Foresight study on the worldwide developments in advancing fusion energy, including the small scale private initiatives

Trinomics B.V.
November – 2022

EUROPEAN COMMISSION

Directorate-General for Energy
Directorate D — Nuclear energy, safety and ITER
Unit D.4 — ITER

Contact: Johannes de Haas

E-mail: *Johannes.DE-HAAS@ec.europa.eu*

European Commission
B-1049 Brussels

Foresight study on the worldwide developments in advancing fusion energy, including the small scale private initiatives

Directorate-General for Energy
Nuclear energy, safety and ITER
2023
EN

Manuscript completed in November 2022

First edition

This document should not be considered as representative of the European Commission’s official position.

Luxembourg: Publications Office of the European Union, 2023

PDF ISBN 978-92-76-62103-4 doi:10.2833/967945 MJ-07-23-023-EN-N

Foresight study on the worldwide developments in advancing fusion energy, including the small scale private initiatives

Final Report

Trinomics

Contract details

DG ENER Unit D4

Foresight study on the worldwide developments in advancing fusion energy, including the small scale private initiatives, Specific Tender ENER/D4/2021-292 under Framework Contract MOVE/ENER/SRD/2020/OP/0008 Lot-2

Presented by

Trinomics B.V.
Westersingel 34
3014 GS Rotterdam
The Netherlands

Contact person

Mr. Matthew Smith
T: +31 6 1292 9246
E: matthew.smith@trinomics.eu

Date

Rotterdam, 30 November 2022

Authors

Koen Rademaekers, Matthew Smith, Frank Gerard, Anna Kralli, Liliana Guevara Opinska, Louise Aeby, Koen van de Loo (Trinomics); Dr Matthew Moynihan (New Light Fusion), Dr Simon Woodruff (Woodruff Scientific), Dr Thomas Dolan
Quality assurance by: Martijn Duvoort (DNV GL)

Disclaimer

Rotterdam, 30 November 2022

Client: DG Energy, Unit D4

Foresight study on the worldwide developments in advancing fusion energy, including the small scale private initiatives

Specific Tender ENER/D4/2021-292
under Framework Contract MOVE/ENER/SRD/2020/OP/0008 Lot-2

Final Report

In association with:

Dr Matthew Moynihan (New Light Fusion)
Dr Simon Woodruff (Woodruff Scientific)
Prof. Thomas Dolan
Prof. Dr Niek Lopes Cardozo
Martijn Duvoort (DNV GL)

TEC5020EU

Abstract

English

This study provides an analysis of the leading public and private fusion initiatives globally which has been used to generate four foresight scenarios for fusion development to inform EC decision making on fusion. The work provides an overview of the state-of-play of fusion globally and analyses of the strengths and weaknesses of various fusion approaches and the initiatives active in them. A timeframe analysis of fusion initiatives provides an overview on when next fusion devices may be foreseen, with a wave of private companies expected to begin operating new devices between 2024-2028 and the possibility for significant milestones to be achieved. Analysis of timelines for pilot plants shows higher risks but it is likely that, in addition to ITER DT experiments in the late 2030's, a handful of private fusion initiatives will also build pilot plants in this timeframe. In a most successful case this could deliver the first commercial fusion power plants in the 2040's but more likely scenarios of public-private collaboration see fusion power arriving in the 2050's or 2060's. In addition, this study provides analysis of the still significant technical challenges, such as public-private interactions, fusion regulation, the lack of staffing, cost and links to other fields.

Français

Cette étude analyse les principales initiatives publiques et privées actives dans le secteur de la fusion à l'échelle mondiale, à partir desquels ont été élaborés quatre scénarios de prospective de développement de la fusion permettant d'éclairer la prise de décision de la CE en la matière. L'étude donne un aperçu de l'état des lieux de la fusion au niveau mondial et analyse les forces et les faiblesses des différentes approches de la fusion ainsi que des initiatives qui y sont actives. Une analyse du calendrier des initiatives permet d'avoir une idée du moment où l'on peut attendre la mise en route des prochaines machine de fusion. Une série d'entreprises privées devraient commencer à exploiter de nouvelles machines entre 2024 et 2028, potentiellement franchissant d'importantes étapes. L'analyse des calendriers des installations pilotes présente des risques plus élevés mais il est probable que d'ici là, outre les expériences ITER DT à la fin des années 2030, une série d'initiatives privées construisent également des installations pilotes. Dans le cas le plus favorable, les premières centrales à fusion commercialisables pourraient voir le jour dans les années 2040, mais des scénarios plus plausibles de collaboration public-privé tablent sur l'arrivée de l'énergie de fusion dans les années 2050 ou 2060. Par ailleurs, cette étude fournit une analyse des défis encore importants, en matière techniques, d'interactions public-privé, de réglementation du secteur, du manque de personnel, des coûts et des liens avec d'autres domaines.

Abbreviations

ALPHA	Accelerating Low-Cost Plasma Heating and Assembly
ARDP	Advanced Reactor Demonstration Program
ARPA-E	USA Advanced Research Projects Agency-Energy
ASIPP	Chinese Academy of Sciences Institute of Plasma Physics
ASN	French Nuclear Safety Authority (in FR, *Agence de Sûreté Nucléaire)*
BETHE	Breakthroughs Enabling Thermonuclear-fusion Energy
CAPEX	Capital Expenditures
CAS	Chinese Academy of Sciences
CFETR	China Fusion Engineering Test Reactor
CFS	Commonwealth Fusion Systems
CN	China
COTS	Commercial Orbit Transport Services
CRADA	Cooperative Research and Development Agreements
CT	Compact Toroids
DD	Deuterium-Deuterium
DEMO	DEMOnstration Power Plant
DOE	USA Department of Energy
DT	Deuterium-Tritium
DTT	Divertor Tokamak Test
EA	UK Environment Agency
EAST	Experimental Advanced Superconducting Tokamak
EC	European Commission
EU	European Union
F4E	Fusion for Energy
FIA	Fusion Industry Association
FRC	Field Reversed Configurations
GAMOW	Galvanizing Advances in Market-aligned fusion for an Overabundance of Watts
HSE	UK Health and Safety Executive
HTS	High Temperature Superconducting
IAEA	International Atomic Energy Agency
ICF	Inertial Confinement Fusion
IEA	International Energy Agency
IFE	Inertial Fusion Energy
IFMIF	International Fusion Materials Irradiation Facility
INFUSE	Innovation Network for Fusion Energy
IPP	Max Planck Institute for Plasmaphysics
ITER	International Thermonuclear Reactor
JET	Joint European Torus
JP	Japan

KFE	Korea Institute of Fusion Energy
KO	Korea
LCOE	Levelized Cost of Energy
LHD	Large Helical Device
MAST-U	Mega Amp Spherical Tokamak–Upgrade
MCF	Magnetic Confinement Fusion
MFE	Magnetic Fusion Energy
MIF	Magneto-Inertial Fusion
MIT	Massachusetts Institute of Technology
MTF	Magnetised Target Fusion
NIA65	Nuclear Installations Act 1965
NIF	National Ignition Facility
NRC	US Nuclear Regulatory Commission
NSTX-U	National Spherical Torus Experiment-Upgrade
O&M	Operation and Maintenance
PPP	Public-Private Partnerships
QST	Japan National Institutes for Quantum Science and Technology
R&D	Research and Development
RAMI	Reliability, Availability, Maintainability, Inspectability
SC-FES	Office of Science – Fusion Energy Sciences
STEM	Science Technology Engineering and Mathematics
STEP	Spherical Tokamak for Energy Production
SWOT	Strength, Weaknesses, Opportunities and Threats
TRL	Technology Readiness level
UK	United Kingdom
UKAEA	UK Atomic Energy Authority
USA/US	United States of America
W7-X	Wendelstein 7-X

CONTENTS

Executive Summary (EN)

Introduction

This report provides an overview of the various fusion activities, both public and private, that are occurring globally and based on this provides scenarios that give foresight into how fusion energy may develop in the coming decades and beyond. The conclusions and recommendations of this study can be used to inform the strategic decisions on the direction of European publicly funded fusion activities, such as DEMO and IFMIF-DONES, in the coming years.

The analysis presented in the study was based on desk review of public information on public and private fusion initiatives, a series of more than 30 interviews with leading staff at public fusion programmes and private fusion companies, a joint survey of fusion companies with the Fusion Industry Association, and technical and scientific review by fusion experts.

Current state of fusion energy

Public programmes

Public fusion research at a global level has progressed significantly with several countries developing fusion reactors and establishing strategies and fusion programmes. **ITER** is the centrepiece of global fusion efforts and international cooperation between the EU, USA, China, Russia, Japan, Korea and India. Under an already revised timeline ITER was intended to reach first plasma by 2025, but due to multiple reasons such as disruption on the supply chain due to COVID-19, issues with nuclear safety regulation and possibly disruptions to cooperation with Russia it is very likely that first plasma will be further delayed by 1-2 years.

In addition to ITER, progress has been made at other public fusion programmes. Experiments performed at **JET** at the end of 2021 achieved a record 5 second pulse that generated 59MJ of energy, further progress is expected prior to its decommissioning at the end of 2023. The **Wendelstein 7-X (W7-X)** stellarator in Germany, is the most advanced stellarator globally, which in 2017 W7-X achieved the world record for stellarator fusion triple product $nT\tau$ (density, temperature, confinement time) and has just started a new experimental campaign following upgrades to cooling systems. The **National Ignition Facility (NIF)** in the US is the largest Inertial Confinement Fusion (ICF) initiative globally and in 2021 NIF facility achieved a world first burning plasma state 'ignition' in which the plasma is predominantly self-heated by fusion reactions in the plasma. Fusion records in temperatures and sustained plasmas have also been set by the **KSTAR** (Korea) and **EAST** (China) tokamaks. The **JT-60SA** tokamak in Japan, an EU-Japan collaboration under the Broader Approach agreement, is hoped to also reach first plasma within the next 12 months.

Private programmes

Private initiatives in fusion energy have gained significant funding and momentum in the last 5 years, with eight new companies being founded in 2021 and 2022 alone. Whilst the US and UK host the majority of private fusion initiatives, European start-ups have also emerged in recent years, such as **Marvel Fusion** (Germany), **Focused Energy** (Germany), **Renaissance Fusion** (France) and **Deutelio** (Italy). According to the FIA survey (jointly carried out with this study), fusion companies declared around $2.8 billion in new funding in 2021[1], bringing the cumulative private funding to around over $4.7 billion to date, hence doubling the total historic funding in the timespan of a single year. Private companies have also recorded important new milestones in temperatures achieved and demonstrated magnetic fields and are in many cases already working on constructing new devices.

Overall, there are a variety of approaches to fusion energy with private initiatives in particular pursuing concepts away from the more mainstream Magnetic confinement tokamak-based fusion energy, some are exploring Inertial Fusion Energy (IFE) and Magneto-Inertial Fusion (MIF) energy, a summary is presented below in Table 0-1.

Table 0-1 Overview of main fusion energy approaches globally, sub-approaches and key devices and initiatives for each (black text = public, blue text = private)

Approach	Initiatives
MFE / MCF	
Tokamak	ITER, JET, JT-60SA (JP-EU), K-STAR (KO), DIII-D (US), EAST (CN) CFS
Spherical tokamak	MAST-U (UK), STEP (UK), NSTX-U (US), Tokamak Energy, ENN
Stellarator	W7-X (EU), LHD (JP), Renaissance Fusion, Type One Energy
Z-Pinch	Zap Energy, MIFTI
Compact Toroids (Field Reversed Configurations [FRC], Spheromak)	TAE Technologies, CT Fusion
IFE Including various direct, indirect and target-based approaches	NIF, Marvel Fusion, First Light Fusion, HB11, Focused Energy
MIF Including Magnetised Target Fusion (MTF), FRC-based, and other approaches	Helion Energy, General Fusion

Timeframes of future fusion development

The timeframe analysis carried out in the study was based around publicly stated timelines for next steps in fusion energy from both the public and private initiatives. The analysis was structured around a loose Technology Readiness Level (TRL) based framework, with a start point of TRL 2-4 for most fusion approaches, meaning that the technology concept is formulated, there is experimental proof and in some cases the technology has been validated in the lab. An assessment of risk is also carried out to provide a view on the chance that the timelines may slip.

Next devices

Next devices represent progress of around TRL 4 or 5, and most have the primary goal is to demonstrate net energy gain/power multiplication (Q>1), burning plasmas, and/or scaling that confirms the potential of the fusion approach. Globally, **public activities** have a more risk-averse approach, with efforts focused on ITER and ensuring strict control over the various components of the device. Timelines for next devices for public fusion efforts are mostly long term, i.e., whilst first plasma at ITER is likely around 2026-2028, the most important ITER DT experiments, those that will demonstrate net energy, are not planned until 2036 at the earliest, and possibly later once the new baseline is

[1] Figures in the FIA survey are presented in US$ but at current exchange rates these can be converted approximately 1:1 to Euros.

announced. In contrast, **private activities** have more aggressive timescales, and have a higher risk tolerance / need to iterate faster. The leading private fusion companies have announced timelines for their next devices in the next 5 years, these devices intend to demonstrate major progress and potential net energy gain/high power multiplication. At least 11 of the leading private initiatives aim to complete next devices before 2028, and with funding secured and construction underway in many cases there is a good chance that at least a few succeed in meeting their timelines, and others with short delays.

Table 0-2 Timeline of public / private initiatives for next device completion. Colour coding represents Trinomics assessment of slippage risk: x = targeted date of next device; red = high risk of slippage from this year; orange = medium risk of slippage from this year; green = low risk of slippage in this period

Approach	Initiative	2023-2024	2025-2026	2027-2028	2029-2030	2031-2032	2033-2034	2035-2036	2037-2038	2039-2040
MFE - Tokamak	Public (ITER)							X		
	Private		X							
MFE – Spherical Tokamak	Public[1]									
	Private		X							
MFE - Stellarator	Public[2]									
	Private		X							
MFE – Z-pinch	Private		X							
MFE – Compact Toroids (FRC, Spheromak)	Private		X							
IFE	Public[3]									
	Private	X								
MIF - FRC	Private	X								
MIF - MTF	Private		X							

[1] No new public spherical tokamak devices planned, however MAST-U and NSTX-U will both continue to operate for much of this period and sit in the TRL 3 range. Upgrades to these devices could also be envisaged in this period.
[2] No new public stellarator device planned, however the W7-X device in Germany will continue to operate throughout this period, in the TRL 3 range. Upgrades (e.g., to wall materials) could be foreseen in this period.
[3] No new public inertial fusion devices are planned in this period, however it is understood that the NIF will continue to operate in the US during the 2020's and some other laser facilities (e.g., ELI-ERIC with facilities in Czechia, Romania and Hungary[2]) which are not dedicated to fusion but potentially available for experiments could also be valuable supporting public infrastructure for firms active in IFE.

Pilot plants

Pilot plants represent progress of around TRL 5-7, with the main goal being demonstrating electricity production. Pilot plants may only be intended for relatively short-term operation and/or low availability, but are expected to demonstrate not only electricity generation, but also how (if used) the tritium cycle is dealt with, resilience of materials, RAMI (Reliability, Availability, Maintainability and Inspectability) and consideration of life-cycle issues. Timelines for next devices for **public fusion efforts** are very long term, and in Europe these are based on DEMO, whose design would be finalised following the ITER DT experiments. A public timeline has not been set but an EU DEMO plant being operational by 2050-2055 seems realistic, accounting for the time needed for the DEMO design and construction. A similar timeline can be foreseen for DEMO equivalents in Japan and Korea. On the other hand, China plans the construction of their DEMO equivalent called CFETR already in the 2040s while the UK also plans a pilot plant, STEP, targeted for 2040 and significant funds are committed to design

[2] https://eli-laser.eu/

and supply chain activities which are already taking place. Mirroring the ambition to construct next devices there are also ambitious timelines for **pilot plants in the private sector**, targeting the completion of a pilot plant between 2030 and the mid-2030's. These plans are judged riskier than for next devices as they rely on: success of the next devices, which is not guaranteed; raising further funding; and resolving design, engineering, procurement and construction issues – many of these are already dealt with for next devices, but not for pilot plants.

Table 0-3 Timeline of public / private initiatives for pilot plant. Colour coding represents Trinomics assessment of slippage risk: x = targeted date of pilot plant; red = high risk of slippage from this year; orange = medium risk of slippage from this year; green = low risk of slippage in this period

Approach	Initiative	2030-2031	2032-2033	2034-2035	2036-2037	2038-2039	2040-2041	2042-2043	2044-2045	2046-2047	2048-2049	2050-
MFE - Tokamak	Public[1] (DEMO)											
	Private		x									
MFE – Spherical Tokamak	Public (STEP)						x					
	Private			x								
MFE - Stellarator	Public[2]											
	Private		x									
MFE – Z-pinch	Private	x										
MCF -Compact Toroids (FRC, Spheromak)	Private			x								
IFE	Public[2]											
	Private			x								
MIF - FRC	Private	x										
MIF - MTF	Private			x								

[1] No specific target date for (EU) DEMO has been set, however the highlighted period is potentially possible for any of the DEMO plants (EU/JP/KO), especially the Chinese (CFETR) plant
[2] No public pilot plant is planned at this point for this approach, this could change in the coming years

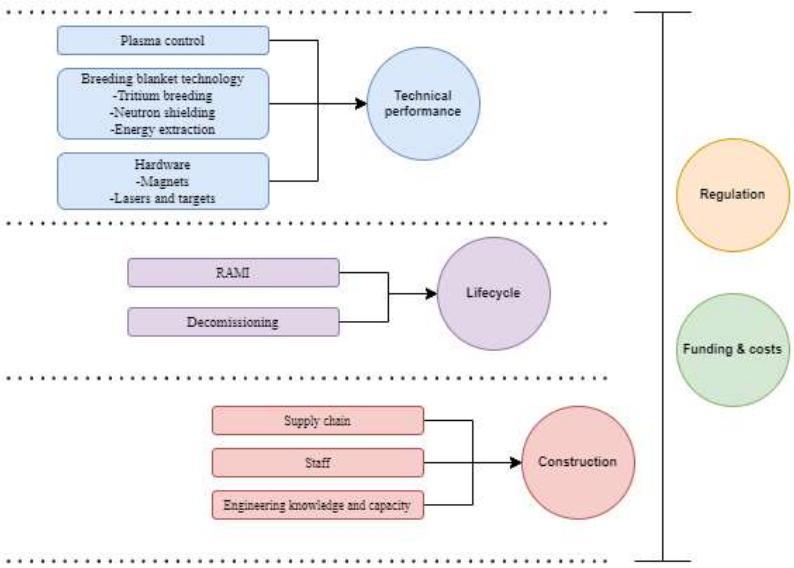
Challenges in future fusion development

There are several key barriers that are identified towards the commercialisation of fusion energy, with the main ones being:

- **Technical performance**: no fusion initiative to date has demonstrated energy gain, improved plasma control can help with this, but other major technical challenges related to Tritium Blanket Module (TBM) technology (tritium cycle, neutron shielding, energy extraction) and hardware (magnets, lasers and targets) and others remain important and difficult.
- **Lifecycle:** RAMI, durability and decommissioning are amongst the longer term challenges that need to be addressed by fusion. By the pilot plant stage greater clarity will be needed on each of these issues to give confidence that fusion power is commercially possible.
- **Construction**: the construction and deployment of fusion plants requires among others availability of the supply chain which remains quite immature and small scale for many key components, highly educated staff which is signalled as an important bottleneck, and deep engineering knowledge.
- **Regulation**: is an overarching challenge, there is a need for fusion regulation that is proportional to the (lower) risks of fusion compared to nuclear fission.

