendix A: Selection of literature

Author and date	Focus	Description	Type of fusion
(Gaio et al., 2022)	Challenges for the concept design of EU DEMO plant	Article lists several technical challenges for the design of DEMO plant. E.g. high active power peaks, power utilization factor, risk of instabilities in the electrical network etc.	Tokamak, MCF
(Buttery et al., 2021)	Development of Tokamak technology into a power plant	Preventing damage from the hot plasma exhaust represents a particular challenge for a compact device that must operate quasi-continuously. These concepts and insights serve as motivation to guide the necessary research and technology development	Compact Tokamak, MCF
(Turcanu et al., 2020)	Public acceptance to Fusion energy	Attitudes towards fusion energy moderately favorable. Attitude towards fusion was most strongly correlated with the attitude towards nuclear energy. Negative aspects mostly long development time, high costs, large amounts of energy needed	Fusion development in general
(Carayannis et al., 2020a)	Nuclear fusion diffusion; theory, policy and politics	GEOPEST analysis. Very different from other articles. Interesting views on geopolitical implications for the future of fusion	Fusion development in general
(R. Pearson, 2020)	Barriers to fusion commercialization	Technology innovation theory. Description of drivers and barriers to commercialization + PESTLE analysis	Fusion development in general
(El-Guebaly, 2018)	Emerging challenges and lessons learned from Fusion research	Extensive overview of challenges. Relation of technical challenges to social, environmental, and economic challenges. Description of essential criteria for a powerplant	Fusion development in general
(Lindberg, 2018)	Path dependencies of nuclear fusion	As nuclear fusion is in the nascent stages of its journey towards commercialization the implications of path dependency are significant. States set-up costs, learning effects etc.	Fusion development in general
(Lopes Cardozo et al., 2016)	Deployment model of fusion	Commercializing fusion requires an ‘investment phase’ to build up industrial capacity. Fusion still has significant technical uncertainty. Presents a Template for a fusion roadmap. Focus on required learning and scaling effects for fusion to be competitive (Horvath & Rachlew, 2016)	Fusion development in general
(Horvath & Rachlew, 2016)	Description of the challenges and possibilities of nuclear fission and fusion	Highlights the potential of fusion energy but focusses on the technical issues that should be tackled. Presents a nice list with bullet points of all the technical critical challenges. For instance, low activation materials, exhaust, tritium breeding, magnet specifications etc.	Tokamaks & Stellarators
(Betti & Hurricane, 2016)	Review of the state of the art in inertial confinement fusion research	Description of achievements to date and how they can be improved (mostly technical). Interesting comment about availability of facilities:	ICF direct and indirect drive

		This is mostly due to the lack of suitable facilities, very limited shot-time allocations on existing facilities, and the reduced size of the effort devoted to alternative concepts.	
(Board on Physics and Astronomy, 2013)	Describes the current status of ICF in the US and describes the challenges of making it an energy source	States factors that influence the commercialization of ICF. Examples: shots must happen repetitively, breed tritium, be reliable and economical. The costs of targets have a major impact on ICF plants. Capabilities to produce enough targets. Need high availability. Maintenance might be an issue	ICF
(Neilson et al., 2011)	State of the art of current DEMO plans and proposition of new roadmap and strategy for commercialization	Calls for a DEMO-1 plant that should attend problems such as inertial components, tritium breeding, powerplant configuration and maintenance etc. A lot of focus on risk in the R&D path. Very valuable list of Socio-economic and scientific/technical prerequisites + issues. Contains a schematic and useful table	MCF
(Goodin et al., 2006)	Commercial production process for ICF targets	Describes the requirements for the economics of ICF targets and mentions the technical challenges of ICF targets such as precision fabrication, filling, cooling etc.	ICF (laser fusion)
(Kulcinski & Santarius, 1997)	Potential solutions for issues in the US MCF community	Lists a number of 7 barriers that were relevant at the time. Mentions integration requirements with electric utilities and mentions involvement of private industry. Good substantiation of barriers	MCF (in the US)
(Rockwood & Willke, 1979)	Conceptual framework for commercialization of MCF to identify issues	Book provides a vocabulary for commercialization, develops a conceptual framework, states requirement and issues that can be expected. High level analysis, lots of focus on market dynamics and role of government. Lists issues as barriers: regulation, entry into the electricity industry, incentives, organizational barriers,	MCF, but general principles that apply to Fusion in general

Appendix B: Overview of interviewed fusion initiatives

Name	Approach	Information	Achievements
Commonwealth Fusion Systems	• Tokamak with HTS magnets • Deuterium Tritium	• Private company • Founded in 2018 • Based in X, USA • +$ 2.0 billion raised to date • 300 employees	• Built and tested a near full-scale, large-bore high temperature superconducting (HTS) magnet, proving a magnet built at scale that can reach a sustained magnetic field of more than 20 tesla. This HTS magnet technology will be used in SPARC and the ARC fusion power plant. • Started construction on pilot plant facility SPARC
Compact Fusion Systems	• Field Reversed Configuration • Deuterium Tritium	• Private company • Founded in 2018 • Based in Santa Fe, USA • Funding is unknown • Number of employees unknown	• Develop a conceptual design with advanced fuels • Many demonstration experiments • Fruitful work on the mitigation of plasma instabilities
CT Fusion	• Dynomak • Deuterium Tritium	• Private company • Founded in 2015 • Based in Washington USA • $23 million raised to date • 10 employees	• Demonstrated reactor-relevant power injection with P > 20 MW, toroidal currents Ip > 100 kA, and injector voltages V > 700 V. Demonstration formation and sustainment, thereby de-risking the design point for the next scaled-up prototype.
ENN	• Spherical Tokamak & Field Reversed Configuration • Deuterium Tritium	• Public research program • Founded in 1989 • Based in China • $ 200 Million raised to date • 100 employees working in the fusion division	• Built several fusion relevant devices. The two major devices are: A Small-sized Field-Reversed-Configuration (FRC) Device Constructed in 2018, called EFRC0, uses Rotating Magnetic Fields (RMF); and A medium sized Spherical Tokamak (ST) Constructed in 2019, called EXL-50 (ENN Xuan-long), which is in operation.
EUROfusion (ITER & JET)	• Tokamak pathway	• Public research program • Founded in X • Funding to date • 4800 employees	• JET is the largest and most powerful operational tokamak • Achieved a record 5 second pulse that generated 59MJ of energy • Performed a lot of important testing and proof of concepts for ITER (including maintenance, Tritium handling and supply chain development)
First Light Fusion	• High velocity impact ICF • Deuterium Tritium	• Private company • Founded in 2011 • Based in • $95 Million raised to date • 70 employees	• Demonstrated the production of neutrons, thereby demonstrating that fusion reactions happen • Optimization of fuel target design
Focused Energy	• ICF with lasers • Deuterium Tritium	• Private company • Founded in 2021 • Located in USA and Germany	• Confidential (no noteworthy results published yet) • Was granted one patent, with two others pending