- **Funding and costs**: access to funding is crucial for both public and private initiatives, and in the end it is also crucial for commercialisation that costs are kept to a level that fusion power can be economically competitive.

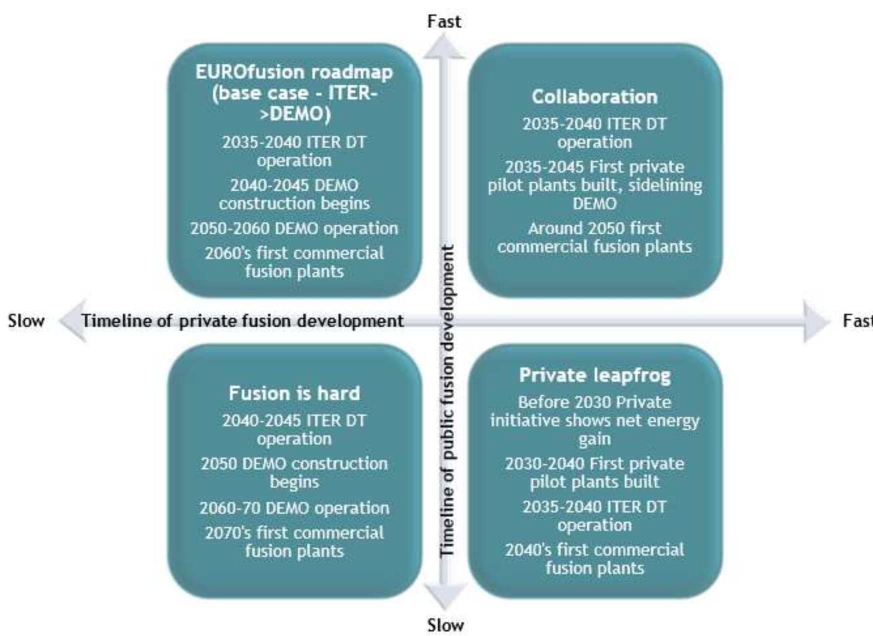
Figure 0-1 Summary of main challenges for fusion energy



Scenarios of future fusion development

This work has developed four scenarios through which to consider and analyse the implications of different pathways of fusion development. The two main axes (Figure 0-2) represent the timeline of success of the publicly funded fusion initiatives (vertical axis) and the timeline of success of private fusion initiatives (horizontal axis).

Figure 0-2 Overview of scenarios of potential fusion development



Scenario n.1: EUROfusion roadmap (base case – ITER->DEMO)
In the **public programmes** ITER first plasma occurs around 2028-2030, ITER begins DT operation in the 2035-2040 timeframe, and demonstrates net energy gain in the order of Q=10. It also achieves ignition showing that a self-heating plasma can be achieved. Other approaches make some progress (e.g., NIF, W7-X, NSTX-U and MAST-U), while **private initiatives** have some successes do not play a major role. Regarding pilot plants, in the **public programmes** DEMO concepts in the EU (and elsewhere) are finalized following ITER DT operation (around 2040) and DEMO construction begins before 2045, beginning operation in the 2050's. For the **private initiatives,** the first private pilot plants only begin operation around 2040 and have varying degrees of success. The last step of commercialisation occurs in the 2060's when first fleet of commercial plants (based on the MFE tokamak approach) are delivered.

Scenario n.2: Collaboration
Regarding the next device, for the **public programmes** this follows the same course as EUROfusion roadmap scenario. **Private initiatives** succeed in demonstrating significant progress prior to ITER DT operation. In the mid-2020's a handful already demonstrate net (scientific) energy gain and one or two of these are also able to demonstrate ignition. When it comes to pilot plants, the first wave of **private initiatives** begin construction of their pilot plants, the first of which are completed around 2036-2038, while net engineering gain and performance is achieved and the first electricity is put onto the grid around 2045. Due to the success of private initiatives DEMO is shelved and public programmes are reoriented towards the final scientific and technical challenges. The first fleet of commercial plants (based on multiple approaches) enters operation around 2050, as a result of collaboration between public and private initiatives.

Scenario n.3: Private leapfrog
The first **private initiatives** succeed in both keeping their timelines for next devices and in achieving many of their targeted goals with these devices. Already from 2024 the first initiatives show results demonstrating significant progress, and more next devices come online each year in the 2025-2030 period. The **public programmes** follow the same timeline as the EUROfusion roadmap scenario; starting around 2035-2040, ITER begins its DT experiments. The **private initiatives** build on the success of their first devices, and move quickly to their pilot plant stage. The first of these are completed in the early 2030's and the first electricity from a fusion pilot plant is put onto the grid around 2035. Due to the speed of success of the private initiatives, ITER funding is slowly tapered off after 2040, and plans for DEMO plants are shelved in all nations, public programmes reorient their activities and funding is reduced. The success of pilot plants in the 2030s and resolution of major technical challenges allows for the first commercial fusion plants to be rolled out from the early 2040's.

Scenario n.4: Fusion is hard
In the **public programmes** ITER first plasma occurs after 2028-2030 with some delays compared to the re-baselining. Issues are encountered in the further upgrade and commissioning of ITER which delay DT operation into the 2040-2045 timeframe. The first of the **private initiatives** to build their next devices do so around 2025, although most slip 1-3 years from their targeted timelines, these are not as successful as hoped for. DEMO construction only begins in the late 2040s, and due to several difficulties DEMO in the end is ready by around 2060 and puts electricity onto the grid. The first private pilot plants only begin operation around 2040 and are unable to address all remaining challenges, attention shifts towards public research and DEMO to help address these final gaps. Lastly, the **first fleet of commercial plants (based on the MFE tokamak approach) in the 2070's.**

Conclusions and recommendations

The key lessons that can be taken from this exercise and recommendations on how the EU can respond to these are:

- Private fusion initiatives are likely to achieve net energy in the 2024-2028 period.
- Few in the fusion sector doubt the value of ITER, and some believe it is still likely to be first to demonstrate Q>1
- DEMO design activities are underway and are likely to become more explicit under FP10. Final DEMO design will await the results of ITER DT experiments.
    - **Recommendation:** Experience from ITER strongly recommends that industrial players and engineering systems integrators are involved in the DEMO design activities.
- Materials are likely to remain one of the key challenges for fusion, the IFMIF-DONES facility would be a welcome major addition to the projects globally that are set to tackle this issue.
    - **Recommendation:** ensure that a positive decision is taken on funding IFMIF-DONES and that work is coordinated with other countries which also work on materials (UK, US, China) and with potential partners (Japan).
- Private fusion initiatives are clustered in the US, and to a lesser extent UK. If there is a desire to build a similar EU private fusion community then urgent action is needed to support the creation of such initiatives.
    - **Recommendation:** For the EU, creating programmes similar to ARPA-E and INFUSE is recommended.
- The visibility of fusion within EU policies, models and programmes is very low and can be improved.
    - **Recommendation:** the EC should ensure that fusion is included within the scope of relevant EU funding programmes, strategies and modelling exercise (e.g., EU Taxonomy for Sustainable Finance, fusion as one of the dimensions in EU long-term energy modelling scenarios (post 2040/2050); fusion among the technologies that can be financed under specific funding mechanisms when it achieves the requisite level of maturity, e.g., Breakthrough Energy Catalyst, Innovation Fund.
    - **Recommendation:** the EC should also be careful to support messaging on fusion that encourages a positive public perception, avoiding strong links to nuclear fission.
- Regulatory approaches to fusion are important – regulation should be proportionate to fusion risks, not based on fission.
    - **Recommendation:** the EC should push for regulatory agencies in the main MS to develop their approaches on regulation for fusion to provide clarity for the sector.
    - **Recommendation:** the EC should continue to work via international agencies, e.g., IAEA, to seek to harmonised regulatory approaches to fusion globally
- A diversity of approaches to fusion is emerging, a narrow focus on tokamaks in the EU is restrictive.
    - **Recommendation:** the EC should examine to what extent upgrades at W7-X or a pilot plant device based on the stellarator could also be funded.
    - **Recommendation:** examine how the EU could leverage its expertise in laser technologies to create a public inertial fusion energy programme.
- Contingency planning would be valuable, in the case that one or more of the private fusion initiatives succeed in developing a functional pilot plant before 2040 which provides a clear path to commercial fusion as this would have significant implications for DEMO.

    - **Recommendation:** The EC should have a clear idea of how to respond to potential 'leapfrogging' by the private fusion initiatives, having given thought on how to progress (or not) with DEMO and how the European fusion programme may be reoriented if such a 'leapfrogging' occurs.
- Staffing is likely to increasingly become an issue in the coming decades, ensuring a pipeline of qualified scientists, engineers and technicians will be crucial to avoiding that staffing becomes a hindrance to the sector.
    - **Recommendation:** The EC should work with EUROfusion and industry stakeholders to better understand the size and nature of this issue, and to develop approaches to retain talent in the European fusion research and industrial community.
- In whichever scenario outcome is closest to reality there will be a massive industrial effort required to scale up the roll-out of fusion power once the first commercial power plants are proven.
    - **Recommendation:** supporting EU industry to be well positioned – either as fusion energy developers, or as key suppliers to leading fusion initiatives, is crucial for EU industry to fully benefit from eventual fusion energy commercialisation.

Résumé exécutif (FR)

Introduction

Ce rapport donne une vue d'ensemble des diverses activités de fusion énergétique, tant publiques que privées, qui se déroulent dans le monde et, sur cette base, fournit des scénarios qui permettent d'envisager comment l'énergie à partir de fusion pourrait se développer dans les décennies à venir et au-delà. Les conclusions et recommandations de cette étude peuvent être utilisées pour éclairer les décisions stratégiques quant à l'orientation à donner aux activités de fusion financées par des fonds publics européens, telles que DEMO et IFMIF-DONES, dans les années à venir.

L'analyse présentée dans l'étude s'appuie sur une analyse documentaire des informations publiques sur les initiatives de fusion publiques et privées. Celle-ci a été suivie d'une série de plus de 30 entretiens avec des responsables de programmes de fusion publics et d'entreprises privées, ainsi que par une enquête conjointe avec la *Fusion Industry Association* auprès des entreprises actives en fusion en collaboration avec elle, et enfin par un examen technique et scientifique réalisé par des experts en fusion.

Etat de l'art de l'énergie de fusion

Programmes publics

La recherche publique sur la fusion au niveau mondial a progressé de manière significative, avec plusieurs pays développant des réacteurs de fusion et établissant leurs propres stratégies et programmes de fusion. **ITER** est la pièce maîtresse des efforts mondiaux en matière de fusion et de la coopération internationale entre l'UE, les États-Unis, la Chine, la Russie, le Japon, la Corée et l'Inde. Dans le cadre d'un calendrier déjà révisé, ITER devait atteindre le premier plasma en 2025, mais pour de multiples raisons, telles que les perturbations de la chaîne d'approvisionnement dues au COVID-19, les problèmes liés à la réglementation de la sécurité nucléaire et les éventuelles perturbations de la coopération avec la Russie, il est très probable que le premier plasma soit encore retardé d'un à deux ans.

En plus d'ITER, des progrès ont été réalisés dans d'autres programmes publics. Les expériences réalisées par le programme **JET** fin 2021 ont permis d'atteindre une impulsion record de 5 secondes qui a généré 59MJ d'énergie. D'autres résultats sont attendus avant son démantèlement à la fin de l'année 2023. En Allemagne, le **Wendelstein 7-X** (W7-X) est le stellarator le plus avancé au monde. En 2017, il a atteint un nouveau record mondial concernant la température, la densité et la durée du confinement du plasma (triple produit de fusion $nT\tau$) et vient d'entamer une nouvelle campagne expérimentale suite à la modernisation des systèmes de refroidissement. Le **National Ignition Facility** (NIF), aux États-Unis, est la plus grande initiative au monde en matière de fusion par confinement inertiel (IFE). En 2021, le NIF a réalisé une première mondiale en rapprochant la technologie du « seuil d'ignition », le moment où les réactions au sein d'un plasma dégagent plus d'énergie que le plasma n'en consomme, lui permettant de devenir une source d'énergie. Des records de fusion en termes de températures et de plasmas maintenus ont également été atteints par les tokamaks **KSTAR** (Corée) et **EAST** (Chine). Le tokamak **JT-60SA** au Japon, fruit d'une collaboration entre l'UE et le Japon dans le cadre de l'accord baptisé « Approche élargie », devrait également atteindre le premier plasma dans les 12 prochains mois.

Programmes privés

Les initiatives privées dans le domaine de l'énergie de fusion ont bénéficié d'un financement et d'un élan importants au cours des 5 dernières années, avec, à titre d'exemple, huit nouvelles entreprises fondées rien qu'en 2021 et 2022. Alors que les États-Unis et le Royaume-Uni accueillent la majorité des initiatives privées dans le domaine de la fusion, des start-ups européennes ont également vu le jour ces dernières années, comme Marvel Fusion (Allemagne), Focused Energy (Allemagne), Renaissance Fusion (France) et Deutelio (Italie). Selon l'enquête de la FIA (réalisée conjointement avec cette étude), les entreprises de fusion ont déclaré environ 2,8 milliards de dollars de nouveaux financements en 2021, ce qui porte le financement privé cumulé à plus de 4,7 milliards de dollars à ce jour, doublant ainsi le financement historique total en l'espace d'une seule année. Les entreprises privées ont également de nouveaux records importants en matière de températures atteintes et de démonstration de champs magnétiques et, dans de nombreux cas, elles travaillent déjà à la construction de nouvelles machines.

Dans l'ensemble, il existe une variété d'approches de l'énergie de fusion, les initiatives privées poursuivant en particulier des concepts plus éloignés de l'énergie de fusion plus conventionnelle basée sur le confinement magnétique tel que le Tokamak, certaines explorant l'énergie de fusion inertielle (IFE) et l'énergie de fusion magnéto-inertielle (MIF). Le Tableau 0-1 synthétise les différentes approches de l'énergie de fusion, listant un certain nombre d'activités ayant été considérées dans le cadre de cette étude.

Tableau 0-1 Aperçu des principales initiatives actives dans le secteur de l'énergie de fusion au niveau mondial, des sous-approches et des principaux dispositifs et initiatives pour chacune d'elles (texte noir = public, texte bleu = privé)

Approches	Initiatives
MFE / MCF	
Tokamak	ITER, JET, JT-60SA (JP-EU), K-STAR (KO), DIII-D (US), EAST (CN) CFS
Tokamak sphérique	MAST-U (UK), STEP (UK), NSTX-U (US), Tokamak Energy, ENN
Stellarator	W7-X (EU), LHD (JP), Renaissance Fusion, Type One Energy
Z-Pinch	Zap Energy, MIFTI
Toroides Compactes (Field Reversed Configurations [FRC], Spheromak)	TAE Technologies, CT Fusion
IFE Y compris diverses approches directes, indirectes et approches ciblées	NIF, Marvel Fusion, First Light Fusion, HB11, Focused Energy
MIF Y compris la fusion magnétiques ciblée (MTF), l'approche FRC et d'autres approches	Helion Energy, General Fusion

Calendrier de développement prospectif de la fusion

L'analyse prospective, effectuée dans le cadre de l'étude, s'est appuyée sur les délais annoncés publiquement par les initiatives publiques et privées pour les prochaines étapes de développement du secteur de l'énergie de fusion. Cette analyse a été effectuée sur base du niveau de maturité technologique (TRL ou 'Technology Readiness Level'), avec un point de départ autour d'un TRL 2-4 pour la plupart des approches de la fusion, ce qui signifie que le concept technologique est « validé », qu'il existe une première preuve expérimentale et que, dans certains cas, la technologie a déjà été

« expérimentée » en laboratoire. Une évaluation des risques est également effectuée afin de fournir une estimation de la probabilité que ces délais soient dépassés.

Prochaines machines de fusion

Les prochaines machines font référence à un progrès d'un TRL de l'ordre de 4 ou 5, la plupart ayant pour objectif principal de démontrer un gain d'énergie net/une multiplication de la puissance (Q>1), des plasmas stables, et/ou un développement permettant de confirmer le potentiel de la fusion. Globalement, les initiatives publiques sont plus prudentes, les efforts se concentrent sur ITER et assurent un contrôle strict des différents composants de la machine. Les échéances pour les prochaines machines publiques en matière de fusion sont principalement à long terme, c'est-à-dire que si le premier plasma à ITER est attendu pour 2026-2028, les expériences DT les plus importantes d'ITER, celles qui démontreront l'énergie nette, ne sont pas prévues avant 2036 au plus tôt, et peut-être plus tard une fois que la nouvelle référence sera annoncée. En revanche, les activités privées sont assorties de calendriers plus agressifs, d'une plus grande tolérance au risque et d'un besoin d'itération plus rapide. Les principales entreprises privées dans le domaine de la fusion ont annoncé des échéances pour leurs prochaines machines au cours des cinq prochaines années, celles-ci devant démontrer des progrès majeurs et un potentiel de gain d'énergie net/de multiplication de puissance élevée. Au moins une dizaine des principales initiatives privées visent à achever les prochaines machines avant 2028, avec un financement assuré et une construction en cours dans de nombreux cas, il y a de fortes chances qu'au moins quelques-unes réussissent à respecter leurs délais, et d'autres avec de légers retards.

Table 0-1 Calendrier des initiatives publiques / privées pour l'achèvement de la prochaine machine. Le code de couleur représente l'évaluation du risque de dérapage selon Trinomics : x = date prévue pour la prochaine machine ; rouge = risque élevé de dérapage à partir de cette année ; orange = risque moyen de dérapage à partir de cette année ; vert = faible risque de dérapage pendant cette période.

Approche	Initiative	2023-2024	2025-2026	2027-2028	2029-2030	2031-2032	2033-2034	2035-2036	2037-2038	2039-2040
MFE - Tokamak	Public (ITER)							X		
	Privé		X							
MFE - Tokamak Sphérique	Public[1]									
	Privé		X							
MFE - Stellarator	Public[2]									
	Privé		X							
MFE - Z-pinch	Privé		X							
MFE - Toroids Compact (FRC, Spheromak)	Privé		X							
IFE	Public[3]									
	Privé	X								
MIF - FRC	Privé	X								
MIF - MTF	Privé		X							

[1] Aucun nouveau tokamak sphérique public n'est prévu, mais MAST-U et NSTX-U continueront tous deux à fonctionner pendant une grande partie de cette période, avec un TRL autour de 3. Des mises à niveau de ces machines pourraient également être envisagées au cours de cette période.
[2] Aucune nouvelle machine publique du type Stellarator n'est prévue, mais la machine W7-X en Allemagne continuera à fonctionner pendant toute cette période, autour d'un TRL 3. Des mises à niveau (par exemple, des matériaux de paroi) pourraient être prévues au cours de cette période.
[3] Aucune nouvelle machine publique de fusion inertielle n'est prévue au cours de cette période, mais il est entendu que le NIF continuera à fonctionner aux États-Unis au cours des années 2020 et que d'autres installations laser (par exemple, ELI-ERIC avec des installations en République Tchèque, en Roumanie et en Hongrie) qui ne sont pas

dédiées à la fusion mais potentiellement disponibles pour des expériences pourraient également constituer une infrastructure publique de soutien précieuse pour les entreprises actives dans l'IFE.

Installations pilotes

Les installations pilotes font référence à un TRL d'environ 5-7, l'objectif principal étant de démontrer la production d'électricité. Les installations pilotes peuvent n'être destinées qu'à un fonctionnement à relativement court terme et/ou à une faible disponibilité mais elles sont cependant censées démontrer la production d'électricité. Elles devraient également démontrer la manière dont le cycle du tritium (s'il est utilisé) est traité, la résilience des matériaux, l'approche 'RAMI' (fiabilité, disponibilité, maintenabilité et inspectabilité) et la prise en compte des questions liées au cycle de vie. Les échéances pour les prochaines machines des initiatives publiques de fusion sont à très long terme et, en Europe, elles dépendent de DEMO, dont la conception serait finalisée après les expériences DT d'ITER. Aucun calendrier public n'a été fixé, mais une centrale DEMO de l'UE qui serait opérationnelle en 2050-2055 semble réaliste, compte tenu du temps nécessaire à la conception et à la construction de DEMO. Un calendrier similaire peut être attendu pour les équivalents DEMO au Japon et en Corée. D'autre part, la Chine prévoit la construction de son équivalent à DEMO, appelé CFETR, dès les années 2040, tandis que le Royaume-Uni prévoit également une usine pilote, STEP, pour 2040, avec d'importants fonds déjà engagés dans les activités de conception et de chaîne d'approvisionnement. À l'image de l'ambition de construire les prochaines machines, il existe également des calendriers ambitieux pour les usines pilotes du secteur privé, qui prévoient la mise en route d'une usine pilote entre 2030 et 2035. Ces plans sont jugés plus risqués que ceux des prochaines machines, car elles dépendent: du succès des prochaines machines, qui n'est pas garanti, de l'obtention de fonds supplémentaires et de la résolution des problèmes de conception, d'ingénierie, d'approvisionnement et de construction. Bien que bon nombre de ces problèmes sont déjà réglés pour les prochaines machines, ils ne le sont pas encore pour les installations pilotes.

Table 0-2 Calendrier des initiatives publiques / privées pour les installations pilotes. Le code couleur représente l'évaluation du risque de dérapage selon Trinomics : x = date cible de l'installation pilote ; rouge = risque élevé de dérapage à partir de cette année ; orange = risque moyen de dérapage à partir de cette année ; vert = faible risque de dérapage au cours de cette période.

Approche	Initiative	2030-2031	2032-2033	2034-2035	2036-2037	2038-2039	2040-2041	2042-2043	2044-2045	2046-2047	2048-2049	2050-
MFE - Tokamak	Public[1] (DEMO)											
	Privé		x									
MFE – Tokamak Sphérique	Public (STEP)						x					
	Privé			x								
MFE - Stellarator	Public[2]											
	Privé		x									
MFE – Z-pinch	Privé	x										
MCF – Toroids Compact (FRC, Spheromak)	Privé			x								
IFE	Public[2]											
	Privé			x								
MIF - FRC	Privé	x										
MIF - MTF	Privé			x								

[1] Aucune date cible spécifique n'a été fixée pour DEMO (UE), mais la période indiquée est potentiellement possible pour toutes les installations DEMO (UE/JP/KO), en particulier l'installation chinoise (CFETR).

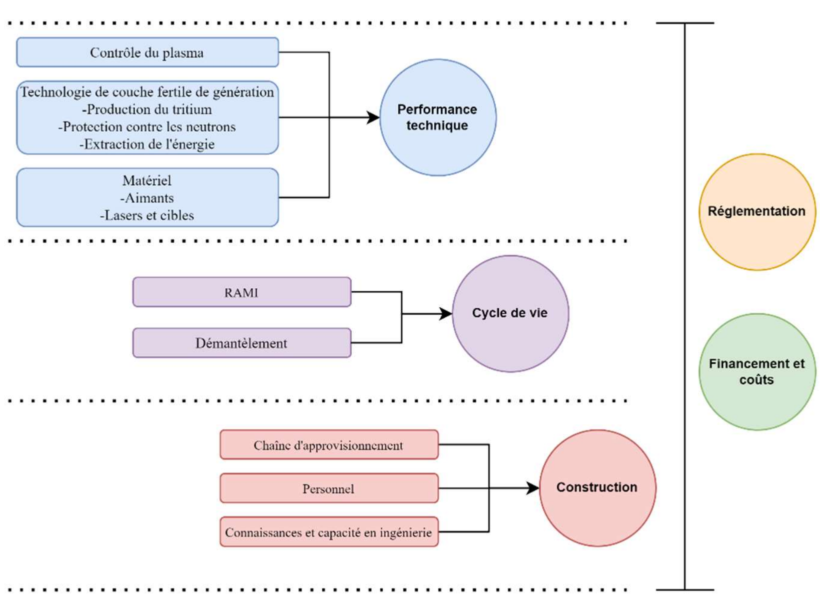
[2] Aucune installation pilote publique n'est prévue à ce stade pour cette approche, mais cela pourrait changer dans les années à venir.

Enjeux pour le développement futur de la fusion

Plusieurs obstacles à la commercialisation de l'énergie de fusion ont été identifiés, parmi lesquels :

- **La performance technique**: à ce jour aucune initiative n'a démontré un gain net d'énergie, bien qu'un meilleur contrôle du plasma peut jouer un rôle important pour y parvenir, d'autres enjeux majeurs liés à la technologie du module de couverture pour la génération du tritium (cycle du tritium, protection contre les neutrons, extraction de l'énergie), aux équipements (aimants, lasers, cibles) et autres difficultés encore considérées significatives ;
- **Cycle de vie**: RAMI, durabilité et démantèlement font partie des enjeux qui devront être abordés à plus long terme par le secteur de la fusion. Lors de la phase des installations pilotes, plus de clarté sera nécessaire sur chacune de ces questions afin de parvenir à commercialiser l'énergie de fusion.
- **Construction**: la construction et le déploiement de centrales de fusion exigent, entre autres, la disponibilité de la chaîne d'approvisionnement, qui reste relativement peu développée et à petite échelle pour de nombreux composants clés. Un personnel hautement qualifié et des connaissances techniques approfondies sont également indispensables, ce qui est signalé comme un obstacle important à l'heure actuelle.
- **Réglementation**: il s'agit d'un défi majeur, il est nécessaire de mettre en place une réglementation du secteur de la fusion qui soit proportionnelle aux risques associés à l'énergie de fusion (plus faibles) par rapport à la fission nucléaire, et dont les risques intrinsèques sont bien plus élevés.
- **Financement et coûts**: l'accès au financement est crucial pour les initiatives tant publiques que privées avec, pour objectif final, que l'énergie de fusion puisse être économiquement compétitive, pour une phase ultérieure de commercialisation.

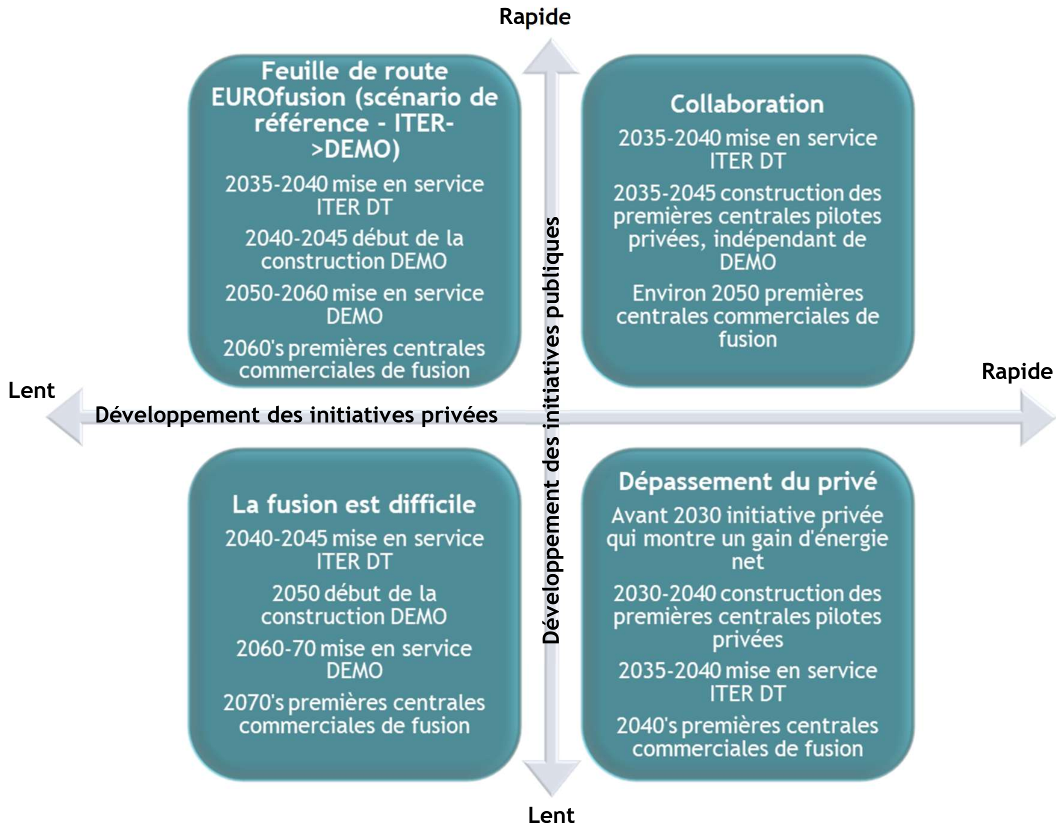
Figure 0-1 Résumé des enjeux majeurs pour le secteur de la fusion



Scénarios de développement futur de la fusion

Cette étude a développé quatre scénarios permettant de considérer et d'analyser les implications de différentes voies de développement de la fusion. Les deux axes principaux (Figure 0-2) représentent le calendrier du succès des initiatives de fusion financées par des fonds publics (axe vertical) et le calendrier du succès des initiatives de fusion privées (axe horizontal).

Figure 0-2 Aperçu des scenarios de développement potentiel de la fusion



Scénario n.1: Feuille de route d'EUROfusion (scénario de référence – ITER -> DEMO)

Dans les programmes publics, le premier plasma d'ITER se produit vers 2028-2030, ITER DT commence à fonctionner à l'horizon 2035-2040, et démontre un gain d'énergie net de l'ordre de Q=10. ITER réalise également « l'ignition », montrant qu'une réaction de fusion devient auto-entretenue. D'autres approches réalisent également des avancées (par exemple, NIF, W7-X, NSTX-U et MAST-U), tandis que les initiatives privées connaissent quelques succès mais ne jouent pas un rôle majeur. En ce qui concerne les installations pilotes, dans les programmes publics, les concepts DEMO dans l'UE (et ailleurs) sont finalisés après l'exploitation d'ITER DT (vers 2040) et la construction de DEMO commence avant 2045, pour une exploitation dans les années 2050. Pour ce qui concerne les initiatives privées, les premières installations pilotes ne commencent à fonctionner que vers 2040 et connaissent un succès variable. La dernière étape de la commercialisation a lieu dans les années 2060, lorsque le premier parc de centrales commerciales (basées sur l'approche du tokamak MFE) est mis en service.

Scénario n.2: Collaboration

En ce qui concerne les prochaines machines, les programmes publics suivent la même voie que le scénario de la feuille de route d'EUROfusion. Les initiatives privées parviennent à démontrer des progrès significatifs avant l'exploitation d'ITER DT. Au milieu des années 2020, une poignée d'entre elles démontrent déjà un gain énergétique net (scientifique) et une ou deux d'entre elles sont également en mesure de démontrer « l'ignition ». Ensuite, la première vague d'initiatives privées commence par la construction de leurs installations pilotes, dont les premières sont achevées vers 2036-2038, tandis que le gain énergétique net est atteint et que l'électricité est mise sur le réseau pour la première fois vers 2045. En raison du succès des initiatives privées, DEMO est mis à l'écart et les programmes publics sont réorientés vers les derniers défis scientifiques et techniques. Le premier parc de centrales commerciales (basé sur des approches multiples) est mis en service vers 2050, grâce à la collaboration entre les initiatives publiques et privées.

Scénario n.3: Dépassement du secteur privé

Les premières initiatives privées parviennent à la fois à respecter les délais fixés pour la mise en service des prochaines machines et à atteindre un grand nombre des objectifs visés avec celles-ci. Dès 2024, les premières initiatives affichent des résultats démontrant des progrès significatifs, et davantage de machines sont mises en service chaque année au cours de la période 2025-2030. Les programmes publics suivent le même calendrier que le scénario de la feuille de route d'EUROfusion ; à partir de 2035-2040 environ, ITER commence ses expériences DT. Les initiatives privées s'appuient sur le succès de leurs premières machines et passent rapidement au stade de l'installation pilote. Les premières installations pilotes sont achevées au début des années 2030 et l'électricité produite par une installation pilote de fusion est mise sur le réseau pour la première fois vers 2035. En raison de la rapidité du succès des initiatives privées, le financement d'ITER diminue lentement après 2040 et les projets de centrales DEMO sont écartées dans tous les pays, les programmes publics réorientent leurs activités et les financements sont réduits. Le succès des installations pilotes dans les années 2030 et la résolution des principaux défis techniques permettent de déployer les premières installations de fusion commerciales à partir du début des années 2040.

Scénario n.4: La fusion reste difficile

Dans les programmes publics, le premier plasma d'ITER se produit après 2028-2030, avec quelques retards par rapport à leur nouvelle feuille de route. La poursuite de la modernisation et de la mise en service d'ITER pose des problèmes qui retardent l'exploitation d'ITER DT à l'horizon 2040-2045. Les premières initiatives privées à construire leurs prochaines machines se concrétisent vers 2025, bien que la plupart d'entre elles enregistrent un retard de 1 à 3 ans par rapport au calendrier prévu et ne rencontrent pas le succès escompté. La construction de DEMO ne commence qu'à la fin des années 2040 et, en raison de plusieurs difficultés, DEMO n'est finalement prêt que vers 2060 et injecte de l'électricité sur le réseau seulement à ce moment-là. Les premières centrales pilotes privées ne commencent à fonctionner que vers 2040 et ne sont pas en mesure de relever tous les défis restants, l'attention se tourne vers la recherche publique et DEMO pour aider à combler ces dernières lacunes. Enfin, la première flotte de centrales commerciales (basée sur l'approche du tokamak MFE) est disponible dans les années 2070.

Conclusions et recommandations

Les principaux enseignements que l'on peut tirer de cet exercice et les recommandations sur la manière dont l'UE peut y répondre sont les suivants :

- Les initiatives privées de fusion sont susceptibles de réaliser une énergie nette au cours de la période 2024-2028.
- Peu de personnes dans le secteur de la fusion doutent de la valeur d'ITER, et certains pensent qu'il est encore probable que ce dernier soit le premier à démontrer Q>1.
- Les activités de conception de DEMO sont en cours et deviendront probablement plus explicites dans le 10eme programme-cadre (PC10). La conception finale de DEMO attendra les résultats des expériences DT d'ITER.
  - **Recommandation** : L'expérience d'ITER suggère vivement que les acteurs industriels et les intégrateurs de systèmes d'ingénierie soient impliqués le plus en amont possible dans les activités de conception de DEMO.
- Les matériaux resteront probablement l'un des principaux défis de la fusion, et l'installation IFMIF-DONES serait un atout important aux projets mondiaux destinés à résoudre ce problème.
  - **Recommandation** : Veiller à ce qu'une décision positive soit prise concernant le financement d'IFMIF-DONES et que les travaux soient coordonnés avec d'autres pays qui travaillent également sur les matériaux (Royaume-Uni, États-Unis, Chine) et avec des partenaires potentiels (Japon).
- Les initiatives privées de fusion sont concentrées aux États-Unis et, dans une moindre mesure, au Royaume-Uni. S'il y a un désir de construire une communauté de fusion privée similaire dans l'UE, une action urgente est nécessaire pour soutenir la création de telles initiatives.
  - **Recommandation** : Pour l'UE, la création de programmes similaires à ARPA-E et INFUSE est recommandée.
- La visibilité de la fusion dans les politiques, modèles et programmes de l'UE est très faible et peut être améliorée.
  - **Recommandation** : La CE devrait s'assurer que la fusion est incluse dans le champ d'application des programmes de financement, des stratégies et des exercices de modélisation de l'UE (par exemple, ajouter la fusion dans la taxonomie de l'UE pour la finance durable ; considérer la fusion comme l'une des dimensions dans les scénarios de modélisation de l'énergie à long terme de l'UE (après 2040/2050); reprendre la fusion parmi les technologies qui peuvent être financées par des mécanismes de financement spécifiques lorsqu'elles atteignent le niveau de maturité requis, tels que Breakthrough Energy Catalyst, ou le Fonds d'innovation).
  - **Recommandation** : La CE devrait également veiller à soutenir un message sur la fusion qui encourage une perception publique positive, en veillant à réduire les liens forts avec la fission nucléaire.
- Les approches réglementaires de la fusion sont importantes - la réglementation devrait être proportionnelle aux risques de la fusion, et non basée sur la fission.
  - **Recommandation** : La CE devrait faire pression pour que les agences de réglementation des principaux États Membres développent leurs approches en matière de réglementation de la fusion afin d'apporter de la clarté au secteur.
  - **Recommandation** : La CE devrait continuer à travailler via les agences internationales, par exemple l'AIEA, afin de chercher à harmoniser les approches réglementaires de la fusion au niveau mondial.
- Alors qu’une diversité d'approches de la fusion est en train d'émerger, une focalisation en UE limitée au confinement magnétique et plus spécifiquement au tokamak apparait très restrictive.