		• $25 million raised to date • 60 employees	
General Atomics	• Fusion expertise company • Supports other fusion companies in research and development	• Private company • Founded in 1980 • The US Department of Energy (DOE) awarded $121.5 Million in 2019	• Highest neutron flux (fusion rate) ever achieved at the time (early 1990s) • Active and passive edge localized mode suppression mechanisms in the 2000s. • Improved boundary cooling approach, replacing a gaseous solution with a boron, Boron nitride, lithium powder mixture (2021) •
General Fusion	• Hybrid approach ICF, MCF and mechanical pistons • Deuterium Tritium	• Private company • Founded in 2002 • Based in Canada, but constructing testing facilities in the UK • +$ 300 million raised to date • 175 employees	• Selection of site for new testing facility in the UK • Over the last 4 months have been working on facility concept design. Currently moving through the bureaucratic consenting and permitting process in the UK. Permit submission. Get permit early next year. Concept design expect to complete it early next year.
HB11	• ICF with lasers • Hydrogen Boron-11	• Private company • Founded in 2017 • Based in Sydney, Australia • $ 4 Million raised to date • 5 employees	• Several Experiments in the Pipeline, • Progress on code development for pB11 Fuel interaction, Part of two different Australian Trailblazer Universities Programs
International Academy of Neutron Science (IANS)	• IANS is a research group which focuses on the fundamental research of neutron transport theory	• Public research program • Funding to date is undisclosed • Based in Qingdao, China • Employees undisclosed	• Since last year, a new project named High Intensity D-T Neutron Generator (HINEG-II) was launched, which aims to build world's top level neutron sources based on international cooperation. HINEG-II is an ultra-high D-T neutron source aimed for fusion component performance validation.
ITER	• Tokamak • Deuterium Tritium	• Public research program • Construction started in 2015 • Funding to date exceeds $ 25 Billion • +1000 employees	• Currently under construction • Planned to demonstrate Q>10 • Lessons in construction management, international cooperation, supply chain development etcetera • Cooperation between 35 countries
KFE	• Tokamak with superconducting magnets • Deuterium Tritium	• Public research program • Founded in X • Funding to date • 400+ employees	• Valuable testing of superconducting magnets (similar as those in the ITER design) • Continuously pushing the boundaries of temperature and pulse duration • In November 2021, KSTAR maintained a 30 second pulse with plasma temperature exceeding 100 million degrees.
Kyoto Fusioneering	• Kyoto Fusioneering develops	• Private research company • Founded in 2019	• Confidential

	specific gap technologies for fusion - Tritium technologies - Heating systems and other reactor components	- Based in Kyoto but people all over the world - $ 20 million raised to date - 45 employees (expected to double within a year)	- Kyoto Fusioneering works with a lot of private fusion companies that must remain confidential
Marvel Fusion	- ICF with lasers - Proton Boron 11	- Private company - Founded in 2019 - Based in Munich, Germany - $ 60 Million raised to date - 40 employees	- Putting the team together and grow the company. - Published first paper on core concept and demonstrated the approach via extensive simulations. - Done first 4 experiments that proved simulated predictions.
MIFTI	- Z-pinch - Deuterium Tritium	- Private company - Founded in 2009 - $ 9 Million raised to date - 9 employees	- Tested the idea on Linear Transformer Driver (LTD) and produced more than 10^8 neutrons for 0.5 MA machine. - Development of higher current experiments
Naka Fusion institute (JT-60SA & ITER)	- Tokamak - Deuterium Tritium	- Public research program - Founded in X - Based in Naka Japan - Funding to date is undisclosed	- JT-60SA has up to 41 MW heating power provided by two different types of heating sources targeting the electrons and ions. - The JT-60SA device is capable of confining breakeven-equivalent class high temperature deuterium plasmas lasting for a duration (typically 100 s) longer than the time scales characterizing key plasma processes
NIF	- ICF with lasers - Deuterium Tritium	- Public research program - Founded in 1952 - Based in California USA - Construction costs exceed $ 3.5 Billion	- The facility indirectly drives fusion targets with a combined 192 laser beams that deliver up to 1.9 megajoules of energy - In 2021 the NIF facility achieved a burning plasma state in which the plasma is predominantly self-heated by fusion reactions in the plasma. This is a fundamental step towards ignition and energy gain
Princeton Plasma Physics Laboratory (PPPL)	- Spherical Tokamak - Deuterium Tritium - NSTX	- Public research program - Founded in 1999 - Based in Princeton, USA - Funding undisclosed - 60 employees	- Currently constructing and procuring NSTX-U device which aims: -To produce stable, high-performance plasmas with low-cost magnetic fields. -To develop the understanding and tools required to start-up and sustain such plasmas non-inductively (i.e., without a solenoid magnet to start the process) -To develop techniques to handle and control the waste heat from fusion reactions.
Renaissance Fusion	- Stellarator with HTS magnets	- Private company - Founded in 2020	- Currently working on a cylindrical demonstrator that aims to demonstrate

	• Deuterium Tritium	• Based in France • Funding is undisclosed • 14 employees (but quickly expanding)	their fusion-enabling technologies (superconductors manufacturing technique HTS and liquid metals), without plasma. • This is the first important milestones (horizon of less than 3 years) – needed to be achieved before plasma experiments can be started
TAE Technologies	• Field Reversed Configuration • Hydrogen Boron-11	• Private company • Founded in 1998 • Based in California, USA • +$ 1.25 billion raised • 400 employees	• Reached 70-million-degree plasma temperature • Commercialized spin-off division for revenue • Raised the money for the next testing device that is intended to demonstrate energy gain
Tokamak Energy	• Spherical Tokamak • Deuterium Tritium	• Private company • Founded in 2009 • Based in Oxford, UK • $ 200 Million raised • 190 employees	• 100-million-degree plasma ion temperature in ST40 prototype.
UKAEA (JET, MAST-U, STEP)	• Multiple devices • Tokamak & Spherical Tokamak • Deuterium Tritium	• Responsible for the public fusion pathway in the UK • 1250 employees	• MAST-U is the upgraded version of MAST and is a Spherical Tokamak that is operational since 2020. One of the main objectives is to work on the heat exhaust: working on the Super X divertor aimed for (and achieved) a 10-fold improvement in divertor efficiency. • STEP (Spherical Tokamak Experimental Program) budget is 220 million pounds, currently undergoing site selection. Goal of STEP is to deliver net energy > 100MW and ensure Tritium self sufficiency
Wendelstein 7-X (Max Planck Institute)	• Stellarator • Deuterium Tritium	• Public research program • Located in Germany • Total funding undisclosed • Construction estimated to cost +$ 1.0 billion • Max Planck Institute +500 employees	• The world's most developed and most advanced Stellarator • World record for stellarator fusion product by demonstrating higher temperatures, densities and pulse durations

Appendix C: Full interview format from Trinomics study

Template for the interviews

(To be tailored for each interview)

Example interview questions

Background information and introductions

We will provide an overview of the study and why the EC is consulting

Part A - Characteristics of the initiative

Where initiative (here and throughout) refers to the fusion approach/device/company/facility as appropriate to the interviewee.

1. Introductory question to ask about the initiative(s) and for interviewee to expand on key features

[for public and private initiatives, we may consider sharing the information we have gathered (fiche) prior to the call, to help focus the interview directly on gaps]

For public initiatives:

- From review of published documentation, we are aware of the main characteristics and initiatives in fusion by your organisation. Could you elaborate briefly on:
    - Your overall strategy for fusion
    - How this is funded/supported in your country

For private initiatives:

- Based on published information on your company we have an understanding of some of the main characteristics of your approach to fusion. Could you elaborate briefly on:
- Your company and key staff
- Funding rounds and investors – how has your company approached and secured funding? Are future funding rounds planned? What are investors asking from you / looking for?

For investors, explore:

- Can you provide details on your investment in fusion (which initiative(s), how much, on which basis)?
- Why have you invested in fusion? *Probe on expectations given likely very long time until a return will be seen*
- Why in the particular initiative you've invested in?
- What kind of due diligence did you carry out? *Probe confidence on understanding the science and risks*
- Over what timeframe are you expecting to see a return? *Probe also on probabilities of any return*
- What role do you expect ITER and other public funding to play in fusion? *Probe wider understanding of fusion science, potential dependencies, public-private partnerships*
- *[skip to Part D]*

Part B – Goals, strengths, and challenges

1. What are the strengths or advantages of your initiative?
    a. *Probe, what is this based on? What sets it apart from the other initiatives? [can tailor a prompt per initiative type, e.g., if inertial confinement, ask what they do better/different than NIF, other ICF approaches e.g. First-light fusion]?*

1. Which spin-offs or other applications are you targeting or expecting?

   a. *Probe, are there potential markets/applications outside fusion? Are other applications [already/expected to be] an important revenue stream to support overall work on fusion?*

1. Which milestones has your initiative achieved in the last 12 months?
   a. *Probe, how are these distinctive? What do they mean for your initiative?*

1. Which milestones are being targeted before 2030?
   a. *Probe, what is the sequencing of the milestones? What are they contingent on? (e.g., is there a critical path? Is the development reliant on external factors?)*

1. What are the main challenges that need to be overcome to achieve these milestones?
   a. *Probe, what are the financial, technological, scientific, other challenge, and any strategies to overcome them, ask on impact of recent developments (JET, NIF, CFS magnets)*
   a. *In term of technology,*