    - **Recommandation** : La CE devrait examiner dans quelle mesure les mises à niveau de W7-X ou un dispositif de centrale pilote basé sur le stellarator pourraient également être financés.
    - **Recommandation** : Examiner comment l'UE pourrait tirer parti de son expertise dans les technologies laser pour créer un programme public d'énergie de fusion inertielle.
- Il serait utile de prévoir des plans d'urgence dans le cas où une ou plusieurs initiatives privées de fusion parviendraient à développer une centrale pilote fonctionnelle avant 2040, ce qui ouvrirait la voie à la fusion commerciale assez rapidement, car cela aurait des conséquences importantes pour DEMO.
    - **Recommandation** : La CE devrait avoir une idée claire de la manière de répondre à un éventuel "saut technologique" des initiatives de fusion privées, après avoir réfléchi à la manière de faire progresser (ou non) DEMO et à la manière dont le programme de fusion européen pourrait être réorienté si un tel "saut technologique" venait à se produire.
- Le personnel et la compétence sont susceptibles de devenir un problème de plus en plus important dans les décennies à venir, et il sera crucial de garantir une réserve de scientifiques, d'ingénieurs et de techniciens qualifiés afin d'éviter que cela ne devienne un obstacle pour le secteur.
    - **Recommandation** : La CE devrait travailler avec EUROfusion et les parties prenantes de l'industrie pour mieux comprendre l'ampleur et la nature du problème sous-jacent, afin de mettre sur pied une approche adaptée pour retenir les talents dans la communauté européenne de la recherche et de l'industrie de la fusion.
- Quel que soit le scénario le plus proche de la réalité, un effort industriel massif sera nécessaire pour accélérer le déploiement de l'énergie de fusion une fois que les premières centrales commerciales auront fait leurs preuves.
    - **Recommandation** : Il est essentiel de soutenir l'industrie européenne pour qu'elle soit bien positionnée - soit en tant que développeur de l'énergie de fusion, soit en tant que fournisseur clé des principales initiatives dans ce domaine - afin qu'elle puisse bénéficier pleinement de la commercialisation éventuelle de l'énergie de fusion.

1 Introduction

This project began in January 2022 with the objectives to:

- Research the various fusion activities, both public and (especially) private, that are occurring globally and based on this develop scenarios that provide, to the extent possible, foresight into how fusion energy may develop in the coming decade and beyond.
- Inform the strategic decisions on the direction of European publicly funded fusion activities in the coming years, and support smart decision making on the allocation of funding to speed up commercialisation of fusion energy in Europe, and support continued European scientific and industrial leadership.

This final report presents the final analysis of the work, including:

- An overview of the methodology and approaches used, including the data gathering methods. (see in chapter 2);
- Analysis of the current status of fusion activities globally, providing an overview of the main approaches to fusion, the general strengths and weaknesses of the initiatives pursuing these approaches, analysis of the timeframes per fusion approach and conclusions on main findings from the research carried out (see in chapter 3);
- Analysis of future scenarios of global fusion development, which build upon the current status, first highlighting the key challenges and barriers for fusion development, then defining and elaborating scenarios of potential fusion development and then analysing the implications of the scenarios for fusion development in the EU and globally (see in chapter 4);
- A summary of lessons learned and recommendations for the European Commission (EC) and the European fusion programme (see in chapter 5).

The Annexes to the report are provided separately, provide further details on public and private fusion initiatives globally.

2 Methodology and approach

2.1 Key terms

In this report we use a number of key terms throughout the work, important distinctions to understand are:

Initiatives: we use this term to refer to individual entities and their approach to fusion, these can be public approaches, e.g., ITER or JET or NIF; or also individual private firms working on fusion.

Approaches: we use this term to refer to a specific type of approach to fusion energy, these are described more in detail in section 3.2. Typically multiple initiatives are working on each main fusion approach.

2.2 Limitations

Important note: Our analysis is sometimes conducted at approach level, this aggregates the analysis across a handful of initiatives. This is done to partly anonymise any assessments being made, the main reason is to reduce the focus of the assessment on individual companies as the team acknowledges that it is not possible to provide a full and fair assessment of each initiative in the scope of this work. To do so would be misleading, as the team is not fully equipped to make such an assessment (despite benefiting from the contributions of experts in the fusion sector), does not have full access to relevant information and has not been able to spend the considerable time necessary to carry out a full, due-diligence style assessment per initiative. Therefore, whilst the analysis is based on best available information and insights from interviews, the assessments and future expectations presented in this report are, as is always the case in scenarios and forward looking assessments, subject to significant uncertainties. The value of our work is in better understanding some of the multiple possibilities for fusion energy development and what the implications of these could be.

One of the most difficult aspects of the work was to interpret the public information and claims of the private fusion initiatives. Typically, these are ambitious and much faster than public initiative timelines. One side argues that this is an advantage and characteristic of the private sector, to be able to make quicker decisions and iterate faster, without the bureaucracy and risk-aversion of public programmes. As a result although timelines are ambitious, it can be argued that these are still realistic. The other side is more sceptical, they believe the timelines are necessarily shorter as private companies need to 'sell' a vision to investors, who have a limited timeline for a return on their investment. Therefore, the timelines may not be realistic. There is also scepticism from some based on their belief that the private initiatives haven't yet grasped the magnitude of the challenges, particularly the longer term challenges, to making a fusion power plant. The other side are optimistic these challenges can be addressed along the way. Whilst we have drawn upon sector expertise to refine our analysis (see below in 2.4), it is impossible to make a firm judgement on either side within the scope of this study, which is also why the scenario approach has been used to explore variations of both sides of this judgement.

Finally, the sector is moving quite quickly, new firms have been founded in the last months to pursue fusion energy. It has not been possible to include more detailed assessments of all firms, especially these most recent ones, some of which could emerge as important players. However, at this point in time we believe that the work has identified and focused on the most relevant public and private initiatives globally.

2.3 Scope

The scope of this work is all fusion initiatives globally. Therefore both public and private programmes in all countries. However, there was a focus on the most accessible and active countries globally, notably in the EU, US, UK, Japan, Korea and China. Other ITER members India and Russia, whilst fulfilling their contributions to ITER, are much less (publicly) active in public and private fusion and therefore were not a major focus of the research.

This work is focused on fusion energy for power (or heat) production. It has not focused on initiatives which look at space propulsion, medical or other fusion applications.

2.4 Approaches

This work employed various approaches to gather data and refine the analysis, contacting all of the main initiatives in the fusion space and using independent sector experts to refine the analysis. In summary:

2.4.1 Desk review

Factsheet fiches have been prepared for a selection[3] of public and private fusion initiatives. The data fiches, strengths and weaknesses, and timeline assessments were prepared on the basis of desk review, supplemented by information from the interviews (see 2.2 below) and survey (see 2.3), and then revised following validation workshops with the fusion experts working on the project (see 2.4).

2.4.2 Interviews

Following the identification of the most relevant fusion initiatives globally during the inception phase we approached these organisations for interview to understand more in depth their initiative, their plans, the strengths and challenges of their approach, their views on public-private cooperation and their opinion on future fusion development. 29 Interviews were carried out with public and private initiatives globally, and others provided written responses. It was difficult to get responses to interview from some countries, notably China, India and Russia.

2.4.3 Survey

As was discussed at inception and subsequently agreed with the EC, a survey was launched in partnership with the Fusion Industry Association (FIA) who distributed an online survey direct to their contacts. This survey was carried out between April-June 2022 and the survey report was launched at an event in Brussels on 14 July 2022[4]. The survey results have been used to inform our analysis, adding additional information on timings, milestones, funding and opinions on main challenges and timelines.

---

[3] The selection was agreed at the inception stage of the project

[4] The survey report can be found here: https://www.fusionindustryassociation.org/about-fusion-industry

2.4.4 Internal validation workshops

Internal validation workshops were used to improve the robustness of the work. The workshops involved the team presenting a preliminary version of the strengths and weaknesses (see section 3.2) and timeline analyses (see section 3.3) of individual initiatives to the panel of three independent fusion experts included in our team. The validation workshops focused on improving the assessments and discussing the timeline and risks associated with each initiative to support the analysis presented in chapters 3 and 4.

2.4.5 Working session to build scenarios

A working session on scenarios of fusion development was carried out with the independent fusion experts on team, this helped in the initial and further development of scenarios, specifically this addressed the quadrant approach and key dimensions presented in chapter 4.

3 Current status of fusion activities

3.1 Overview of current fusion activities

3.1.1 Public programmes

This section describes the developments in the public fusion research domain and presents an overview of the key devices, noteworthy news and achievements recently and a short overview of strategies in key fusion nations. For an introduction to the different fusion approaches and an overview of their progress towards fusion energy please refer to Annex A.

ITER

The International Thermonuclear Reactor (ITER) is the largest (major radius/minor radius = 6.2m/2.0m, plasma current = 15MA) and highest funded fusion initiative in the world. ITER is a public endeavour between the EU, USA, China, Russia, Japan, Korea, and India. The EU, in addition to hosting the reactor, finances around 45% of its costs and the other nations provide 9% each. The reactor, located in the south of France, has experienced significant delays since the start of the ITER project. Originally intended to being operation in 2020, the most recent aim was to have first plasma by the end of 2025 but this is very likely to be delayed. The reasons are multiple.

Firstly, the COVID-19 pandemic has resulted in supply chain disruptions delaying the construction. As a consequence, the late ITER Director General, Bernard Bigot, said that the 2025 target of first plasma is 'no longer technically achievable', and that the budget could be exceeded due to ongoing running costs that cannot be eliminated. Additionally, as of late January 2022 the construction has been halted by the French Nuclear Safety Authority (ASN) after noticing misalignments between the welding surfaces of the first two out of nine total vessel sections that make up the torus vessel. This is problematic as they should fit together with sufficient precision to make high-quality welding possible. The ASN also adjudged the planned two-meter-thick concrete radiological shielding, and in particular the additional shielding of the openings in it, as inadequate to protect personnel once experimental operations get underway, however increasing the shielding would push the total weight of the reactor past the maximum capacity of the foundation. These issues need to be satisfactorily addressed before ASN will lift its construction hold. ITER staff are confident these issues can be resolved.

It was estimated by ITER Organization that COVID-19 alone will push back ITER's completion by at least 17 months, without accounting for the recent regulatory issues. These delays have resulted in re-baselining the construction and operation timeline and this was presented to the governing ITER Council in June and in November but will not be official until the council's ratification, expected only in 2023 as a new Director General was appointed[5] and he needs time to take ownership of the new baseline which has to include the resolution of recently surfaced technical problems. The Russian invasion of Ukraine and related sanctions appears to have only caused minor delays to the timeline, with major components such as the Poloidal field coil produced by Russia being shipped to ITER in December 2022. However, the significant number of small disruptions are likely to lead to delays, and ITER may not be complete nor achieve first plasma until 2027 or later. It is still uncertain what any delays would mean for the planned Deuterium-Tritium (DT) fuel experiments to attempt energy gain, originally scheduled for 2035.

[5] The new ITER Director General Pietro Barabaschi was appointed in September 2022

JET (UK & EU)

Until ITER is constructed, the Joint European Torus (JET) in Culham, UK (2.96m/1.25m, 4.8MA) and operated by the UK and EUROfusion is the world's largest and most powerful operational Tokamak[6]. It has been operational since 1984 and was the first reactor to run fifty-fifty DT experiments. The reactor has been running close to forty years and is moving towards the very final phase of its lifetime as it planned to be decommissioned at the end of 2023. Experiments performed at JET at the end of 2021 achieved a record 5 second pulse that generated 59MJ of energy. The pulse length 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.

EAST (CN) and K-STAR (KO)

The EAST (1.85m/0.45m, 1MA) and K-STAR (1.8m/0.5m, 2MA) 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. These reactors continue to do many relevant experiments for ITER.

JT60-SA (JP & EU)

The JT60-SA tokamak (3.4m/1.0m, 5.5MA) in Naka, Japan is a collaborative effort between the EU and Japan under the Broader Approach programme. The project is closely related to ITER and was intended to be completed 5 years ahead of ITER to serve as a test case for efficient implementation and risk mitigation. Key contributions from JT60-SA operation will be research and experiments for higher tokamak plasma pressures and the testing of a divertor concept. 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 in the first half of 2023.

Wendelstein 7-X (EU [DE])

The Max-Planck institute for Plasmaphysics (IPP) in Germany operates the Wendelstein 7-X (W7-X) experiment (5.5m/0.53m, no plasma current), the world's most advanced public Stellarator design. It achieved its first plasma in 2015 and has been running experiments to investigate the suitability of the stellarator design for a powerplant, eventually aiming for pulse durations up to 30 minutes. In 2017 W7-X achieved the world record for stellarator fusion triple product $nT\tau$ (density, temperature, confinement time). Several upgrades were implemented to increase the performance. Amongst these are water cooled cladding that will enable longer pulses and a divertor system consisting of 120 plates. A potential upgrade that is still undecided is the upgrade of the first wall material, which is currently graphite but could potentially be upgraded to metal (likely tungsten-based).

[6] World Nuclear Association (n.d.). Nuclear Fusion Power. Available at: https://world-nuclear.org/information-library/current-and-future-generation/nuclear-fusion-power.aspx

NIF (US)

The National Ignition Facility (NIF) is the largest Inertial Confinement Fusion (ICF) initiative globally and is based in California (USA). 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. Early this year two papers were published about the achievement that explained that various parameters were increased to achieve these results stating that the capsule scale, coupling efficiency and implosion symmetry were increased[7].

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.

Country strategies and programmes

Europe

The European strategy towards fusion energy is based on the EUROfusion programme and its European Research Roadmap to the Realisation of Fusion Energy[8]. This roadmap consists of three main pillars: (1) operating ITER; (2) the International Fusion Materials Irradiation Facility – Demo Oriented NEutron Source (IFMIF-DONES); and (3) consequently constructing a demonstration plant called DEMO. Parallel research into stellarators also under the roadmap umbrella. As noted above, the construction of ITER is ongoing. A decision on funding the construction of IFMIF-DONES will be taken in the next few years. The facility is proposed to be built in Granada (Spain), could cost around €1 billion and would serve as the research center for testing, validation and qualification of the materials for fusion. Its neutron source should produce fusion-like neutrons (~ 14 MeV) with high enough intensity for accelerated testing of fusion reactor material properties. IFMIF-DONES would build upon the neutron source built as part of the IFMIF-EVEDA project conducted by the EU and Japan as part of the Broader Approach. Both the ITER and IFMIF-DONES activities are intended to serve as important inputs for the DEMO reactor.

Euratom’s contribution to ITER is channelled through the EU Domestic Agency, Fusion for energy (F4E), a European Joint Undertaking, established in 2007. As defined in the Council Decision of 18 December 2020 amending Decision 2007/198/Euratom, Euratom’s contribution to the Joint Undertaking (F4E) is fixed at 5.6 billion euros for the period 2021-2027.

The EU’s commitment to nuclear fusion research and development is complemented by research programmes, presently under the umbrella of the Horizon 2020 program. European fusion research is executed by EUROfusion a consortium organization of 30 research organisations and associated entities across Europe.

United Kingdom

[7] https://www-nature-com.tudelft.idm.oclc.org/articles/s41586-021-04281-w.pdf
[8] https://www.euro-fusion.org/eurofusion/roadmap/

Besides also participating in the EUROfusion programme and hosting the JET facility, the UK has, as one of the outcomes of Brexit, developed its own national fusion strategy. The UK government's Fusion strategy is outlined in the 2021 "Towards Fusion Energy"[9] that is intended to create the right conditions that enable fusion to flourish in the UK, both for private and public research programmes. The UK Atomic Energy Authority (UKAEA) is responsible for the development of fusion energy and manages the operation of the Mega Amp Spherical Tokamak–Upgrade (MAST-U) reactor and the development of the Spherical Tokamak for Energy Production (STEP) reactor which would act as a pilot plant for fusion power from a spherical tokamak approach.

Besides these public initiatives, the UK has also determined it wants to move quickly in terms of governance and policy coordination to create a proportionate, risk-based regulatory environment for fusion. It is the first nation to propose fusion specific regulation, extending the approach applied to JET, proposing to regulate it under Health and Safety Executive and environmental regulators, rather than by the Office for Nuclear Regulation. This means that fusion energy facilities are not subjected to nuclear site licensing requirements. The regulatory proposal and consultation process were completed[10] and the government is using the Energy Security Bill[11], currently passing through Parliament, to amend the Nuclear Installations Act (1965) (NIA65) to explicitly exclude fusion energy facilities from the nuclear (fission) regulatory and licensing requirements.

United States

The United States presented its new fusion strategy during the first ever Fusion White House summit in March 2022. At this "Bold Decadal Vision for Commercial Fusion Energy" the Department of Energy (DOE) announced an agency-wide fusion initiative to coordinate fusion energy research under one umbrella and stimulate public-private partnerships (PPP). Additionally, two additional funding opportunities totalling $50 million were announced for basic fusion energy research such as plasma modelling, studying of plasma interactions and control, that supports the design of a fusion pilot plant and is complementary to the PPP program. This built upon recommendations from the US National Academies that reported on 'Bringing Fusion to the Grid' in 2021[12].