What is the status/how you are addressing issues around: i) heat shields, ii) power multiplication(Q)/pulse duration, iii) RAMI (reliability, availability, maintainability and inspectability)? Iv) nuclear safety; v) materials (neutron exposure)

   a. *If fuel is Deuterium-Tritium (DT), How is Tritium self-sufficiency (sourcing, handling, breeding) addressed?*
   a. Could regulatory requirements constitute a bottleneck to your initiative?
      i. *Probe, to what extent regulatory barriers constitute a worry?*
   a. *Are you having difficulties to source skilled staff?*
   a. *What are the risks / likely outcomes if these challenges cannot be overcome?*
   a. *Have you already taken into consideration issues around waste, recycling, and decommissioning? Probe to what extent these issues are being addressed in the current state of the project, are they being left for later or are they already being considered?*

1. What does your initiative hope to achieve after 2030?
   a. *Probe, what is the sequencing of the milestones? What are they contingent on? (e.g., is there a critical path? Is the development reliant on external factors?)*

1. What are the main challenges that need to be overcome to achieve these long-term goals?
   a. *Probe, what are the financial, technological, scientific, other challenge, and any strategies to overcome them*
   a. *What are the risks / likely outcomes if they cannot be overcome?*

Part C- Relation to other public and private initiatives and research

1. How do you interact with other public and private organisations, including the scientific community?
   a. *Probe, role of public funding, partnerships, research*
   a. *Probe, how much competition / cooperation is there between private initiatives*

1. To what extent do you think the success of your initiative will depend on the outputs of:
   a. ITER – please elaborate
   a. DEMO – please elaborate
   a. Other public funded fusion experiments and research? – please elaborate

   Probe also - to what extent the recent record-breaking pulse by JET has an impact

   a. *Private initiatives*

   Probe [public]: To what extent do you see private initiatives supporting/contribution to the success of publicly funded fusion programmes? [private] to what extent can successes of others help/hinder your initiative?

1. Do you think the approach to fusion projects differs significantly between public and private initiatives? If so, in what ways and what can each learn from the other?

Probe value of international cooperation, efficiency, attitude to risk, speed of iteration, quality of teams, pressures to bring in/satisfy investors

1. Some in the fusion sector are sceptical of private fusion approaches, believing they only address part of the challenge(s) of fusion power, and that this focus will ultimately see these approaches struggle/fail – others believe that a private initiative will succeed before ITER is complete - what is your view?

1. How could the EU best improve its engagement with and promotion of public-private partnerships and/or private initiatives?

Part D- Foresight

Part of our work involves creating potential scenarios for future fusion development, we will collect opinions from a variety of experts to help form these scenarios. We understand there are high uncertainties but would appreciate your best estimates and thoughts.

1. ITER is anticipated to be the first fusion plant to achieve net energy (Q>1) once it begins D-T operation in around 2036. Do you think another initiative will be quicker?

1. In which year do you think the first pilot fusion plant will deliver electricity to the grid?
 i.e., will this be a public DEMO plant in 2045-2055? Or something else?

1. How do you think fusion development could best be accelerated? (Where are funding, research and resources most needed? How much faster could it go?)

1. Do you foresee any major technological advances (inside or outside the field of fusion energy) that could significantly speed the successful achievement of fusion energy? E.g., advances in superconductors/magnets, AI (e.g. reinforced learning, plasma control systems), 3D printing, precision manufacturing, materials science, etc.
 Probe what kind of impact might these have
 Probe, are they already exploring such technologies or partnerships with those?

1. How do you foresee the costs of the first commercial fusion energy plants?
    a. Capital costs [value and unit, plus capacity]
    a. Operating costs [value and unit, per MWh]
    a. Levelized cost [value/MWh]
 Probe details on each cost, possible/likely variations, degree of certainty
 Probe on potential first markets, energy system complementarities

Appendix D: Interview notes

The following section displays the summarized answers of the interviewed fusion initiatives on the challenges, issues, and barriers they experience. The companies have been anonymized to adhere to the confidentiality agreement

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Interview 1

We aim to use a fuel beyond tritium, because Tritium is scarce, destructive to components and looking at the world's supply it hard to envisage how this can be used at large scale. Whilst DT is scientifically the easiest fuel for achieving energy gain, other fuels obviously make the science a lot more challenging but do offer advantages in the long term. We have chosen for FRC because we believe that it has higher chance of practical and commercially viable fusion energy. Conventional approach has around 90% working on DT fusion, which scientifically makes sense, but once the science is done, you need to utilize the energy gain and produce electricity. At DT the energy comes out in neutrons, very harsh on components 'turn metal into dust'. If you look at JET, it did run on tritium, but this resulted in very long downtimes due to the radiation damage. Harvesting energy is difficult too. Makes DT more difficult in terms of engineering and making a viable powerplant. We look at making engineering easier but have more difficult science. Our approach has easier energy harvesting, no damage, easier maintenance. It is a lot more practical, less expensive, less waste. But it does take higher plasma temperatures to ignite.

The trick is maintaining the current in the plasma, we do this with neutral beam injectors. The efficiency between the accelerators and the energy into the plasma is high and that's why we have little doubt that we can reach the temperatures needed for pB11 fusion.

We have worked 10 years on the stability. We can control the shape and evolution. Before these reactions ran 1/million seconds. Now we can sustain it 1/1000 seconds and our reaction are limited by the amount of energy that we can draw from the grid or have stored. The science is there, we have published over 150 papers, backing up our research and we have done a lot that we can't share. In conclusion, even if we don't manage with pB11 we can still run our device with DT and it will be more economical than a functional tokamak.

We are working on our next device to prove technical viability and beyond that we hope to move towards commercial powerplants. However, these would probably not be economically viable at the outset and will require significant subsidies. But before we reach this stage, we need to have regulation and recognition to avoid adoption delays.

In terms of staffing: the field is more competitive, and the talent pool hasn't grown, maybe even shrunk a little bit. The lead-time of training and increasing the students starting in fusion is large and won't make an impact in the short term. Furthermore, we don't only need physicists but also data scientists, control engineers, etc. We are competing also with Silicon Valley companies, not only fusion. We need to offer better salaries to stay competitive.

We need to move now to prevent the problems that are forecast from climate change, we need to make available more resources, period. Look at COVID, how much can be achieved in a short time with an unlimited amount of capital. Unfortunate that on climate we don't feel the water at our feet yet. The urgency is still not felt. Regulation: fusion and fission can't be regulated the same. Currently there are EU plans that suggest this.

Barrier is lack of clarity (UK done well, US is working on it, EU should do the same) This is a multiyear effort. Regulators should be involved now already, otherwise you get behind and this slows down the adoption process once a solution has been found.

Interview 2

Currently working on improving many of the components in our machine to improve its performance. Essential topics that we are developing are:

- Plasma heating by strong adiabatic compression
- Fusion reactor first-wall
- Magnet coil
- Reactor blanket (with Li to breed T for D-T fuel)
- High-energy neutron shield
- Initial thermal reservoir for neutron energy and losses due to viscosity and magnetic diffusion
- Heat transfer medium
- Roughing pump to reduce pressure of vapor from liner and impurities by liner expansion after peak compression to allow several Hz repetition rates

Other interesting comments:
The timeline of the first fusion plant is not that much of a technical problem. Need to have the political will, convince people, and set up the right regulatory framework.

On supporting companies:
There are companies that provide supporting services or products. For alkaline metal handling, magnets, and software for instance. Not all these companies provide good service or quality. If you pick the wrong company, you can get burned (have been burned twice). Need to get the right companies.

Interview 3

Many of the required systems are high TLR (80% of tokamak is ready). The fusion industry has built 150tokamaks already, we are actually pretty far. Plasma science is harder, but once you have the right conditions in the plasma you need to build a device around it – becomes more of an engineering challenge.

On Tritium: people use tritium, it is a commercial thing. It is not a crazy thing unless used at the scale of ITER (kg's) but at the scale of 10 grams it is not such a big deal. However, there is not so much expertise in it yet within our company therefore we had to hire chemical engineers, and train people to get experience and knowledge in it, for instance by sending them to places or institutes that handle or research tritium.