Further investments in fusion have also been announced, however the complexity of the US budgetary process, means it is unclear if all funding authorised by the appropriate committees will be included in budget resolutions and appropriations, nor if the overall budget is passed. However, some highlights of funding increases include increases in funding as part of the CHIPS and Science Act[13] passed in July 2022 which has authorised: $50 million annual funding for fusion materials research; extended inertial fusion R&D; extended the milestone-based fusion program through to Fiscal Year (FY) 2027; requires the establishment of a high-performance computing program for fusion; directed the construction of the Material Plasma Exposure Experiment; and, authorised an upgrade to the Matter in Extreme Conditions endstation at the Linac Coherent Light Source. It also authorised:

9 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1022540/towards-fusion-energy-uk-government-fusion-strategy.pdf

10 https://www.gov.uk/government/consultations/towards-fusion-energy-proposals-for-a-regulatory-framework

11 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1088456/energy-security-bill-factsheet-fusion-regulation.pdf

12 https://nap.nationalacademies.org/read/25991/chapter/1

13 https://www.commerce.senate.gov/services/files/1201E1CA-73CB-44BB-ADEB-E69634DA9BB9

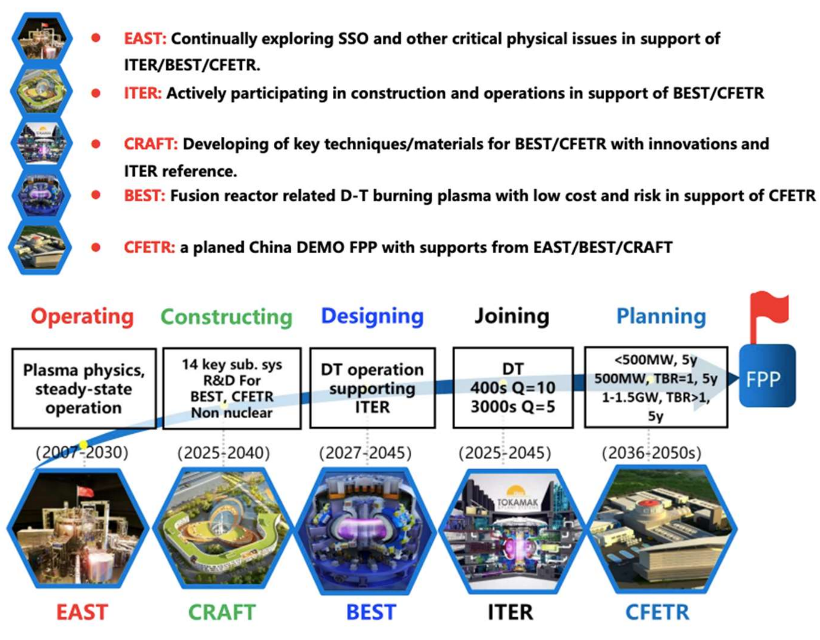
- $310M between 2023-2027 for the establishment of two national teams to develop conceptual designs and technology roadmaps for a pilot fusion plant
- Annual funding of the Fusion Energy Sciences program of:
    - FY2023 $1.025B
    - FY2024 $1.043B
    - FY2025 $1.053B
    - FY2026 $1.047B
    - FY2027 $1.114B
    - Representing a significant increase on the estimated $713M budget in FY2022
- $1.995B for U.S. Contributions to ITER for FY2023-FY2027

The public programme in the US supports fusion activities on a number of devices, most prominently (but not only) the NSTX-U at Princeton, the National Ignition Facility, and the D-IIID run by General Atomics (see in chapter 3 for more information on each). It also funds research into fusion across a network of national laboratories.

China

China is a participant of ITER and in addition to this significant commitment to international fusion development, China also has a national strategy that is leveraged around ITER. This national pathway was presented by the Chinese Academy of Sciences Institute of Plasma Physics (ASIPP) during its annual meeting and symposium for fusion power associates[14] and is demonstrated in the figure below. Besides funding the construction of the EAST reactor, the government awarded an additional $900 million in funding[15] for running the reactor to continue its valuable research for ITER and DEMO up until 2030.

Figure 3-1 Chinese fusion pathway[8]



[14] Song, Y. (2021). Fusion Research and Activities in ASIPP.
[15] https://www.fusionindustryassociation.org/post/chinese-fusion-energy-programs-are-a-growing-competitor-in-the-global-race-to-fusion-power

The next step in the Chinese pathway is CRAFT, a facility that will test specific subsystems for magnetic confinement fusion and materials. The facility is currently under construction[16] and serves a comparable purpose as the European IFMIF-DONES as it is a supportive testing facility. Currently in the design phase is the BEST reactor that is intended to demonstrate burning DT plasma and serve as the predecessor of the ultimate goal of this pathway: the China Fusion Engineering Test Reactor (CFETR). This is the Chinese equivalent of DEMO, and preliminary design work has been carried out. CFETR is intended for steady-state operation, as well as tritium self-sustainment. In phase one it should have 200MW fusion power and in phase two it should have power of 1GW.

Japan

The Japanese Fusion roadmap is based around eight main strands, the timelines and activities of which are quite similar to the European Roadmap, and with the Broader Approach cooperation with the EU being a key component of Japanese fusion activities:

1. ITER project
2. JT-60SA – as part of the Broader Approach activities and which will carry out research to benefit ITER and DEMO design into the 2030's – commissioning of the JT-60SA in 2022-2023 will bring a globally important new tokamak into service.
3. Fusion neutron source – which would be constructed by 2030 and carry out neutron irradiation testing
4. DEMO R&D – to develop the concept, then full engineering design and technologies, with a decision on DEMO linked to ITER DT operation
5. Blanket development – engineering tests of test blanket modules
6. Research on large helical devices – advancing academic research
7. Research on high power lasers – advancing academic research
8. Social relations activities – mostly linked to DEMO from the mid-2030s

In addition, the National Institute for Fusion Science (NIFS) in Toki hosts the Lage Helical Device (LHD), the world's second largest stellarator. NIFS guides national efforts and studies plasma simulation, fusion reactor materials, and fusion reactor designs, such as DEMO. In addition, various universities are active including: Tsukuba University has studied the Gamma-10 tandem mirror. Kyoto University has hosted a team studying inertial electrostatic plasma confinement (IEC), which has collaborated with the University of Wisconsin. Tokyo University has developed compact toroid research with the TS-4 experiment. Osaka's Laboratory for Laser Energetics is a leader in the use of metallic cones to focus energy and ignite fuel pellets.

Korea

The Korean Fusion roadmap is based around four main strands, the timelines and activities of which are also quite similar to the European Roadmap, with a decision point on DEMO the main foreseen goal by 2040:

1. KSTAR – experiments at the reactor to demonstrate core plasma technology and explore high performance scenarios. Supplemented by virtual experiments and simulations.
2. ITER – construction contributions and contributions to experiments and operation. Related to ITER a further strand of activities addresses test blanket modules design and development, and later manufacturing, installation and advancement.

[16] https://english.cas.cn/newsroom/mutimedia_news/202205/t20220524_305724.shtml

3. DEMO – to develop the concept, design and core technologies, aiming towards a decision point on DEMO construction in the late 2030's after ITER DT operation.
4. Supporting activities – including on fusion regulation and enhancing industrial capabilities

Russia

The Russian fusion programme roadmap from 2007 aims towards a commercial DEMO plant around 2050. In addition to its ITER contributions the Russian programme has proposed to develop a fission-fusion hybrid facility called DEMO Fusion neutron source which would harvest fusion neutrons and use these to convert uranium into nuclear fuel and to destroy radioactive waste.

India

The Indian fusion programme appears to be relatively small compared to the other countries, and public information is not very up-to-date. In addition to its ITER contributions, its programme is based around operating it's SST-1 experimental device and in the future building an SST-2 device which would contribute to its DEMO design and technology development. Its timeline for DEMO is similar to others.

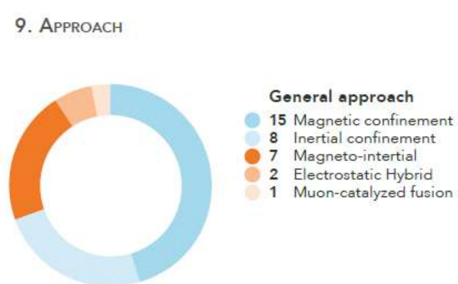
3.1.2 Private initiatives

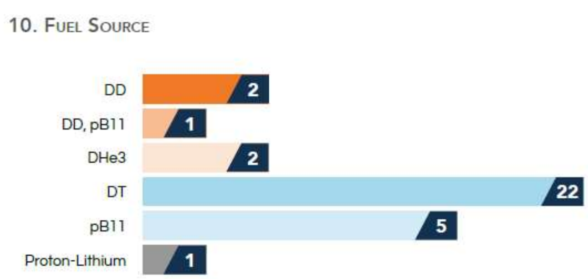
Whereas public fusion programs are expected to deliver energy to the grid in 2050, provided that everything goes well, a growing number of private fusion companies claim they can achieve this in a far shorter timeline. In July 2022, the FIA published its yearly survey[17] (produced in cooperation with Trinomics as part of this report) and this section presents the most important highlights.

Companies

The survey received responses from 33 active companies, an increase from 23 in 2021, with eight new companies founded in 2021 and 2022 and others identified that did not participate in earlier years. The survey responses highlighted the range of approaches and fuel sources being pursued, which are much more diverse than the public programmes, with a higher number pursuing inertial and magneto-inertial fusion approaches, and also pursuing DHe3 and pB11 fuels (see Figure 3-2). Of the 33 initiatives, 3 are primarily pursuing fusion for space propulsion, whilst the remainder are focused on fusion for power or heat production.

Figure 3-2 Extract from FIA survey 2022: Approach and Fuel source of private initiatives



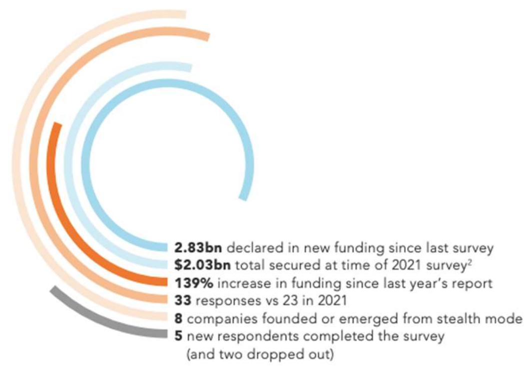


[17] FIA (2022). The global fusion industry in 2022. https://www.fusionindustryassociation.org/about-fusion-industry

Funding

The survey revealed that not only the number of private fusion companies is rapidly growing, but also the flow of private capital into these companies. Since the last FIA survey a year prior, fusion companies declared to have raised $2.8 billion in cumulative funds bringing the total private funding to over $4.7 billion to date. Thereby more than doubling the total historic funding in the timespan of a single year. Shortly after the FIA published its survey, TAE technologies announced an additional $250 million raised for the development of their next experimental device.

Figure 3-3 Funding developments (FIA, 2022)



The vast majority of funding went to US based companies, Commonwealth Fusion Systems (CFS) raising $1.8 billion for the construction of their next device, SPARC, which aims to demonstrate net energy gain, and also to further develop their follow-up pilot plant design, ARC. Helion Energy secured $500 million with an optional additional $1.7 billion that is contingent on demonstrating specific milestones. Furthermore, ZAP energy secured $160 million to continue development of their Z-pinch device. Additional noteworthy funding raises are Canadian based General Fusion that raised $130 million in 2021, whilst Tokamak Energy (UK) and ENN (China) have also raised more than $200 million since their founding. New companies continue to be founded, with one very recent addition only just making it into the survey, Princeton Stellarators, spun out of Princeton University, and which aims to leverage recent breakthroughs and IP to accelerate the path towards commercial stellarator plants.

Experimental successes

The obtained experimental successes of companies in the industry are one of the catalysts for private fusion funding in 2022 and there is a strong and logical correlation between obtained successes and raised capital. **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 SPARC device that CFS is currently constructing will use these magnets and aims at demonstrating net energy gain in 2025.

Tokamak Energy is also utilizing HTS magnets but do that in combination with a spherical tokamak design. The company was able to reach 100 million degree plasma ion temperature in their latest prototype: the ST40 reactor. This temperature was also reached by **Helion Energy** in their pulsed FRC device. **TAE Technologies** also use an FRC design and reached a plasma temperature of 75 million degrees in its device, a significant achievement.

European start-ups

Whilst the United States is the leader in private fusion (21 out of 33 fusion companies that responded to the FIA survey) a few European fusion start-ups have also emerged in recent years. Whilst just over the channel near Oxford in the UK, a further three firms and a fusion cluster centred around JET and UKAEA is forming, bolstered also by being selected by **General Fusion** as the site for their next fusion device.

The oldest European company is Munich-based **Marvel Fusion**, founded in 2019. The company pursues Proton Boron 11 (pB11) fusion with laser driven ICF. It has carried out extensive simulations to prove the core concepts of its approach and has published its first paper. Marvel also did several experiments to prove its simulated predications were correct. Marvel has secured €60 million funding in the past year that will allow expansion of its activities.

Renaissance Fusion was founded in 2020 and is located in Fontaine (Grenoble), France. The company pursues a stellarator concept using High Temperature Superconducting (HTS) magnets. Renaissance is currently working on demonstrating many of the core concepts, but is not expected to initiate plasma experiments within the next three years.

Focused Energy is partially European with offices both in the US and in Germany (Headquarters in the US and therefore classified as US in survey) was founded in 2021. The company aims at DT fusion via laser driven ICF but is secretive regarding its achievements. Funding to date amounts to $25 million and Focused Energy currently employs 60 people over the two countries.

The most recent addition to the European private fusion sector is Italian fusion company **Deutelio** founded in 2022. Starting out with $0.5 million in funding, the start-up is pursuing a Polomac magnetic confinement configuration.

In addition to firms working on fusion directly, big energy companies in Europe have also been participating in the development of fusion. The Italian energy company ENI has developed a number of partnerships with both Italian and international initiatives that are working on magnetic confinement fusion research (e.g., MIT, CFS)[18]. For example, ENI has invested $50 million in CFS and it is now one of its main stockholders through the group's corporate venture capital company, ENI Next[19]. In addition, ENI has also established, together with ENEA, a scientific and technological centre for fusion called Divertor Tokamak Test (DTT) in 2020[20]. The project is worth €600 million and ENI owns 25% of it. The DTT project will be built over 7 years and aims to deliver scientific and technological solutions for certain challenges faced by the fusion process (e.g., management of high temperatures).

Figure 3-4 Private fusion company locations (Source: FIA, 2022)

[18] https://www.eni.com/en-IT/operations/magnetic-confinement-fusion.html
[19] https://www.eni.com/en-IT/operations/collaboration-commonwealth-fusion-systems.html
[20] https://www.eni.com/en-IT/media/press-release/2020/01/energy-enea-and-eni-join-forces-for-international-dtt-project-worth-600-million-euros.html

3.2 General strengths and weaknesses of fusion activities

Methodology and categorisation

This, and the following sections, shortly describe and assess the most promising and most pursued **approaches to fusion**. These can be characterised or classified in multiple different ways. For the purposes of this work, we have defined 3 main types of approach: Magnetic Fusion Energy (MFE), often also referred to as Magnetic Confinement Fusion (MCF); Inertial Fusion Energy (IFE), sometimes also referred to as Inertial Confinement Fusion (ICF – although this category is more apt for the non-energy purposes of experiments at NIF); and Magneto-Inertial Fusion (MIF) energy. There are also various sub-categories of approaches within these three fields, some of which are also expanded upon in the structure of the work, these are summarised, along with the key initiatives (devices or firms) pursuing them, in Table 3-1 below. Whilst further approaches to fusion exist, and other initiatives are active, those that are included below and reviewed in this work are regarded as the most serious initiatives at this point in time. For the interested or non-expert reader Annex A provides a more detailed overview and explanation of the main fusion approaches.

Table 3-1 Overview of main fusion energy approaches, sub-approaches and key devices and initiatives for each (black text = public, blue text = private)

Approach	Initiatives
MFE / MCF	
Tokamak	ITER, JET, JT-60SA (JP-EU), K-STAR (KO), DIII-D (US), EAST (CN) CFS
Spherical tokamak	MAST-U (UK), STEP (UK), NSTX-U (US), Tokamak Energy, ENN
Stellarator	W7-X (EU), LHD (JP), Renaissance Fusion, Type One Energy
Z-Pinch	Zap Energy, MIFTI
Compact Toroids (Field Reversed Configurations [FRC], Spheromak)	TAE Technologies, CT Fusion
IFE Including various direct, indirect and target-based approaches	NIF, Marvel Fusion, First Light Fusion, HB11, Focused Energy
MIF Including Magnetised Target Fusion (MTF), FRC-based, and other approaches	Helion Energy, General Fusion

Other characteristics of interest include the eventual size of power plant, the type of operation, e.g. pulsed or continuous (steady state) and fuel type (see figure 3-3). For the power plant size, the main ITER and DEMO tokamak stream aims towards power plants with continuous operation and power production of 1 GW or more. Private fusion firms, regardless of the approach, also typically aim at similar capacity ranges, of units providing hundreds of MW of capacity. A handful look at smaller devices, of the order of 50MW per unit, these are intended to be provided as modules, scaling the number of units to the size of the power need. In terms of operation, the MFE approaches are primarily designed around continuous operation, whilst the IFE approaches are based on pulsed approaches – with the frequency of the pulses varying significantly.

3.2.1 Methodology

We have conducted a Strength, Weakness, Opportunities, Threats (SWOT) analysis of each of the activities considered in the frame of this study. This analysis was based on a series of 7 criteria depicted in the table below

Criteria	Description
Technological concept in general	• Provide a general appreciation of the technological solution • Consider maturity / viability of overall approach • This could be on paper (with high expectation) or thanks to strong experiments
Encompass the entire system	• Entire system encompasses electricity production, fuel production, operation • Dealing with the entire system, either internally, or externally with partners, like other fusion technologies, engineering, machinists, utilities… • The company/organisation is not expected to integrate all components of the system, but it should at least grasp the entire system, and find the right expertise and technology outside the company/organisation (when not in-house) • It should demonstrate it can deliver a complete system
Connection to the community	• Assuming none of the actors knows what will succeed or not, collaboration and synergies are clearly showing openness • Partnerships and cooperation with research institutes, universities, ITER, other private initiatives, industry • Important not to work in SILO, to also extract lessons from others' successes
Anticipation of challenges and difficulties (risk management practice)	• Have they realistically identified risks and have plans to manage them? • We don't need to rate here the severity of risks, robustness of solutions, that comes in the next table. Although risks that are gaps in the system can be taken into account in the 2nd criteria in this table. • This is to make a distinction between those having a very short term perspective, without considering what is coming next, and will certainly bring new challenges and difficulties, from those being able to anticipate what would come later, when addressing the integration into a power plant e.g., Reliability, Availability, Maintainability and Inspectability (RAMI), tritium self-sufficiency, overall plant efficiency, availability of materials and trained human resources, and in the longer term; waste management, recycling, neutron material, decommissioning…
Building on past experience and results	• Not just the initiative, but from the community in general (considering the activity can make use of it, or is building its work on it) • Encompasses actual achievements demonstrated so far by the firm. And by others if it is plausible they can use it
Funding success	• Evaluating the amount of funding raised by private initiatives • For public, generally rate as 0. Typically they have large, though multi-annual budgets, but these are under pressure and often uncertain. If significant budget cuts are noted then the mark can be negative, similarly positive if significant increase, but these are likely exceptions.

Commercialisation focus	• State of thinking on future markets and costs, revenue streams (for public initiatives can set this to N/A unless there is a particular commercialization aspect they have from spin-offs/other applications)

The analysis is then compiled by technology type, combining the evaluation of the different activities to extract the main trends for a complete technology. The analysis per activity is kept for internal use only due to the confidential nature of some of the information.