We are currently building a ITER class machine for 1% of the cost and the construction of our facility is executing 10X faster than ITER (both are currently in the construction process). It is not theoretical; we know exactly how much everything costs and exactly what fusion costs. You must go out and build these things, start the procurement, licensing and construction process and then you will have a very good indication of what it costs. We are really bullish; we are executing it on the ground

We need places like ITER to provide innovation and scientific value, be a centre of excellence, to help train up a workforce. Supply chain and workforce are extremely important for scaling the technology. We need them to move in that direction. I think the EU is very late to that thinking. If SPARC works, and if we can build an industry around fusion, that would be one of the greatest accomplishments of our generation. We need to plan around that.

When we get to 2035 and the oil crunch is going to impact many, many, many industries. The fossil fuels market by that year is very uncertain. From an industrial standpoint, there needs to be a huge transition but at the moment fusion is being excluded from the energy sector. Many people within utilities are not really thinking about fusion. However, there are a lot of developments. ENI (energy company) is building a fusion division; we also see public private partnerships now. A lot of things happening in the sector. However, if this is going to be an industry, it needs to stand on its own and have its own regulatory framework. Don't put it in an existing framework just because it is convenient.

We have well established what we want from the government. We need the basic science done by the government, and much more focus on applied programs. We need to decrease the costs. A lot of scepticism still exists on certain elements needed for fusion, for instance new materials and breeding blankets. This is mainly because no one cared about some of elements, and they were not pursued so much. They have a low TRL but are not perse very difficult. Total investments in breeding blanket technology accumulate to only few tens of million dollars so far, so understandably the TRL is low (3 or less).

Interview 4

Tritium breeding ratio of 1.4 is simulated – using lead lithium mix.
Q: Breeding has been demonstrated? A: it's based on science. Not new science – most calculations have been peered-reviewed. Our calculations are based on 60 years of existing science. However, these figures are not demonstrated in experiments yet

Regulatory considerations:
UK – taken a lead and are the most aggressive in their approach. 2021 GF participated with the UK consultation on looking how the regulation might look like for commercial fusion power plant.
UK – proposed regulation will fall under health and safety and environmental agencies and will only need some further refinement

CA – regulator expected to publish a White Paper soon. Recognise there is a big difference between fission and fusion – it will be regulated different than fission.
US – second year of public meetings – by 2027 they must have a solution (regulatory) by law.

Important to note, fusion risk much lower. Accident scenarios in the fusion space, no explosion danger, no proliferation issues and much less volume and long-lived waste – discussed during a meeting yesterday. Interesting conversations are happening.

UK,CA.US – leaning towards a risk appropriate regulatory framework.
The regulation is probably there, just need to add fusion to the list – just adjustments/don't start from scratch.
Fusion should not be regulated the same as fission.
Comment from Matthew: France – some issues with ITER based on regulation being applied based on fission standards.

Fusion: no long-term, high-level waste, no nuclear proliferation. A lot of people look at ITER as a prototype – a private ventures approach is so much smaller – the tritium used/waste is so much smaller. Between 2 and 14 g vs. 24 kg in ITER
Governments had said 'When fusion is close, we will regulate it'. Now they are starting to look into it closely – sign that fusion is close.

We move at the speed of business – don't have the luxury for the regulator to spend 10 years writing new regulation. Want it to tweak existing ones.

Proposed Model:
1) recognition of fusion as an energy source that fits into strategy for decarbonisation; 2) infrastructure/programme focused on commercialisation of fusion and funding it; 3) risk-appropriate regulatory framework.
Q: Site selection FDP – did you consider sites in the EU?
A: CAN, US and UK were the main focus and shortlisted, no EU sites made it past first screening.
Brownfield sites were interesting. It came to: who can de-risk the project with funding, infra etc.? UK had the programme quicker than anyone.
Biden just launched fusion programme (milestone based) that GF was advocating for 4 years. But too late.
UK has infra, the expertise and talent, demonstrated success
EU focus is ITER – perceived that their openness to new ideas wasn't there. ITER sucked out all the budget, took away 250M in front of our noses. Programme is quite fixed.
US – budgets also ITER constrained, they wrote short checks for a couple of years, playing catch up for funding ITER.

Interview 5
There are a number of challenges that we try to solve with our experimental facility, many of these are related to plasma physics. We still have a bucket list of scientific questions – understanding fast ion confinements, instabilities, turbulence in 3D magnetic fields at high plasma pressure. We want to improve energy and plasma confinement as well as avoid plasma instabilities. Understanding how remaining turbulent transport processes work in 3d magnetic configurations is important for this. The idea is to shape the magnetic fields to overcome this. Furthermore we want to minimize or mitigate losses as much as possible and therefore we need to optimize our system.

The goal is to demonstrate several optimization criteria working at the same time at high plasma pressure. Demonstration of integrated (long-pulse (30 minutes), high-performance) operation (18GJ power throughput with working power exhaust), the preparation of metallic wall operation as expected for reactor designs and the validation of computer codes including turbulence and fast-ion physics.

The development strategy in the EU is: Validate the physics basis from the experiments and develop/foster theoretical capabilities to predict the physics for the next generation. Provide solution for generic, 3D engineering problems (examples for open questions: how could the breeding blanket look like in 3D geometries? What is a maintenance scheme of a stellarator device?

Stellarators provide a number of advantages over tokamaks but require additional research, as the stellarator concept is still 1.5 generations behind the tokamak.

The long term vision is to offer an alternative line for fusion to standard tokamaks (something like like diesel and petrol for engines). The Roadmap is quite good on this high-level risk mitigation, bringing to concepts forward which are complementary in strengths and challenges – provide a plan B, if ITER runs into difficulties such that DEMO still could be pursued with a stellarator principle. Moreover, the two lines are most advanced for economic exploitation of fusion and the physical differences offer more options for an economic future deployment of fusion electricity.

Interview 6

On plasma physics:
Don't have plasma science that is DEMO compatible yet – Part of the energy is in the neutrons. 20% is radiated in the plasma and need to spread that uniformly. Working on having a blanket which radiates uniformly.

On Tritium breeding
There are still many challenges. On paper it works, but... We are considering multiple approaches to Tritium breeding: Consider something called 'flowy lithium'. Lithium (Li) – lead (Pb) is a fluid. However, a Tokamak has a magnetic field and this can influence how the flow streams (can be, stagnation points, etc.) – this requires fundamental science.

Li-Pb – corrosive fluid. Need to work on permeation reduction layers. Aluminum oxide has shown good results, improvements by a factor of 1000.

Currently working on 4 different concepts for the breeding blanket module. 2 baselines, 2 for testing in ITER and 2 more on the R&D level. Some of the concepts could ultimately be economically more viable but more difficult to get working. We're considering one concept with Beryllium (neutron multipliers) – but found out that it would cost 6 billion EUR to fill the blanket of DEMO – need to look for cheaper solutions.

On maintenance
When operate the reactor, at some point you need to replace components (e.g. blanket modules to be replaced every 30-40 years). Cost of fusion is also related to availability of the plant. Expensive infrastructure but should be running for a long time. Maintenance needs to be efficient.

Building – need to design in a good way. Not in the way ITER is doing. They designed the building at the same time as the project.

On cooperation:
Follow what the companies are doing, see them at conferences, meetings but otherwise contact is at low level. Find it can be difficult to work with them. Tokamak energy, Commonwealth Fusion Systems (CFS)– try to work with them but need to sign NDAs immediately. Then in a meeting they discussed the different projects of EUROfusion. D/T data at JET would be of interest to these private initiatives but not clear what EUROfusion gets back in return. Should strive for mutual benefits. Find that private initiatives – want to profit from public research but they don't give back. For example, they are working on strong magnetic fields, according to the calculations at EUROfusion this would create problems, but they don't want to share more.

Interview 7
Technological specifications that need to be achieved:

- Lasers that need to be 10 % efficient and fire at 10 hertz.
- High rate of production of targets (9,000 per day at 10 cents per target)
- Tritium Breeding using a lithium blanket.
- Diffraction gratings to compress the laser beam into shorter pulses to hit the target.
- Demonstrate ignition

Fusion is a difficult problem. It requires technologies that we alone will not be able to develop, partners and collaborations are needed.

Building an ignition-scale facility is very costly (approximately 2.6 billion dollars to construct a machine). Another of the biggest challenge is supply chain. E.g. laser glass – the quality needed does not yet exist.

A future challenge in EU and US will concern resources, especially linked to Ukraine war. Supply lines is one of the key issues. It does not only trace back to vendors/manufacturers but also directly to materials. Good news: it is currently top priority of EU and US. Another challenge concerns the people. FE's challenge is not going to be 'raising enough money' but 'get right people to spend the money wisely'; get the right expertise. A lot of people will have to be trained in this area to build it by 2030. This is also the reason why FE is a US-DE company: one foot in both continents in order to attract the best brains from both sides.

Also waste stream issues are considered when modeling final cost of electricity, but not a lot of effort is put in this yet. However, it is linked to the three technologies in which they are doing R&D (e.g. waste stream are part of reactor technology). One of the big benefits of an IFE power plant compared to magnetic is that there is a broader choice in the material that can be used because the reactor only has to confine the explosion.

Interview 8

Current challenges are mostly technical and focused on increasing the technology and performance of compact fusion. We are working on high field magnetic technology, plasma heating, plasma confinement and so on. The most important challenge should be: how to obtain well plasma confinement and how to generate electricity.

Collaboration is really important, if other initiatives can do something then we want to bundle forces and work with them. If no one can do this then we work on it ourselves. ITER tech can be helpful for ENN but maybe focus on other tech.

When the technological challenges have been solved the first powerplant can be constructed but this requires enormous funding. The costs for a plant will be in the magnitude of billions of dollars, this needs to be raised probably also with public money.

Fusion costs are difficult to predict. However, it would be very expensive for the first commercial fusion energy plants. The cost would reduce quickly after that once the technology scales.

Interview 9

-We need a sustained effort from scientist and engineers.
-Strong collaboration between private and public fusion programs.
-Recognize the work already done in the community to address these challenges (sustain fusion energy
-Production and breeding Tritium to keep the device self-sufficient, safe operations etc)
-Integrated nature of the fusion: synergy between all the aspects
-Staff can be a challenge, talent is coming in, but it takes time to transfer knowledge. It is very important to have a lot of people expertise/knowledge of past generation (human capital)-this takes a lot of time.

On funding: Funding is a crucial aspect, increase needs to be done especially if we want to achieve the aggressive timelines. Would need to accept higher risks/costs – and explore multiple solutions in parallel. To divert funds away from other research to something with high priority is not entirely correct. It undermines the other areas. So we need to add resources instead of shifting the budget around.

Another barrier is the capital cost of a fusion plant, now it is too high (order of 5 billion – see National Academy of Science report). A lot has to be done to make this achievable (advance the physics and technologies). LCOE depends on the emphasis of decarbonization, e.g. subsidies (for instance for the cost of RES has been reduced).

Interview 10

Technical challenges

We achieved these results on ARPA-e budget. ARPA-e sets boundary conditions of 3 years with funding between 1-10 million, so we have a limited budget. Our logic was to do as much meaningful work within this budget and time. What we really want to do is demonstrate scaling, but we needed to demonstrate reactor-relevant power Injection (25MW) first and were really successful: we did achieved half of ITER's power drive for only a hundred of the cost.

In terms of specifications we really want to demonstrate that scaling is feasible so we want to increase plasma radius 2.3 times, resulting in a plasma volume that is approximately 10x bigger. We also want to substantially increase the pulse length of the device to demonstrate that we can operate steady state (show that it is not a fluke). These steps are really important to go from our current R&D towards a commercial plant.

We envision DT for the first generation (it is pretty challenging enough) the next device we can try to go for other fuels. That helps to avoid the NRC and tritium supply issues (breeding & procurement). Tritium at the earliest 2026 or 2027. Proton Boron is crazy physics wise. For fuel cycle we are looking at lead lithium and molten salts

External coils in other MCF approaches are stationary which makes it easier to optimize the plasma conditions because you know exactly where the magnetic fields are. We use far less of these coils and create a lot of the magnetic fields by the current in the plasma, making the magnetic fields related to the underlying plasma conditions. This makes the plasma science more difficult

Regulation: Only confident once I know what it is. They are currently developing it. Probably be a compromise. We as an industry don't want to be associated with fission. It is not the same technology at all, especially in terms of waste and technology. We are much closer to a particle accelerator. UK regulatory framework is more like health and safety. We applaud that, we would love the NRC to not be involved at all in fusion.

Staffing: We have been able to attract exceptional people, but as we scale there is a supply and demand problem. We have had to attract from different industries (Space-X, Boeing) these people are easy to retrain, there are a lot of similarities with the space and aero industry (many components, safety important, large engineering etc) we don't need universities to specifically focus only on fusion. But there is a lot of poaching going on in the industry indicating that staffing is an issue.

Long term challenges: I think there is a bit of over aggression of what happens after gain. We need to look at RAMI, costs and etc. They have not really played a big role during the development but are really important towards commercialization and actual powerplants. I think early 2030's is plausible. However, significant market share and scaling will take time (multidecadal) building supply chain and industry etc. Once energy gain is hit, more money will flow into the industry to make that happen. Net gain will be a catalyst. Money has become a lot smarter in fusion, more due diligence and performance-based funding. NIF last year demonstrated ignition and energy gain but has not resulted in a flood of funding towards ICF.

Costs: Depends on size and position, we have done simulations with different configurations and see results between 35 and 50 euro's per MWh. I think we need to start in the more expensive markets. There is this huge focus on LCOE, but I think the total capital costs are more important. If it gets so big that the prospect of a single institution takes on the risk becomes small, the chance that it will get build is so small. For instance reactors with a capital cost of 10B, I can assure you that those will never get build. Our goal is to have the capital costs lower than 1 B, makes it competitive with natural gas and coal. There will probably be more approaches that work, the market will decide which one gets more share. I don't think we need subsidies because it can lead to a product that is subpar.

Interview 11

High intensity neutron source is a complex system. There are a lot of technical issues to be solved, such as design methods, magnet, heating, measurement, control and diagnosis, etc. In addition to technical issues, it also needs extensive international cooperation and national financial support, a lot of work needs to be done.

First, sufficient technological progress is needed to technically support long-term development goals. In addition, the breakthrough of any important technology is inseparable from the recognition and support of the government and the public for the technology, which is what needs to be strengthened at present.

Interview 12

Long-pulse High beta operation is not developed yet for the reactor relevant conditions, efficient current drive, metal wall, high performance etc. Iit is not easy to fulfil those conditions at the same time. KSTAR will address above key conditions including high ion temperature and demonstrate its sustainment for steady-state operation in addition.

A big challenge is to maintain all parameters to the desired conditions at the same time. We have to do very good control of the plasma instabilities and need to develop efficient current drive (new class wave current drive) and we have to deal with the metal wall. Current wall material is graphite, which, it is good for the experimental machines but not so good in case of tritium fuel reactor for the triple product.

We don't have the available technologies yet before K-DEMO construction for the tritium breeding blanket, remote handling and neutron resilient materials. These are the challenges for 2030. We are trying to build a breeding blanket R&D facility. Until 2030 it would be a good milestone for the breeding blanket technology achievement.

Super-X divertor is very interesting but we pursue technologies that will apply to ITER. We are dealing with more than 10MW/s^2 and that is already very challenging in itself.

Regulation policy is very challenging. The second one is tritium breeding and first wall materials. Also the funding is a challenge, because everything is really expensive. K-DEMO would be dependent on ITER, so we need to have the confident results before design can be finalized.

Regulation policy: Regulation policy for K-DEMO is not clearly undecided yet., As the technologies between fusion and fission are different so that and it should be considered to be regulated separately. But it is challenging how to do this. The USA are still developing their policy under Nuclear Energy Innovation and Modernization Act (NEIMA), the UK, EU and Japan also. Nuclear safety policy and the ITER safety protocol would be important for our K-DEMO program.