3.2.1 Tokamak

Technological concept in general

The “basic” tokamak is the most advanced and well-established concept in fusion, having a history dating back to the 1950s and multiple active research devices globally. A tokamak is a torus (doughnut/ring) shaped vessel which is completely enclosed by toroidal coils, creating a strong magnetic field. This magnetic field confines the plasma and keeps it away from the reactor walls. A pulsed central solenoid induces poloidal fields that drive the plasma current. The largest current tokamak, the Joint European Torus (JET) (major radius/minor radius = 2.96m/1.25m, plasma current = 4.8MA) has achieved records in fusion energy production and duration, notably in December 2021. However, JET will be decommissioned at the end of 2023. Other notable devices globally include D-IIID (1.67m/0.67m, 2.0MA) in the US, EAST(1.85m/0.45m, 1MA) in China, KSTAR (1.8m/0.5m, 2MA) in Korea, and the JT60-SA(3.4m/1.0m, 5.5MA) in Japan, which will take over from JET as the largest tokamak globally once it completes commissioning in 2022/2023. ITER (6.2m/2.0m, 15MA) is a tokamak-based design that is intended to demonstrate net energy (Q~10) when it enters Deuterium-Tritium operation. Most research tokamaks run on a DD fuel mix to avoid various issues related to Tritium handling, neutron exposure and activation. Amongst private initiatives, Commonwealth Fusion Systems pursues the conventional tokamak design concept with their high magnetic field (12.2 T) SPARC (1.87m/0.57m, 8.7 MA) device. They are seeking to leverage the development of high temperature superconducting (HTS) magnets which can support designs that hope to achieve high performance in a more compact form. HTS magnets are more expensive than other magnet types, however the additional cost is expected to be balanced by large savings in the cryoplant as HTS magnets require much less cooling. Although this approach looks highly promising, it still needs to be demonstrated, this is among the key goals of SPARC. General Atomics also consider following this line with a Compact Advanced Tokamak concept, but details are far less concrete.

Encompass the entire system

The tokamak concept, as the leading focus of public research over the last decades, has built up knowledge, experience and technology on the necessary aspects for fusion energy: from fusion performance requirements, magnet coils, long pulse sustainment, tritium breeding and handling, first wall lifetime, maintenance, and waste management. Large experiments bring confidence about plasma stability control and use of DT and DD fuels.

However, none of the current tokamak devices have been designed to generate electricity. They are experimental, typically designed to test new technologies and answer important scientific questions for fusion. In recent decades the main focus of leading research tokamaks has been supporting the design, construction and future operation of ITER.

To date none of the tokamaks has encompassed a full array of systems to demonstrate electricity production from fusion. ITER will also not encompass the full system. While it is intended to demonstrate sufficient fusion power multiplication (high Q) it will not produce electricity. In the European Fusion Roadmap (and similarly in the Chinese, Japanese and Korean equivalents) the DEMO tokamak which will follow ITER is intended to demonstrate this full working fusion power system.

In the private sector, CFS have the SPARC and ARC designs, with the former device currently under construction, aiming for first plasma in 2025. Whilst these devices may demonstrate particular aspects of a fusion power plant system, with a particular focus on net energy / power multiplication (e.g., CFS aims for a Q~5 in SPARC), it is expected that significant gaps will remain towards a full power plant. Many of these gaps will be the technical challenges mentioned previously for tokamaks and which are common across all fusion concepts, e.g., Tritium cycle and breeding, neutron shielding, materials, plasma control, etc.

Connection to the community

The tokamak concept, with ITER as the leading international cooperation framework and device, is the most advanced globally regarding bringing together the public international scientific and technological community. Private fusion initiatives are not heavily involved in tokamaks, although private companies in industry play a major role in supply chains for ITER.

The network on tokamaks goes beyond the established ITER community, as each partner is itself connected to its national fusion network, steering the collaboration with laboratories, universities, research centres and industry. In Europe EUROfusion is central to the fusion community and is heavily focused on tokamaks and ITER. Industry is expected by most players to become more and more important to all fusion concepts, including tokamaks, as these move towards pilot plants and commercialisation.

Anticipation of challenges and difficulties (risk management practice)

Given the long track record and experience with tokamaks, most of the active devices and programmes have made an extensive analysis of challenges, and have first-hand experience, therefore there is a clear view of the remaining challenges. This includes technical issues (such as tritium fuel cycles and breeding, divertor, pulse duration, materials etc). As most are FOAK devices, they usually face challenges but mitigation channels are put in place on the basis of long standing risk management practice – addressing technical, financial, supply chain, and political risks. Unanticipated challenges are mostly based on external factors, such as geopolitical influences.

Potential issues in future, also common across other fusion approaches include staffing, integration (construction, engineering, fusion science), and gap technologies such as the tritium fuel cycle and breeding, neutron shielding, remote maintenance, plasma control, current drive and divertor. These issues will especially come into focus in the context of DEMO. The planned DEMO devices strongly rely on the progress and results of ITER, strengthening the collaboration, but possibly weakening alternative research.

Building on past experience and results

Tokamak technology has more than 60 years of experience from national research and international collaborations (from universities, laboratories, institutions, and industry), building on each's successes and failures. It is also one of the concepts with a clear roadmap towards fusion. Globally, the tokamak has achieved several milestones and records in fusion energy, such as plasma temperature, long pulse operation.

The leading private initiative in tokamaks, CFS, has demonstrated record strength of magnetic fields in their HTS magnets, which could be a significant breakthrough when integrated into a fusion device, the SPARC device will test this.

Funding success

So far, the Tokamak has been significantly funded by the public fusion programmes (through agreements, international collaboration frameworks, national institutes or agencies) and ITER is amongst the most expensive and complex international projects ever undertaken.

Continuation of the tokamak line in public programmes e.g., DEMO, will require significant further funding. Whilst many countries are pursuing DEMO concept and design activities no country has yet fully committed to fund a next tokamak device.

The record $1.8 billion investment in Commonwealth Fusion Systems is enabling them to build their next device, the SPARC reactor, and further develop ARC design. Funding has been attracted from a variety of sources including oil majors such as ENI, institutional investors, pension funds, sovereign wealth funds, venture capital and high wealth individuals. It has been noted that for CFS, close ties to MIT and the various alumni and networks of this institution provide an advantage in securing funding and other support.

A desired advantage of using HTS magnets in tokamaks is that reactors can be smaller size, which can lead to cost reductions. However, the cost of HTS magnets may reduce this advantage. Private firms companies themselves are more confident that costs can be controlled, particularly as production of key technologies such as ReBCO[21] superconducting tape is increased and costs reduce with this scale-up.

Commercialisation focus

A limited number of the Tokamak activities are focusing on developing spin-offs, and producing commercial products/services, this is largely due to the fact that tokamaks are publicly funded research devices. However, some spin-offs and applications outside fusion do exist or may emerge, like in aerospace; electromagnetic launch systems; microwave technologies; design of materials; high tech fabrication; robotics and remote handling; machine learning capabilities.

The private fusion sector sees a number of opportunities for commercialisation, particularly HTS magnet technologies. However, the core goal of their activities is to produce electricity and therefore this is the primary focus, rather than dedicating significant resources into the commercialisation of these technologies.

3.2.2 Spherical Tokamak

Technological concept in general

The spherical tokamak reactor is a variation on the tokamak concept. Its spherical shape improves the efficiency of the magnetic fields, therefore improving plasma confinement at high pressure in more

[21] Rare-earth barium copper oxide

compact devices, which can help to sustain steady-state plasmas. Spherical tokamaks are typically expected to be compact, as they can operate with smaller magnets than tokamak designs, and certainly most design concepts currently on the table are smaller than ITER. Among the advantages of a more compact design with smaller magnets is the reduction in cost, with a rough estimate that in a tokamak power plant the magnets and buildings each account for around 1/3 of the total costs. Therefore, reducing the need for magnets and size of buildings required can significantly reduce costs.

The narrow ST central post contains both toroidal and poloidal field coils. Its protection from hot plasma heat flux and neutron damage are critical issues that limit its lifetime.

Tokamak Energy, the leading private firm working on spherical tokamaks, has developed very high field HTS magnets and they are seeking to use these to leverage a more compact fusion device.

Encompass the entire system

The MAST-Upgrade in the UK is among the few active spherical tokamaks globally, it is conducting various experiments and also serving as a testbed for key components that could be used in multiple concepts. The Super-X divertor has been among the most important successes, contributing significant improvements to the heat exhaust function of this key component in most fusion concepts. This is particularly important in addressing the key challenge for spherical tokamaks, the additional heat flux. The work of MAST-U in the UK is intended to contribute to the construction of a fusion power plant pilot plant called STEP by around 2040.

In the private sector, Tokamak Energy are pursuing designs to further scale up their approach and utilise the HTS magnets they have developed. Similarly to CFS, their device may demonstrate particular aspects of a fusion power plant system, with a particular focus on net energy / power multiplication but it is expected that, in common with tokamaks, significant gaps will remain towards a full power plant.

Connection to the community

Given the close similarities to tokamaks there are significant links between public initiatives on spherical tokamaks and the broader fusion community and ITER. For the private initiatives these also demonstrate strong links to multiple research leading institutions both inside and outside fusion.

Anticipation of challenges and difficulties (risk management practice)

One of the key challenges for spherical tokamaks in comparison with standard tokamaks is that the shape leads to higher heat stress on the walls of the reactors, with heat exhaust remaining a priority – the demonstration of the Super-X divertor at MAST-U has therefore been a significant step forward in addressing a key challenge.

Other challenges are common to tokamaks in general as mentioned previously.

Building on past experience and results

The similarities between tokamaks and spherical tokamaks provide a long line of research to build upon, and the experiments carried out at MAST, now MAST-U and the NSTX-U[22] in the US provide a solid and continuing stream of scientific and technical progress.

The leading private initiative in spherical tokamaks has made important achievements and results in the last years, with Tokamak Energy achieving 100 million degree temperatures in their test device, and having demonstrated very high field HTS magnets. Whilst the temperature demonstration is unremarkable for public programmes that regularly work with such regimes, it was a major first for a private fusion firm, highlighting the significant and rapid progress being made.

Funding success

Funding of spherical tokamaks has been successful so far, with funding of two leading public devices, in the UK and US (although the US device has struggled in the last decade), and with significant investment in the UK already committed to design activities for the follow-on pilot of a spherical tokamak power plant (STEP).

Tokamak Energy has attracted around $250 million in funding, marking it as one of the best funded private initiatives.

A desired advantage of spherical tokamaks is that their smaller size would make them less costly than tokamaks. However, for the same reasons as noted for tokamaks the cost of HTS magnets may reduce this advantage.

Commercialisation focus

Fusion activities in the area of spherical tokamaks see a number of opportunities for commercialisation, similar to tokamaks. For the private sector, these opportunities are particularly in the areas of divertor and HTS magnet technologies. However, private firms in this area are focused primarily on producing electricity.

3.2.3 Stellarator

Technological concept in general

A stellarator utilizes magnetic confinement to run a plasma through a helical torus reactor vessel. This configuration creates a spiral-shaped magnetic field. Stellarators do not suffer from disruptions (sudden loss of plasma current and therefore plasma confinement) and associated runaway electrons, which occur in tokamaks. No power is needed to drive a high current through the plasma, which reduces recirculating power requirements to sustain long-term operation of the reactor. Stellarators could operate with low input power, in contrast to tokamaks. Overall, stellarators offer a number of potential advantages over tokamaks in terms of their ability to achieve steady-state operation, reduce plasma instabilities and quench. However, Stellarators are known for being “hard to build but easier to operate (than tokamaks)”. They are harder to build due to the complex twisted/helical geometry of the magnets, but advanced computer-aided-design and modelling techniques have allowed for the required precision in manufacturing. Further research is ongoing to simplify these magnets by means of simpler

[22] NSTXU has not been operational in recent years following a technical issue after an upgrade, however efforts are being made to bring it back into service within the next 1-2 years.

coils. Other simplification options also exist, such as thinner walls, to further “simplify” the construction, and make the reactor more compact.

Stellarators are amongst the most promising fusion concepts, being easier to maintain steady-state operation, as the design mitigates issues such as disruption, which are challenging for tokamaks. As it resides within the magnetic confinement family of approaches there are links and learning from tokamaks, however the concept has not been pursued seriously for as long as tokamaks due to the complexities in design and construction, therefore less research has been carried out than for tokamaks. It is regarded by many as being ‘a generation behind’ tokamaks, but also as a good ‘Plan B’ in case tokamaks run into insurmountable issues. Stellarator research, based around the Wendelstein 7-X stellarator (5.5m/0.53m, no plasma current), is one branch of the EUROfusion roadmap.

Encompass the entire system

There are only a handful of active stellarator devices globally, foremost among them are Wendelstein 7-X (W7-X) in Germany and the Large Helical Device (LHD) in Japan. These devices are still at the experimental stage, and like tokamaks, still miss many system elements towards a power plant. There is also, amongst the public programmes no established pathway to a pilot power plant. Therefore, whilst short-medium term research goals are clear for stellarators, the next steps are much less clear, and ideas are focused rather on incremental upgrade of existing devices for further research, e.g metallic wall material upgrade, improving superconductors, developing liquid metals.

Stellarators have become an area of increased private interest within the last few years, with a handful of start-ups entering this space (Renaissance Fusion [FR], Type One Energy [US], Helical Fusion [JP], Princeton Stellarators [US], N.T. Tao [Israel]) and having raised seed capital. As only recently founded, none as-yet have built a device, and therefore concepts are relatively immature at this stage. The start-ups in general are trying to leverage the new knowledge generated by W7-X, the advances in HTS magnets and improved modelling and simulation of stellarator designs. Some also see a role for liquid metal components.

Connection to the community

Stellarators are connected to the broader magnetic confinement research community, and there is also an active public sub-community on stellarators through IAEA and researchers in the EU, US & Japan especially, establishing scientific exchanges during conferences. There are various dependencies and synergies for stellarators when engaging with the broader tokamak/magnetic confinement community.

The private sector is quite new in the area of stellarators and the collaborations with the public research community do not appear as strong yet as in other fields.

Connection with industry is particularly important due to the complexities in manufacture and construction of stellarators. They also face challenges for key components common to some other approaches (e.g., on development of steady-state microwave sources).

Anticipation of challenges and difficulties (risk management practice)

Within the public programmes there is a good understanding of the limitations of the devices and where the boundaries should be pushed, and can be pushed. A clear assessment of risks and challenges is made, with an approach putting risk management at high priority, via a good identification of the challenges associated with the stellarator. This is a necessary approach in the public sector as serious damage to devices can lead to significant problems in securing funding for repair, and also significant delays.

Private firms also noted some of the key risks and contingencies for stellarators (e.g., for challenges linked to HTS, the need to demonstrate wide tapes with several superconducting layers).

Building on past experience and results

Within the field some important achievements have been made already, particularly at W7-X (e.g., ran 100 second pulses and demonstrated stellarator optimisation; recent completion of upgrade cycle, cooling systems; magnetic field shaping benefits of the stellarator design). However, private initiatives are yet to demonstrate significant achievements. Overall the stellarator concept can be said to remain at least 1 generation behind tokamaks despite promising results so far. The application of new technologies by private firms may help to close this gap in the coming years.

Funding success

Public funding (via EUROfusion and Max Plank IPP) for the W7-X in the EU has always been in competition with ITER, and whilst W7-X is funded and active, this competition for scarce funds is part of the reason that a future path for stellarators is unclear.

Private firms have attracted seed investment in the last years, Type One Energy is the leading firm on this metric having raised around $50 million, the other firms much less, although this is growing.

Commercialisation focus

Commercialisation is naturally not a major focus for public stellarators. For the private firms, at this early stage the focus is more on resolving technical issues and developing first devices. However, some innovations are being foreseen as spin-offs.

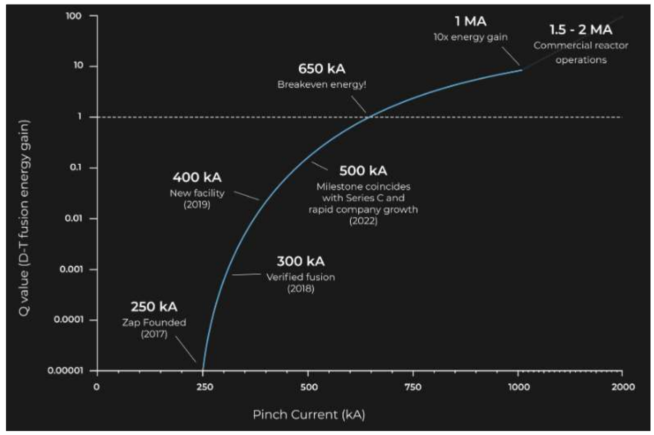
3.2.4 Z-Pinch

Technological concept in general

In pinch approaches fusion conditions are created by “pinching” the plasma. This is done by passing a high current down a column of plasma, which in turn creates a compressing magnetic field around the outside. This compresses the plasma and creates the conditions that allow for fusion reactions to take place. Although the principle of a plasma pinch is fairly simple, there are problems with the stability of the plasma under compression that have proved highly problematic. Research on pinch approaches to fusion date back to the 1950’s but public research into pinches was scaled back significantly due the instability problems. In theory, the pinch approach has a number of advantages, allowing for potentially more efficient energy accumulation than conventional fusion approaches, and therefore helping to avoid plasma instability, improve confinement and heating. The pinch approach can avoid the need for external magnets or laser energy, thereby eliminating some of the challenges and costs of other MFE and IFE approaches.

In recent years, a small number of private firms in the US have focused on Z-pinch based concepts, where they claim to have developed approaches (e.g., sheared-flow stabilisation) which overcome the instability issues. The leading firm active in this area is ZAP Energy (US) who claim that their concept will deliver scientific breakeven (Q=1) on their recently installed FuZE-Q device[23] and that this can be scaled towards commercially viable levels of energy gain, see Figure 3-5.

Figure 3-5: Zap Energy - concept towards fusion power, relationship between Z-pinch current and energy gain (Q value)



Encompass the entire system

Z-pinch is still currently in the R&D/experimental phase, although firms in the sector hope to make rapid progress on moving forward towards a full system. However, there is limited information on how the full systems aspects are dealt with by these firms, question marks remain around tritium cycles and breeding for example – both in terms of continued supply and blanket technologies. Some firms noted that they have already thought about waste streams, waste storage and decommissioning.

Connection to the community

There are collaboration frameworks between private players, and the handful of labs and universities (mainly in the US such as Lawrence Livermore National Laboratory, University of Washington, University of California) that have expertise in pinch approaches. Private firms active in this area are also talking to each other in some cases to exchange practices, results and components (e.g., pulsed power hardware, capacitor bank supply, switches). Overall, the community for this approach is relatively small.