Tritium breeding and first wall materials: we joined the ITER TBM project to obtain the full breeding blanket technology. We think some70% of the technology can be obtained from ITER, so we need to obtain more information for K-DEMO. Therefore, we try to construct a R&D facility and do more research and development. We also need to test the breeding blanket concept and test the structure materials. With that facility we try to upgrade our breeding blanket first and later focus on the materials. With that facility we will also try to produce and handle tritium, so we could gain experience with tritium handling too.

Interview 13

Tritium tech is a significant missing piece for fusion: there is a lot of technology to be developed. It has to be developed in parallel to current plasma experiments. There is a big difference between tritium production and tritium breeding inside a reactor, breeding inside the reactor is the most significant problem

Technical: materials – the vast majority of components in a fusion reactor are ultimately based on a materials problem (whether it is a scientific challenge, or an issue associated with cost, manufacturing etc). Material science is very important and we should focus on that for now, whilst focusing on commercially attractive options.

In terms of policy and regulation it is important to get a unified, fair regulatory framework (the UK is proceeding faster and more openly than the U.S., in my opinion, and the UK's approach is becoming the "gold standard"). I am unsure what the EU are working on, but the ITER model for regulation (under ASN in France) is certainly not a suitable model for fusion.

Funding - we need to keep the momentum up. The funding rate and quantities needs to be maintained; we need a big level of funding (avoid a huge drop after the current hype). Funding in an appropriate way so private and public sector work together- labs can do what private industry cant and vice versa. Bridge between TRL 4-6 (valley of death) is particularly important.

Interview 14

Main challenge is the laser system, it needs to be sufficiently powerful, short pulsed, and efficient to allow for operation on industrial scale. We will move to a diode laser that is able to fire at a much higher rate (10 times / second). This is possible because diodes are significantly better at thermal management). However, this also should be economic. Laser setup would probably need to be modular. Achieving these specifications is a challenge.

Targets are another key challenge because they introduce significant operational costs. Although we don't use cryogenic targets and this is easier, it is still a challenge. We will need to adapt semi-conductors manufacturing technology to manufacture nano-targets with precision, high-volume, low cost.

Additional comments:
Target chamber will also be something. But as a lower neutron exposure this is less challenging than for other approaches.

Energy conversion, Siemens already has a standard design in mind. But they are also looking at electro-static and other concepts as these could also have advantages.

For regulation, use of pB11 in discussions with others, e.g. TUV Sud, it is comparable to existing medical processes.

Waste, decommissioning – half life of materials is a matter of weeks, so is not anticipated to be a big issue.

Interview 15

It is currently unknown yet what the best shape and configuration is yet, therefore we are trying to to test all these different machines, the performance and the physics in order to understand what will be the best shape and configuration to pick. Plasma physics is one of the core priorities of our current and following experimental device. We are looking into innovative ideas on how to deal with interaction of plasma with the materials).

There are major questions regarding the viability of tokamaks with fusion. One challenge is the pulse machine (small duration pulses), so in the US there is a push to explore if the currents can sustain the plasmas in steady state. In that regime the spherical tokamaks might have some advantages, more self-driven current, may be able to shrunk the magnets for the same fusion performance (might reduce the cost). Some evidence exist that the confinement could improve the lower aspect ratio.

Based on the experiments and data, the confinement scales favourably as we go up in magnetic field strength à that is a key challenge/milestone, i.e., demonstrating what confinement we observe for the higher field strength and if it matches the projections we have. Understanding the confinement is one of the priority questions. If it is as favourable as expected, the efforts will be on setting up the steady state (high priority).

The heat and particles have to come out, so understanding how to interface the high performance core plasma with the materials, how to manage the heat and particles is one priority as well.

Funding is the crucial issue, if governments prioritize fusion development and fund it, we have more than enough resources to reach our goals. Difficulties remain in finding the work force and knowledge base (across the world) to achieve that- nuclear technologies, breeding, blankets etc need a lot of work.

Interview 16

On regulations:
Regulations (and in particular the Nuclear Regulation) are an obligation to be followed by any such facility, anywhere in the world. In the case of the French Nuclear Regulation, the regulatory body (ASN) has set-up a number of rules; IO is proposing a design (and ultimately a constructed facility) a priori compliant with such rules. The regulator then checks the proposed configurations and solution and releases the so-called "hold points", allowing the facility to move forward, step by step. In the particular case of ITER, one must superimpose to this very formal safety process, the fact that a fusion nuclear facility is a worldwide First-Of-A-Kind, deserving a special attention from both sides, more discussion and elaboration than usual. The ultimate goal is the same: the safe operation of ITER.

On Russia-Ukraine conflict:
As we speak, the Russia-Ukraine conflict is mostly impacting ITER in a series of "practicalities": delayed and/or complicated transportation of deliveries from Russia to ITER site, and/or between Russia and the other ITER Members; contractual or payment issues between Russia and their non-Russian contractors; sanction impacts of some key (or dual) technologies; etc. However, none of these aspects so far have had any consequential impact on the overall schedule, nor is such an impact foreseen at this time.

ITER has produced recently the exhaustive list of such elements to the French Government, in view of triggering a possible derogatory process at the European level. The ITER Director General has also approached the ITER Council Members on this matter. Our Russian counterparts have made clear that the Russian government remains fully committed to the delivery of its commitments to the ITER project.

On supply chain:
As a FOAK, ITER is regularly facing technical issues, to be properly identified, rationalized and addressed. The mitigation channels are manifold, depending on who's responsible for the corresponding technical or financial scope, and are monitored by the Configuration Change system (CCB, EPB, MAC), depending on the level of complexity and responsibility. The supply chain issues also exist. They can be related to the technical ones or not. ITER Organization is similarly investigating with its Members the best ways forward. In fact, the management of risks – technical, financial, supply chain, and political risks – should be seen as one of the great strengths of the ITER project. From Day One, we have faced the complexities of a First-of-a-Kind machine, composed of thousands of First-of-a-Kind components and technologies requiring technological innovation – all compounded by ITER's multinational procurement arrangements. ITER's success to date can only be attributed to the development of international project management of unprecedented robustness – an approach with lessons learned that are of great relevance to the management of other global challenges with scientific/technological solutions.

On cooperation
International cooperation is an important element. ITER encourages and maximizes it, every time this is necessary or possible (within the frame of the ITER Agreement rules). This is not seen as a particular issue for DT operation. On the contrary, fusion R&D globally for the past 6-7 decades has been a singularly positive model (unlike nearly any other advanced scientific or technology field) of international collaboration. In the specific case of ITER, the complexity of building the tokamak and support systems has been, without question, accentuated by the procurement arrangement in which the seven ITER Members manufacture components on three continents and deliver them as in-kind contributions for centralized assembly at the ITER site. This has required an unprecedented level of

international project management. But as ITER succeeds, it has also created many advantages that will be to the great advantage of the future fusion industry: establishment of a global supply chain, enhanced understanding of logistics, expansion of global awareness, access to global markets, and much more. If those insights are properly harnessed, ITER's "challenges" on this aspect will apply even beyond the fusion arena, to other aspects of energy and efforts to combat climate change through advanced scientific and technological collaboration.

On Funding:

ITER is financed by an in-kind/in-cash contribution of its Members. The in-kind contributions are accounted for through a dedicated system of ITER credits (the ITER Unit of Account). One indeed observes some difficulties by some ITER Members to provide in time their in-cash contributions to the Organization, for a series of reasons or circumstances. In a few instances, the reduction of funding for the Domestic Agencies in a given budget year has also resulted in challenges to the procurement of in-kind contributions (components), but so far this has not resulted in any late deliveries of components in a way that impacted the overall schedule. The Members treat such issues at the ITER Council level. So far, ITER Organization managed to operate under such conditions.

On staff:

The Human competences and resources are clearly one of the key for the success of such long-term and large endeavours. ITER is conducting a careful management of its staff, including possible evolutions within the Organization, in order to maximize this capital. DT operation, in particular, requires as well to attract new competences on-site, on the top of the present staff working, together with the Domestic Agencies, on the Tritium aspects. This is managed through the ITER staffing plan, submitted regularly to the ITER Council.