Anticipation of challenges and difficulties (risk management practice)

Those active in this area are strongly focused on solving the main technical problems for pinch-based fusion (heating, stability and confinement). There is some lack of information on how key challenges are being addressed by those active in this area, and therefore question marks remain as to the key challenges and how well these are understood and being addressed. However, indications have been given that waste and decommissioning has been considered, as has tritium supply.

Building on past experience and results

As noted previously, pinch approaches have a long history, but were very niche in the fusion research community for a long time. The firms now focusing on Z-pinch approaches have been founded relatively recently, although spun-out of institutions that were among those few still doing work on pinch approaches. Zap Energy have announced various achievements since their founding in 2017, see also Figure 3-5, including verified fusion and increasing pinch currents to more than 500 kA. This rapid success is promising to deliver further results, with an ambitious goal to demonstrate scientific breakeven by 2024.

[23] https://www.zapenergyinc.com/news/first-plasmas-fuzeq-series-c

Funding success

The total cumulative funds are significant, with Zap Energy among the best funded private initiatives, disclosing funding of $200 million, including a raise of $160 million in June 2022. Prior to this funding was secured from public programmes and other investors. Zap Energy is the most successful story of the ARPA-E fusion participants having been funded by the programme.

Commercialisation focus

Firms in this area are primarily focused on fusion energy for electricity, and are targeting costs of energy competitive with renewables, fission and fossil fuels (with carbon pricing). Some see potential spin-off applications of the technologies in nuclear medicine and transmutation, which could act as revenue generating activities whilst growing the fusion business.

3.2.5 Compact toroids (FRC-based, Spheromaks)

Technological concept in general

Compact toroids (CT) based on either Field Reversed Configurations (FRC) or Spheromak approaches offer a further alternative in the magnetic confinement approaches. The overarching distinction with the tokamak-based approaches is the way in which the magnetic field is generated, with the tokamak approaches achieving this through the use of toroidal and poloidal coils, whilst the FRC and spheromak approaches are able to generate magnetic fields through the plasma current. Field Reversed Configurations (FRC) have only poloidal magnetic fields generated in this way, whilst spheromaks generate both poloidal and toroidal magnetic fields.

A compact toroid using Field Reversed configuration (FRC) can achieve a much higher beta (ratio of plasma pressure to magnetic field pressure) than a tokamak, as the field is created by the current running in the plasma itself. This has advantages for achieving fusion conditions and also opens up possibilities for alternative fusion fuel cycles to the extent that most initiatives looking at FRC consider pB11 or D-HE^3 fuel mixes, due to their advantages in lower neutron production and eliminating the need for tritium breeding. FRC allows for direct energy conversion, that can be achieved via the use of a pulsed approach. Plasma material interface during the high temperature compression can be avoided. However, the use of alternative fuels is more challenging in terms of the fusion conditions that need to be achieved, e.g., higher temperatures. There are also challenges in sustaining the plasma current (which drives the magnetic fields), stability issues, radiation losses and heat exhaust.

A spheromak sustained by external “inductive helicity injection” has been dubbed a “dynomak” by those working on this approach. It induces high-frequency (tens of kHz) radio waves in external loops which inject twisted magnetic fields into the main plasma chamber. The plasma is heated via Ohmic heating, reducing the need for auxiliary heating systems, and the reconnection of magnetic field lines provides additional heating. Those investigating this line hope to significantly reduce the number of magnetic coils required for a reactor (i.e., potentially eliminating central solenoid and toroidal coils), saving space, cost and reducing the number of sensitive components. However, the Dynomak concept faces challenges. For stability, it needs proximity to a conducting wall. Therefore plasma-material interactions remain a challenge, as it is difficult to allow much space between plasma and wall. High radiofrequency (RF) power fluxes may be needed to sustain dynomaks at fusion conditions. To date research into the concept has been quite small scale, the leading private initiative is CT Fusion.

Encompass the entire system

Mainstream CT-FRC research is built on a long term vision and systemic approach, efforts have been made to chart a pathway to a commercial powerplant design. These efforts have a focus on the construction and scaling of the eventual powerplant design, although detailed information is necessarily not public. The advantages of the approach simplify some crucial challenges, e.g., Tritium breeding, but the approach has its own unique system challenges.

The spheromak approach is relatively early in its practical application, although a 2014 article describes a conceptual Dynomak power plant, aimed at developing a low-cost, on-demand, carbon-free power generation with 100+ MW output. However, a detailed design and cost estimate are not yet available.

Connection to the community

The leading CT-FRC initiative (TAE Technologies) is one of the longest active private fusion companies and has built many collaborative partnerships both inside and outside the fusion community. Notably cooperation with Alphabet (Google) on AI is among the highlights, but connections to national laboratories in the US, and international researchers on fusion are also strong.

On spheromaks there is close collaboration between private actors and at least one university (University of Washington). Much of the development so far has been in a public-private partnership (PPP) structure, i.e., via ARPA-E, but the way forward is likely to be more in the private domain.

Anticipation of challenges and difficulties (risk management practice)

For CT-FRC there is well established risk management practice, as a core component of industrial strategy and the long-term vision which encompasses potential challenges for an operational powerplant, including waste, maintenance, reliability etc. Among the technical risks mentioned: the first wall needs to be designed for power fluxes ~10MW/m^2; pulse coils need replacement and maintenance; the use of pB11 requires higher ion temperatures.

For Spheromaks, those working in the sector understand that there are some trade-offs in the approach, particularly that plasma physics can be more difficult than other approaches. At this stage simulation and computation are heavily used to understand and mitigate risks, further validation will require larger devices.

Building on past experience and results

The leader in the CT-FRC approach was founded in 1998 are currently experimenting with their 6th device. It is able to draw upon a significant volume of past experience and results, this is a positive for this approach. There are limited results from other initiatives to draw upon given the small number of past experiments using this approach.

The spheromak, and the Dynomak variation are based on a breakthrough paper, back in 2014. It demonstrated a reactor-relevant power injection (with $P > 20$ MW, toroidal currents $I_p > 100$ kA, and injector voltages $V > 700$ V). Although the science is very well supported and documented, the small dynomak experiments have not produced neutrons yet or demonstrated fusion-like conditions (n, T, τ). The next important step is demonstrating that the concept can be scaled up.

Funding success

Funding for CT-FRC approaches is amongst the highest of all approaches, reaching more than US$1 billion. This funding has been indicated as sufficient to enable completion of the next experimental device in this area. This approach is backed by a variety of private investors, venture capital, large institutions, or a high network of individuals and multiple governments.

For the spheromak approach, funding has primarily been public to date so far ($23 million total, mostly from ARPA-E), but it is understood that a funding round to secure private finance is currently ongoing.

Commercialisation focus

Those active in CT-FRC are aware of the commercial potential of the innovations developed along the way of its pursuit of fusion power. Steps have already been taken to commercialise some innovations, such as accelerator technology for cancer treatment, other opportunities are also considered, but it is noted that these activities should proceed at a pace that does not disrupt the core fusion energy focus. In terms of eventual markets for fusion energy, thought has been given towards a desired price of electricity production of around $50/MWh.

For spheromaks it remains quite early to consider spin-offs although some potential avenues have been identified that could be interesting for these initiatives in future.

3.2.6 Inertial Fusion Energy (IFE)

Technological concept in general

Inertial fusion is a completely different approach than MFE as it does not make use of magnetic fields to hold and confine a plasma. Instead it makes use of small pellets which contain a cavity filled with fusion fuel. Compressing these pellets or targets, by shooting them with high amounts of energy causes them to implode, and the fuel is compressed to very high temperatures and densities that allow for fusion reactions to take place. In IFE, confinement is not achieved by external fields, but by the inertia of the hot fuel that keeps it together for a finite time. Various different approaches to IFE exist that differ in the manner of driving energy into the target and the fuels that are considered. 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.

The advantages of Inertial Fusion Energy compared to Magnetic Fusion Energy, include that powerful magnets are not required; lasers when used as drivers can be installed as a modular system which makes it easier to break into different applications; the pulsed nature of IFE which allows for plasma fuelling and ash removal (i.e., easier to shut down plant); target flexibility; and that the first wall is decoupled from any of the implosion plasma physics. There are also significant challenges to IFE including delivering sufficient energy, in an efficient way to the target; mass producing targets precisely and at low cost; and dealing with overheating of lasers; amongst others.

Encompass the entire system

For the mainstream IFE approaches, the number of experiments that can be done is limited at the leading institutions e.g, NIF in the US, as fusion research is only a part of the purpose of the facility in addition to weapons maintenance and testing. This is a limitation across the IFE field which hinders the full detailing of a fusion energy system based on IFE, although some active in this approach have worked out their overall concept[24].

Thought has been given to the necessary system components with initiatives in this area actively engaging with industrial players to explore these issues, refine designs and identify potential supply chains.

There is considerable focus, and differentiation, within this approach on the target technology and drivers considered. These are currently the major focus of efforts of those active in this area with most initiatives still focusing on securing experimental time at other facilities, carrying out simulations and developing their targets. The medium and long-term view of the system is less clear for IFE than MFE-based approaches.

Connection to the community

Interactions between IFE and other approaches in fusion are limited, as there are not many synergies to explore.

Some private actors collaborate closely with academic organizations, and labs, e.g., in the UK but also at international level (Australia, US, EU), they also utilise public-private mechanisms such as CRADA in the US. As noted above, some private initiatives are already in contact with the industry. The public sphere is well interconnected and partnering, especially in the US (intergovernmental, academia, laboratories, etc). Finding enhanced mechanisms for private firms to utilise public facilities for fusion experiments is seen as an important goal by private initiatives. A private-public-partnership could be used for this purpose.

Anticipation of challenges and difficulties (risk management practice)

Globally, there is a good identification of the limitations of IFE technologies and the key challenges (e.g., mass manufacturing at low cost for target fabrication, inexistence of a large dedicated IFE laboratory/facility, need for very high gain factor, high efficiency industrial laser and efficient low-cost target production, repetition rate of the shot and the separation of materials, etc.). All are essential for the development of a commercial plant. However, in the first instance for the newer IFE approaches and initiatives the largest challenge remains demonstrating fusion.

Initiatives also consider challenges beyond the technical issues, such as cost of building a new test facility, supply chain and quality of materials, resource scarcity, human resources and expertise.
The approaches vary regarding the anticipation of long-term issues (e.g., waste streams), even though it is partly encompassed in R&D about important fusion technologies.

Building on past experience and results

IFE research dates back decades but was largely centred on NIF until the last decade, with high scepticism in the fusion community about its potential for energy generation. The last decade has seen an evolution, firstly through significantly improved results at NIF, and secondly, through advances in laser and other technologies that also signal potential for IFE to work, this has attracted a handful of

[24] For example https://marvelfusion.com/technology/

private start-ups to IFE. The first of these are starting to produce some experimental results, but it would be fair to say that the starting point is much less developed for IFE compared to tokamaks.

The largest milestone for IFE was achieved by NIF in 2021, which achieved a record Q value of around 0.7 and was evaluated to have achieved ignition. However, this result has not been reproduced.

Funding success

Public funding of NIF in the US is tied to the National Nuclear Security Administration of DOE, this is sufficient to carry out current work. There does not seem to be a tangible prospect of a publicly funded facility dedicated to IFE, funding is an important issue for this. In this absence of such funding private initiatives will need to either build their own facilities or seek time on relevant non-fusion laser devices of which there are a handful globally.

Private initiatives in IFE have been successful in raising first rounds of funding, highlighting investor interest in the approach. Significant further funding will be necessary to take the next steps.

Commercialisation focus

The focus of most IFE activities is on power generation. There are potential secondary applications, such as for medical operations and cargo screening. Some initiatives have identified these opportunities, but broadly consider them as plan B's if electricity generation is not successful. Amongst the potential opportunities are other applications of high-powered lasers in: biomedical engineering, quantum computing, semiconductor manufacturing, and proton and related medical therapies. For one company, spin-off technologies are an integral part of the business plan, with already around 50 commercial partners interested in their technology for various applications in non-destructive testing, remote sensing, cement engineering, detection of illicit cargo, etc.

3.2.7 Magneto-inertial fusion

Technological concept in general

Magneto-inertial fusion (MIF) represents a set of approaches that sit between MFE and IFE, these are based on achieving an intermediate plasma density, higher than MFE, lower than IFE, but also work with targets (like IFE), typically seeking to magnetically compress these (like MFE) towards fusion conditions. This approach can be paired with adapted versions of the Field Reversed Configurations (FRCs) and Spheromaks discussed earlier. Private initiatives in this approach are pursuing both FRC variations (Helion Energy) and magnetised target fusion (MTF) variations (General Fusion).

Details on the MIF-FRC approach are somewhat limited, as the main proponent, whilst highly ambitious is also quite secretive, therefore there are considerable uncertainties surrounding the concept. The choice of D-He3 as a fuel is also unusual, although it is claimed an industrial process has been created to manufacture this fuel, which does not naturally occur on Earth in any useful quantities.

For MIF-MTF approaches such as General Fusion the design intends to avoid HTS magnets or expensive and complicated lasers, by using specialised mechanical pistons. A liquid (lithium) metal cavity around the fuel is created and serves multiple purposes including acting as a first wall material, neutron blanket, tritium breeding, heat extraction and neutron shielding, in doing so this could eliminate/avoid many of the known problems with the blanket and first wall materials. However, the technology is unconventional with a number of uncertainties surrounding it.

Encompass the entire system

The MIF-FRC approach is targeting an ambitious timeline for a pilot plant, already by 2030, this will require full consideration of the fusion power system. Published information suggest that multiple aspects are considered already but many uncertainties remain.

The MIF-MTF approach also has an ambitious timeline. Most aspects of the system are considered, indeed this fusion concept is based around addressing a number of the most difficult systems considerations through the concept, although this introduces new system considerations unique to the concept.

Connection to the community

It is unclear to what extent the MIF-FRC based approaches are connected to the broader fusion community beyond being members of the FIA.

The MIF-MTF approaches appear well connected to the broader fusion community, with significant engagements with industry, supply chain and utilities, and also with national laboratories in the US and Canada.

Anticipation of challenges and difficulties (risk management practice)

It is unclear to what extent the MIF-FRC based approaches fully anticipate and address challenges, the approach is designed to avoid significant challenges of other approaches, but information on specific challenges to this approach is limited.

For the MIF-MTF approaches there is some appreciation of key challenges, including regulation and staffing, technical challenges are also considered although these are believed to be surmountable, albeit with few details on how.

Building on past experience and results

The MIF-FRC approach has demonstrated fast iteration cycles and also significant technical achievement, such as high temperatures. Other significant claims are made regarding efficiency, pulse frequency and plasma lifetimes. The approach has not been widely followed, so there is limited past experience outside the leading initiative.

The MIF-MTF approach is also quite unique, with limited past experience outside the leading initiative. The leading initiative has successfully demonstrated particular aspects of its approach separately, including the liquid metal cavity and plasma compression technology. The next steps will be important to bring together these technologies.

Funding success

The MIF-FRC approach has been one of the most successful of all approaches, it has raised the capital necessary for its next device (~$500 million), with promised increases to more than $2billion in total if technical milestones agreed with investors are met. It was also originally funded under the ARPA-E ALPHA programme.

The MIF-MTF approach has also been well funded (>$300m), with a funding round completed in 2022 providing the funding to move forward with the planned next device, to be built in the UK.

Commercialisation focus

The MIF-FRC approach claims to be on a pathway to produce fusion energy at very low cost ($0.01/kWh), this is significantly lower than other approaches and technologies, and scarcely believable. It would certainly cause an energy revolution if it could actually be achieved.

The MIF-MTF approach shows consideration of the target market and Levelized Cost of Energy (LCOE), looking towards a desired price of electricity production of around $50/MWh.

3.3 Timeframe analysis

In this section, we present our framework for the timeframe analysis, including how this links to the commonly used Technology Readiness Level (TRL) framework; the stated timeframes towards fusion energy of each of the main fusion initiatives globally; and an assessment per technology approach of the stated timeframes and the potential risk of slippage. The analysis presented here is based on public information per initiative and qualitative assessment by the team at the fusion approach level based on the analysis in 3.2, validation exercises with experts and the opinion of the team. It is important to note that the analysis of slippage risks in the later sections does not mean that these delays are **expected or will** occur, but that there are realistic risks that such a delay **could** occur.

3.3.1 Timeframe analysis framework

Current status

As a starting point for the analysis it is useful to take stock of the current status of progress for each of the main approaches to fusion, building on what has been presented in sections 3.1 and 3.2:

1. **Current status -** we would broadly evaluate the major fusion approaches as at the following TRL[25]:
    a. **MFE - Tokamak - TRL 3-4**, current tokamaks such as JET, EAST, KSTAR representing early prototypes to validate components, science and engineering, these are beginning to operate close to text conditions, e.g. sustained operation, high temperature for sustained periods.
    b. **MFE - Spherical tokamak - TRL 3,** current spherical tokamak at MAST-U is operating around TRL 3 and pushing further on some aspects, e.g., divertors, and will continue to make progress in the next decade. Some aspects of the work at CFS and Tokamak Energy for example on magnets may also be pushing TRL 4 or 5 – but are not rated at

[25] We use the technological readiness level framework, summarised as:
1. Initial idea: basic principles have been defined
2. Application formulated: concept and application of solution have been formulated
3. Concept needs validation: solution needs to be prototyped and applied
4. Early prototype: prototype proven in test conditions
5. Large prototype: components proven in conditions to be deployed
6. Full prototype at scale: prototype proven at scale in conditions to be deployed
7. Pre-commercial demonstration: solution working in expected conditions
8. First-of-a-kind commercial: commercial demonstration, full-scale deployment in final form
9. Commercial operation in relevant environment: solution is commercially available, needs evolutionary improvement to stay competitive
10. Integration at scale: solution is commercial but needs further integration efforts
11. Proof of stability: predictable growth

this level as they remain untested in the right conditions, however the overall system for all these devices, particularly the two private examples, is at best TRL 3.

c. **MFE – Stellarator – TRL 2-3,** current stellarator at W7-X maybe close to TRL 4, but private initiatives on stellarators are at TRL 2-3.
d. **MFE – Z-Pinch – TRL 2-3,** the current pinch device at Zap Energy may be pushing towards TRL 4 in some aspects, but overall a rating of TRL 2-3, encompassing others in this field, is fair.
e. **MFE – Compact Toroids (FRC, Spheromak) - TRL 2-3,** little public work, the experiments by TAE Technologies and CT fusion are validating parts their overall concepts, the former are closer to TRL 3, whilst the latter closer to TRL 2.
f. **IFE – TRL 2-3**, work at the NIF in the US on inertial confinement is validating aspects of the inertial fusion concept (around TRL 3), and these are applicable also for IFE. However, private initiatives in IFE are mostly operating at TRL 2 and only just beginning to validate their theories and concepts through experiments.
g. **MIF – Field Reversed Configuration (FRC) – TRL 2-3,** whilst there is little public research on FRCs the progress made by Helion Energy, on existing devices has validated significant parts of this fusion power concept.
h. **MIF – Magnetised Target Fusion – TRL 2-3,** this also receives little attention from public programmes, the main proponent of this approach, General Fusion, has made progress in validating significant parts of their fusion power concept.