Interview 17

Technology:

- Divertor issue: resolving this issue we need 1) use of a good divertor-design and manufacturing- (European contribution), and 2) we need divertor plasma control ability
- Power multiplication: N/A because we don't use tritium
- Pulse duration: target 100s of high pressure operation- almost equal to steady state. To achieve this target the divertor treatment is key.
- Control the high pressure plasma in steady state: apply advanced control scheme
- RAMI: fundamentally important; high temperature and low temperature components are located close to each other in the system so RAMI is important to control the whole system
- Materials: the neutron yield is not so large (compared to D-T) so this is currently not really a problem .

Skilled staff: very important and a real issue. We need to enforce the next generation; we are sending experienced people to ITER. Future ITER employees (total number is less than the target). Encouragement of young generation to join the JT-60. International school (future plan); collab with Japanese and European universities to construct some program to train young people.

Interview 18

We don't view the laser technology to be an overwhelming technical challenge but rather an economic one. We already use efficient laser because of our advanced laser architecture. Additionally, commercial diode lasers are being developed that are very efficient (e.g. >50%). The eventual configuration and amount of beams that will be used remains an interesting question – there is a conceptual technology called a Star driver with 1,000's of beams for a plant.

The major challenge is with the targets. One of the biggest challenges for mass manufacturing for target fabrication is that an IFE system will need up to 500k-800k a day - that need to be finely manufactured at a low cost. This will have major impacts.

Also, a few very good shots with valuable results have been performed but the challenge is to reproduce this consistently and frequently. With a limited data, quality of the simulations for modelling fusion is also limited and its is difficult to develop a deep quantitative and predictive understanding for high gain ICF. This shows the need for a laboratory or facility that can do many more experiments for an increased learning curve and to exploit modern learning tools such as machine learning and artificial intelligence.

There is a beginning discussion with the NRC around regulatory process. It is hard to regulate something that does not exist. It is a nuclear process and we should be transparent about this. Advocating will need to be dealt with. But, for the next step, it may be easier to get around because the regulations can be gentle. The NRC is beginning to explore fusion needs. They are far less difficult than the regulatory issues with fission reactors and their spent fuel and possible safety issues.

Public funding leads to complexity: issue with public funding which is linked to slowness of government funding. Public budgets do not come when they are supposed to. This budget uncertainty has substantial impact on project. Startups move much faster and so things are actually cheaper in the private sector. This is a barrier for public-private partnerships.

Interview 19

Staffing

The company is rapidly growing and at this hiring rate we will face difficulties. The EU does not produce enough PhD in fusion. In addition, fusion companies are growing more rapidly than the number of trained people. Finally, a lot of people will retire in the next years.

Funding & partnerships

About funding, there needs to be a private-public partnership. The private sector will not achieve fusion alone. For example, BPI is very helpful at the level of funding.

Our strategy is not to be the operator of power plants as there are some established players, nor plant constructors. Plant constructors will buy subsystems from several actors (turbines, heating systems, etc) and buy tokamak or stellarators from reactor manufacturers.

Public-private partnership are essential to enable synergies - everybody contributes in the area in which they are strong. We should avoid duplicating work.

On fusion regulation

We have participated in a call with the nuclear agency of OECD, about liability in terms of accident. Not exactly fusion regulation but it is related. We are also a member of the FIA, which is very active in the US and UK regulation. However, the FIA so far hasn't been very active in discussing on EU fusion regulation (only a few EU start-ups). It is a political subject. Our involvement in regulation discussion is limited as their aim to first work on their technology and have it safe and robust enough before engaging with regulators. Collaboration with ITER on these issues is very valuable, lots of lessons learned.

On fuel supply
We use the common D-T. Tritium is self-bred in the device – the layer of Lithium breeds the Tritium. This is done by the selective precipitation technique. In the process of cooling the fluid down, We also precipitate Lithium tritide from which we extract Tritium and then reinject in the device. In short, the fuel supply shouldn't be an issue. Our estimated Tritium breeding ratio is 1.2 or higher (1.5).

Lithium is not an issue in terms of abundance but there is a worry about increase in cost. However, only need a few tons so fusion technologies would be less subject to price volatility.

On technical challenges
The configuration of a stellarator makes them easier controllable and avoids the need for a current in the plasma (like tokamaks do). However, stellarators are notoriously difficult to construct, because it uses magnets with complicated shapes. These magnets are HTS magnets and also pose risks. They are manufactured in very narrow and long tapes and are single layer. For our approach, we need to demonstrate very wide tapes with several superconducting layers (number benefits, e.g. more electricity and stronger fields). If this works, it will be very advantageous but it still needs to be proven.

The stellarators is donut-shaped: neutrons are emitted in every direction. Need a layer covering the device interior completely. The layer needs to hang from the ceiling. The thinner it is the easier to make it hang from the ceiling. Also, the thicker it is the more expensive it is.

Interview 20

We are currently working on three challenges: firstly, we want to work together and otherwise license the technology of another private fusion company. Secondly we are trying to increase the current within our device, attempting to increase the performance and lastly we are designing and raising money for a new testing facility.

Funding is the big issue at hand, we need money to pursue our activities. A big part of the necessary funding is used to pay the "brains", we need to engage the talented people and get them on board.

We don't see the regulatory framework as a barrier. Our concept will not produce nuclear waste and pose no danger. Therefore we believe that our concept will require the least regulation of all current approaches.

On funding: A lot of money went into this as can be seen from the Jason Report 2018: 24 billion dollars for MCF and 18.3 billion for ICF. Alternative ideas are not being funded. Public funding is very hard to come.

Interview 21

There are a lot of technical challenges: choice of materials, plasma facing materials and neutron-resistant materials. The blanket design is also a very complex problem, DT fusion, produce high energy neutrons, lithium rich blanket, neutrons hit lithium and produce more tritium (closed cycle). We are closely following the work done at ITER, although we take a slightly different approach.

Control systems and plasma scenarios for tokamaks have some commonalities (although spherical tokamaks are slightly different). Another technical challenge is the development of measurement techniques/diagnostics: it is very complicated to measure temperatures and densities of plasma accurately and needs a lot of underpinning science

Need to raise more funding to achieve new milestones, but we believe very large amounts of private funding will become available as the technology comes closer towards commercialization.

There are a couple of challenge which are particularly important in spherical tokamaks:

- Neutron-shielding around the central solenoid with high temperature superconducting magnets – it needs to be as thin as possible but also efficient enough to stop neutrons from damaging the high temperature superconductor. We have our own work in that area in collaboration with universities.
- Heat load on the component called 'divertor' in the tokamak which handles the exhaust from the plasma – objective is to achieve very high heat loads and high particle loads on that component. We are working on this but there is also publicly funded work on this area that is useful (e.g. Super-X). Our next device can test divertors with very high heat loads (experiments haven't been done yet but the device is capable of generating high heat loads).

In the UK, there is a good regulatory framework for fusion, greatly because of the good safety track record of the JET tokamak, that has been operating for 45 years and been using Tritium for more than 35 years ago without any safety concerns, nor problems. Current practices seen a very effective review of safety concerns and waste management for fusion. It comes to the conclusion that worst possible accident with spherical tokamak would not be very serious such as Fukushima scale. It is in this way better than fission and comparable to other energy processes such as oil refinery or chemical power plant. Conclusion: changes to the regulatory framework are proportional and risk appropriate

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Interview 22

Technical aspects of fusion stay difficult, as new tests have to be done that have never been done before. Therefore there is an inherent first-of-a-kind risk. Furthermore we need to integrate all the different disciplines and make everything work at the same time.

We aim to provide integrated capability and capacity; in general, you need a big engineering firm to support big fusion projects – from an integration perspective, need a company with sufficient scale/capacity to deal with the size and complexity of this problem. This is the problem with ITER: some of the big contracts are with SMEs but those don't have the capacity to get the work done quickly, and this has slowed down the overall progress, e.g. on vacuum vessel.

If fusion ends up being regulated as fission it will never happen; the capital cost of fusion is higher than fission. If the same (expensive) regulatory regime is put on top, then it cannot be cheaper than fission, and will never make it to the market because is not competitive. It has to be safe, but not treating fusion the same as fission hazard, it isn't the same. As there is no risk for chain reactions, we shouldn't treat fusion as fission.

If we don't get that right the whole fusion efforts should stop. The regulatory bodies of the UK are quite reasonable though. Under proposals (out for consultation, expected to be made law later this year) Fusion will be regulated by the environmental agency (not under the nuclear regulation).

The amount of skilled people is also a huge bottleneck- it costs a lot of money to find the right and skilled people, it is the factor that limits us from spending our full budget. We are funding further trainings (apprenticeships, post-docs) to improve that.

Approach is that you first need to qualify all the materials before building, then you need a materials testing facility (this can take up to 10 years to build itself). But if you first build the reactor and then check whether it works as you go, learn and replace as needed, then the process goes faster (e.g. Chinese approach).

Interview 23

Further understanding block ignition from radiation pressure laser drivers. The long-term aim of this stream of experiments is to use the currently available (and soon to be online) laser systems to confirm plane geometry picosecond block ignition using H/B fuel and optimize the laser conditions in order to achieve the largest reaction gains in a fusion reaction.

Understanding the laser requirements – Laser development over the next decade such as those driven by advances for the European ELI project, and others, should enable this capability to be developed. Lasers with performance of ~10 PW and rep-rates of less than 1 shot per minute are examples of the ongoing rapid development of the field.

Understanding the kilo Tesla magnetic field – the physics of laser generation of the ultrahigh magnetic fields in the coils is an active field of research. Additional and ongoing research on the field properties, the time dependence, and further improvements of technology are required to evaluate and optimize the concept.

Reactor sphere – a better understanding of the operations / physics of the reactor sphere will provide a critical step in understanding future scientific and engineering design parameters for building a reactor.

Fuel – A better understanding of the ideal fuel and the construction and characteristics of the target will be required in order to achieve the most efficient interaction and the highest gain fusion reaction.

Computation modelling – all experimental efforts will be supported by the efforts of a computational modelling team.

Appendix E: Y-factor fusion framework

Category	Factor	Value 0 No barrier	Value 1 Potential barrier	Value 2 Significant barrier	Definition
Technology	Plasma physics	Not	Considerably	Severely	The degree to which plasma physics understanding is lacking
	Fuel cycle technology	Advanced	Medium	Beginner	The level of advancement in fuel cycle technology
	Hardware	High	Medium	Low	The level of hardware advancement
Operation	RAMI	High	Medium	Low	The degree to which RAMI can be implemented in the design
	Radiation shielding	High	Medium	Low	The degree to which the reactor design can be effectively shielded against radiation
	Energy production	Not	Considerably	Severely	The degree to which energy production is problematic
Cost & Financing	Difficulty in raising funding	Low	Medium	High	The degree to which the required investment costs are significant
	Capital costs required	Low	Medium	High	The degree to which raising funding to finance the development is difficult
	Cost Of Electricity	High	Medium	Low	The degree to which the COE are competitive in the market
Governance	Regulation	Not	Considerably	Severely	The degree to which regulation hinders development and deployment of fusion energy
	Cooperation between actors	High	Medium	Low	The level of cooperation between the actors
	Governmental support	High	Medium	Low	The level to which the government supports the development
Engineering	Supply chains	High	Medium	Low	The degree to which supply chains are mature
	Staffing	Not	Considerably	Severely	The degree to which the availability of staffing limits activities
	Construction complexity	Low	Medium	High	The degree to which plant construction is problematic due to its complexity

Appendix F: Framework application scoring results

Own scoring:

Category	Barrier	Tokamak	Spherical Tokamak	Stellarator	FRC	ICF
	Plasma physics	1	1	1	2	1
Technology	Fuel cycle technology	2	2	2	1	2
	Hardware	1	1	1	1	2
	RAMI	2	2	2	1	1
Operation	Radiation shielding	2	2	2	0	1
	Energy production	2	2	2	1	2
	Difficulty in raising funding	0	0	1	0	2
Costs & financing	Capital costs required	2	1	2	1	1
	Cost Of Electricity	1	1	2	1	2
	Regulation	1	1	1	1	1
Governance	Cooperation between actors	0	1	1	2	1
	Governmental support	0	1	1	2	2
	Supply chains	1	1	1	2	2
Engineering	Staffing	1	1	1	1	1
	Construction complexity	2	2	2	1	1

Respondent 1: 2 senior consultants of Trinomics (5 fusion projects experience)

Category	Barrier	Tokamak	Spherical Tokamak	Stellarator	FRC	ICF
	Plasma physics	1	1	1	2	1
Technology	Fuel cycle technology	2	2	2	1	2
	Hardware	0	0	0	0	0
	RAMI	2	1	2	1	1
Operation	Radiation shielding	2	2	2	1	1
	Energy production	2	2	2	2	2
	Difficulty in raising funding	1	1	1	0	1
Costs & financing	Capital costs required	2	1	2	1	1
	Cost Of Electricity	1	1	1	1	1
	Regulation	1	1	1	0	0
Governance	Cooperation between actors	0	1	1	1	1
	Governmental support	0	1	1	1	1
	Supply chains	1	1	1	1	1
Engineering	Staffing	1	1	1	1	1
	Construction complexity	1	1	2	1	1

Respondent 2: Simon Woodruff – Fusion Scientist, Fusion Consultant, PHD plasma physics

Category	Barrier	Tokamak	Spherical Tokamak	Stellarator	FRC	ICF
	Plasma physics	2	2	2	2	1
Technology	Fuel cycle technology	2	2	2	2	2
	Hardware	2	2	2	2	2
	RAMI	1	1	1	2	1
Operation	Radiation shielding	2	2	2	2	2
	Energy production	1	1	1	1	1
	Difficulty in raising funding	2	2	2	2	2
Costs & financing	Capital costs required	1	1	1	1	1
	Cost Of Electricity	0	0	0	0	0
	Regulation	1	1	1	1	1
Governance	Cooperation between actors	0	0	0	0	0
	Governmental support	0	0	0	0	1
	Supply chains	2	2	2	2	2
Engineering	Staffing	2	2	2	2	2
	Construction complexity	1	1	1	1	1

Respondent 3: Niek Lopes – Professor in plasma physics Technical University of Eindhoven

Category	Barrier	Tokamak	Spherical Tokamak	Stellarator	FRC	ICF
	Plasma physics	0	0	0	NA	1
Technology	Fuel cycle technology	2	2	2	NA	2
	Hardware	2	2	2	NA	2
	RAMI	1	1	2	NA	1
Operation	Radiation shielding	0	0	0	NA	0
	Energy production	0	0	0	NA	0
	Difficulty in raising funding	NA	NA	NA	NA	NA
Costs & financing	Capital costs required	2	2	2	NA	2
	Cost Of Electricity	NA	NA	NA	NA	NA
	Regulation	NA	NA	NA	NA	NA
Governance	Cooperation between actors	NA	NA	NA	NA	NA
	Governmental support	NA	NA	NA	NA	NA
	Supply chains	2	2	2	NA	2
Engineering	Staffing	2	2	2	NA	2
	Construction complexity	1	1	1	NA	1

Average scores of respondents:

Category	Barrier	Tokamak	Spherical Tokamak	Stellarator	FRC	ICF
	Plasma physics	1,3	1,3	1,0	2,0	1,3
Technology	Fuel cycle technology	2,0	2,0	2,0	2,0	2,0
	Hardware	2,0	2,0	2,0	2,0	2,0
	RAMI	1,3	1,3	1,7	2,0	1,3
Operation	Radiation shielding	1,3	1,3	1,3	2,0	1,3
	Energy production	1,0	1,0	1,0	1,5	1,0
	Difficulty in raising funding	1,5	1,5	2,0	1,5	1,5
Costs &	Capital costs required	1,7	1,7	1,7	1,0	1,3
financing	Cost Of Electricity	0,5	0,5	0,5	0,5	0,5
	Regulation	1,0	1,0	1,0	1,0	1,0
Governance	Cooperation between actors	0,5	0,5	0,5	1,0	0,5
	Governmental support	0,5	0,5	0,5	1,0	1,5
	Supply chains	1,7	1,7	2,0	2,0	2,0
Engineering	Staffing	2,0	2,0	2,0	2,0	2,0
	Construction complexity	1,3	1,3	1,3	1,0	1,3