Framework for future timeline analysis

The analysis in the following sections and the scenarios is largely based around analysis of 3 main steps expected in the further development of fusion energy, we define these as:

1. **Next device** – typically representing progress of around TRL 4 or 5. ITER represents the next device in the tokamak line (this would be around TRL 5), whilst the most advanced of the private initiatives are currently working on next devices that would also land in the TRL 4-5 range. The primary goal of many of these next devices is to demonstrate net energy gain/power multiplication ($Q>1$), burning plasmas, and/or scaling that confirms the potential of the approach. However, it should be noted that as very few of the planned next devices address the full system needs for fusion power, and that some elements for a full fusion power plant will either not be ready for long-term operation (e.g., first wall materials not at the required level of neutron resilience) or be missing (e.g., blankets), these components will remain at lower TRL levels, e.g., Tritium breeding blankets could be noted at TRL 1-2 currently and likely to remain at this stage as these are not developed in most of the next devices.
2. **Pilot plant** – typically representing progress of around TRL 5-7. DEMO would register in this category at TRL 7. Some of the private initiatives also elaborate pilot plant concepts to reach this level e.g., CFS with ARC, TAE Technologies with DA-VINCI; they also estimate timelines for these. Pilot plants will typically have the goal to demonstrate electricity production. They would normally have brought all major, necessary systems into their design so that the TRL level would apply to the whole system. Pilot plants may only be intended for relatively short-term operation and/or low availability, but should be expected to demonstrate not only electricity generation, but also how (if used) the Tritium cycle is dealt with, resilience of materials, RAMI and consideration of life-cycle issues. However, in some cases these elements or other sub-systems may still lag behind the rest of the plant and potentially pilot plant

upgrades, more than one pilot plant, or side projects would be needed to raise TRL across the full power plant system.

3. **Commercial plant** – representing TRL 8/9 and above. This timeline milestone is intended to represent when the first handful of commercial fusion plants that come onto the grid. A commercial plant built based on the learnings from the DEMO would be one example. As would the commercial roll-out of any of the private fusion initiatives. These plants should provide, with public support as appropriate, the ability to reliably deliver power to the market at a reasonable cost compared to the utility provided.

3.3.2 Publicly stated timelines per initiative

The following table illustrates the timelines officially communicated by the different fusion activities analysed in this study and when they intend to reach the three steps defined above. These show that a handful of private initiatives already hope to complete their next devices before 2025, and that the most ambitious already target pilot plants by 2030, and in any case most target this in the 2030-2035 period. No specific timelines for commercial plants are announced, but these could be expected 5-10 years after the pilot plants, assuming these are successful.

Note: These timelines are the stated timelines by the initiatives themselves, they effectively represent a best case for development. In reality there is likely to be some slippage, the risk and length of which is likely to increase with each step and the further into the future the expectation is. This risk is discussed further per main step in the following sections.

Further analysis at initiative level is provided in Annex B.

Table 3-2 Timeline expectations of all initiatives for next experimental device = (existing device =), the first pilot fusion plant = . Blue initiative names are private initiatives. All year indications are approximate and represent the BEST-CASE Scenario

Approach	Initiative	2020-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
MCF - Tokamak	ITER / DEMO		First plasma 2026		DT operation 2036		2050
	ARC / SPARC (CFS)		2025	2031-2032			
MCF - Spherical Tokamak	MAST-U / STEP (UK)	2020				2040	
	NSTX-U (US)	2024					
	EXL50 - ENN		2030		2037		
	Tokamak Energy		2026	2033			
MCF - Stellarator	WX-7 (EU-DE)	2015					
	Renaissance Fusion		2027	2032			
	Type One Energy		2028	2034			
MCF - Z-pinch	Zap Energy	2024	2030				
MCF - Compact Toroids (FRC, Spheromak)	CT Fusion		2026	2034			
	TAE Technologies	2025		2032			
IFE	(ICF) NIF (US)	2009					
	First Light Fusion	2024					
	Focused Energy		2028- 2030	2035			
	HB11		2027		2030's		
	Marvel Fusion		2027				
MIF - FRC	Helion Energy	2024	2030				
MIF - MTF	General Fusion		2026	2032			

Note: Estimates are based on publicly available information, and in some cases our assumption, e.g., if estimates are 'early 2030's' then a year is assumed. Actual timelines could be faster or slower.

3.3.3 Timeline analysis: Next devices

Table 3-3 presents at the approach level an assessment of the potential risk of slippage for the building and operation of the next devices, separating the public and private routes. Globally, public activities have a more risk-averse approach, with efforts focused on ITER and ensuring strict control over the various components of the device. The scientific goals of ITER also encompass more of a whole fusion system. The private activities have more aggressive timescales, and are more willing to risk devices to iterate faster. The "x" in the table represents the targeted date of next devices within the aggregate of initiatives active in each approach, effectively the best-case scenario for this approach (if all potential challenges are overcome). Red shading represents our assessment of a high risk of slippage from this timeframe, an orange box represents a medium risk of slippage, a green box signifies the risk of slippage is low at this moment. The slippage assessment represents our opinion based on the assessments presented in section 3.2 and 3.3.1. A white box after shading represents the risk that if the next device is not built in this timeframe it will not be built at all, representing the fact that a technology approach will have to deliver by a certain time horizon to continue getting support. Approaches beginning with medium risk have initiatives which have demonstrated funding and have taken steps towards design and construction of devices.

Timelines for next devices for **public fusion efforts** are mostly long term, i.e., whilst first plasma at ITER is likely around 2026-2028, the most important ITER DT experiments, those that will demonstrate net energy, are not planned until 2036 at the earliest, and possibly later once the new baseline is announced. The other new public effort of note in this timeframe is the JT60-SA which while likely to produce useful science is unlikely to achieve major fusion milestones such as net energy gain. Continuing work on NIF, MAST-U, W7-X, EAST, K-STAR, NSTX-U will underpin scientific progress, but will be unlikely to move the TRL forward in the same way that ITER could.

In contrast there is considerable ambition from **the private sector**, with announced timelines for multiple next devices in the next 5 years, which intend to demonstrate major progress and potential net energy gain/high power multiplication. The ability to demonstrate energy gain in some cases is contingent on whether tritium is used or not (as a DT fuel mix), many of the next devices will not use tritium and will use only a DD fuel mix. This choice is made to simplify the approach at this stage, and these initiatives may use simulations/extrapolations to estimate the likely power multiplication if a DT fuel mix were used in the same conditions. As shown previously in Table 3-2 at least 11 of the leading private initiatives aim to complete next devices before 2028. With funding already secured for many of these devices, and with design, and sometimes also construction, well underway, then it is likely that at least a few will meet or keep close to this ‘Best case’ schedule. At the same time it is likely that a few of the initiatives, will take longer to build their next devices, with multi-year delays more than possible.

Looking at the timescales, in our estimation those with the lowest slippage risk have a good chance to all complete their next devices around 2024-2026, and if this timeframe slips then still the next devices are very likely before the end of 2028. Even allowing for some failures, or unexpected setbacks, the experimental campaigns on these devices are likely to set a number of new landmarks for fusion energy, notably net energy gain, but possibly also others on temperature, confinement times, pulse length or power output. Net energy will be a landmark moment for fusion energy, and could prove a major catalyst for the sector as a whole.

It is notable that there are a range of different approaches to fusion that are in this ‘early’ group. This highlights that there are a variety of potential ways forward within fusion, which can provide for healthy competition, and also opportunities for cooperation and learning from each other, in the race towards fusion power. However, it is notable that Stellarator and IFE lines are assessed to be lagging the other approaches, with higher risks of slippage, this is primarily due to the relative newness of initiatives founded in these approaches, their lower levels of funding than other approaches, and less established track record in constructing and operating devices.

Overall, a note of caution is also necessary, as these next devices will still remain far from proving a fusion power plant, with many key aspects of a power plant not addressed and remaining at low TRL levels at this time. These other aspects will come into focus for the next step: building and operating pilot plants.

Table 3-3 Timeline of public / private initiatives for next device completion. Colour coding represents Trinomics assessment of slippage risk: x = targeted date of next device; red = high risk of slippage from this year; orange = medium risk of slippage from this year; green = low risk of slippage in this period

Approach	Initiative	2023-2024	2025-2026	2027-2028	2029-2030	2031-2032	2033-2034	2035-2036	2037-2038	2039-2040
MFE - Tokamak	Public (ITER)							X		
	Private		X							
MFE – Spherical Tokamak	Public[1]									
	Private		X							
MFE - Stellarator	Public[2]									
	Private		X							
MFE – Z-pinch	Private		X							
MFE – Compact Toroids (FRC, Spheromak)	Private		X							
IFE	Public[3]									
	Private	X								
MIF - FRC	Private	X								
MIF - MTF	Private		X							

[1] No new public spherical tokamak devices planned, however MAST-U and NSTX-U will both continue to operate for much of this period and sit in the TRL 3 range. Upgrades to these devices could also be envisaged in this period.

[2] No new public stellarator device planned, however the W7-X device in Germany will continue to operate throughout this period, in the TRL 3 range. Upgrades (e.g., to wall materials) could be foreseen in this period.

[3] No new public inertial fusion devices are planned in this period, however it is understood that the NIF will continue to operate in the US during the 2020's and some other laser facilities (e.g., ELI-ERIC with facilities in Czechia, Romania and Hungary[26]) which are not dedicated to fusion but potentially available for experiments could also be valuable supporting public infrastructure for firms active in IFE.

3.3.4 Timeline analysis: Pilot plants

Following the next devices, those that are successful will aim towards the pilot plant that full demonstrates the generation of electricity from fusion energy.

Timelines for next devices for **public fusion efforts** are very long term (see Table 3-3), in Europe these are based on DEMO, whose design would be finalised following the ITER DT experiments, assuming these deliver the expected success and results. With the timeline for this DT campaign at best beginning in 2036 and risks of delays evident, then it could realistically be 2040 before the DEMO design is complete. Allowing 10 years for construction, which as shown by ITER and other major projects is at high risk of slippage, then an EU DEMO plant being operational by 2050-2055 seems realistic. A similar timeline can be foreseen for DEMO equivalents in Japan and Korea. Two other public programmes with planned pilot

[26] https://eli-laser.eu/

plants hope for an accelerated timeline, the first, China with their plan for their DEMO equivalent called CFETR already in the 2040s. China is one of the few nations that could bring the required resources to bear to accelerate their programme, albeit with possible greater risks to quality and not fully digesting ITER results. Secondly, the UK also plans a pilot plant, STEP, this uses the Spherical Tokamak approach, and will be the main successor to the currently operating MAST-U device. This is targeted for 2040 and significant funds are committed to design and supply chain activities which are already taking place. It is unclear if there are dependencies between STEP and ITER, the ambitious timeline suggests any dependencies are small, however STEP slippage into the 2040's would not be unexpected. For IFE, there are no concrete plans or signals regarding the delivery and operation of a next device, nor pilot plant from the public side, at this moment in time, NIF is the end point for public IFE research, although laser facilities globally, though not fusion specific, can provide an infrastructure to support further public and private fusion research.

Mirroring the ambition to construct next devices there are also ambitious timelines for **pilot plants in the private sector**. As shown in Table 3-1, continuing the focus on the 15 leading private initiatives, these initiatives are all targeting the completion of a pilot plant between 2030 and the mid-2030's. this shows the very ambitious timescale between the operation of the experimental devices (already with some risk of time slippage) and the operation of a power plant.

Looking this far ahead there are more uncertainties that can affect timing than for the construction of next devices, for pilot plants these uncertainties include:

- **The dependency on the success of the 'next experimental device'** – taking this next step requires successful completion and operation of the next experimental device. It is the view of many in the sector that not all devices/approaches will perform as hoped, and a few of the initiatives may not make it to the pilot stage, or face much more significant delays e.g., requiring another iteration next device pushing further the delivery of a pilot plant.
- **Funding** – none of the initiatives have yet needed to confirm funding for pilot plants, but it is highly likely in every case that the funding required for a pilot plant will be significantly higher than for the next device. This could prove more challenging to raise. However, success at the 'next device' stage is very likely to convince existing investors to continue, and attract other investors to the sector. The bigger funding challenges could arise in the event of an incident or major delays – it could be foreseen that in the case of repeated problems that investors withdraw from one or more initiatives.
- **Technology challenges** – a pilot plant involves a more complete appreciation and coverage of the full fusion power system, significantly beyond what has been demonstrated at the next device stage. There are significant uncertainties on the extent to which technologies and knowledge essential to a pilot plant will have evolved in the coming years to make a pilot plant feasible. Although it is notable that a range of firms are increasingly targeting providing services and technologies to address specific challenges, firms such as Kyoto Fusioneering, Oxford Sigma, Woodruff Scientific and others[27].
- **Developing the supply chain** – a power plant requires much more than fusion science, it is about bringing an entire system into operation, integrating engineering, construction, mechanical and energy practices together, to construct and operate the plant. Building the appropriate relationship, ensuring all blocks of the system can work together can take several

[27] See the FIA affiliate members listing for a more complete list of firms involved in this way https://www.fusionindustryassociation.org/members

years. Without anticipation of considering the integrated system, this could seriously impact the delivery, and increase the delay.

- **Other issues** – many of these are addressed in more detail in the following section of the report, but include risks related to regulation, public acceptance and staffing. These could all potentially increase the risk of slippage for some/all initiatives.
- **Positive uncertainties** – these are more difficult to account, and are less integrated in the table, but could encompass supporting developments both inside and outside fusion, for example for Stellarator based approaches further successes at W7-X could help to accelerate progress, or other public funded initiatives such as the new public-private programme in the US could produce results that help reduce slippage risks for some/all approaches. Outside of fusion, developments in AI, machine learning, precision manufacturing, materials could all help to accelerate progress in fusion, these may only be incremental improvements, but also more radical leaps could be made that reduce slippage risks or even allow for accelerated timetables (these are discussed further in section 3.4.8).

Whilst the focus of these uncertainties is on the private initiatives they can also apply to a lesser or greater extent to the public pilot plants.

Looking at the timescales, despite all having high slippage risk (i.e., at least around 5 years) in our estimation, there remains a chance that at least for some approaches an initiative is able to keep to their own planned timeline. Indeed, the firms making the most ambitious plans have access to a deeper understanding of their devices and information that is not public that informs their optimism on timing, or they already conducted experiments and run fusion machines. However, many within the sector (particularly, but not only, on the public side) believe there is quite a lot of hype around timelines, necessary to attract investors, but unrealistic in practice. Taking this onboard, in our opinion whilst a few initiatives may build pilots before 2035 – indeed, this is a possibility that should not be ruled out - it is more likely that there will be some slippage, with a greater likelihood for pilot plants for most approaches to arrive after 2035, and closer to 2040 than 2030.

Overall, the analysis of timelines, as illustrated in Table 3-3, shows a very strong divergence between public and private pilot plant ambitions. Indeed, there is the possibility that a private initiative will build a functioning pilot power plant before ITER even begins its DT operation, but likelihood is still limited. Successful private fusion pilot plant(s) would mark a massive milestone for the sector, paving the way for commercialisation of a first generation of fusion power plants. A note of caution is necessary, as there could remain a few technical challenges not fully resolved by the pilot plants, and beyond this, a first generation will require a huge scale-up of staff and skills, and in industrial capacity, and the pilot plants will also need to give confidence that a commercial plant will be able to scale to meet market needs on CAPEX, operating costs and availability.

Table 3-4 Timeline of public / private initiatives for pilot plant. Colour coding represents Trinomics assessment of slippage risk: x = targeted date of pilot plant; red = high risk of slippage from this year; orange = medium risk of slippage from this year; green = low risk of slippage in this period

Approach	Initiative	2030-2031	2032-2033	2034-2035	2036-2037	2038-2039	2040-2041	2042-2043	2044-2045	2046-2047	2048-2049	2050-
MFE - Tokamak	Public[1] (DEMO)											
	Private		x									
MFE – Spherical Tokamak	Public (STEP)						x					
	Private			x								
MFE - Stellarator	Public[2]											
	Private		x									
MFE – Z-pinch	Private	x										
MCF -Compact Toroids (FRC, Spheromak)	Private			x								
IFE	Public[2]											
	Private			x								
MIF - FRC	Private	x										
MIF - MTF	Private			x								

[1] No specific target date for (EU) DEMO has been set, however the highlighted period is potentially possible for any of the DEMO plants (EU/JP/KO), especially the Chinese (CFETR) plant

[2] No public pilot plant is planned at this point for this approach, this could change in the coming years

3.3.5 Timeline analysis: Commercial plants

All private players are clear that commercialisation of fusion energy is their goal, but at this stage only broad estimates of when this can be achieved are given. The main range of estimates span the late 2030's into the 2040s, the wide range of time covering the large amount of uncertainty in looking so far ahead, but also a development cycle that a commercial plant could or should follow a successful pilot plant within 5-10 years. Others, especially those working in the public fusion initiatives, are much more cautious, and wait until they can confirm all aspects of the technology before speculating as to when commercial electricity production may arrive. The nature of the public timelines, i.e., DEMO only by 2045-2050 makes commercialisation unrealistic before the mid 2050's at the earliest. The rationale behind this is understandable, as the challenges and technical difficulties increase at each milestone, and it becomes very difficult to think today on how these very difficult issues may be solved. It also remains unclear or even impossible to determine what could be the LCOE of fusion energy, given the huge and various uncertainties. Greater certainty on the timeline for commercial plants may emerge when the first set of next devices operate successfully.

One question that does relate to timelines is at which point in the fusion development cycle the leadership for commercialisation should pass to the private sector. The EUROfusion roadmap suggests this will happen after a public DEMO plant, i.e., the public programmes lead the technology development to the verge of commercialisation, at which point the private sector could be expected to take over to build a first wave of commercial plants. Others envisage this moment occurring after successful DT experiments at ITER, in response to the fact that a public DEMO would take too long and funding could be politically difficult. Whilst some already believe that the public sector, due to being so slow and cumbersome, has already mostly lost its leadership and will be 'leapfrogged' in the coming years – and would better play a role in researching on specific key challenges that need to be addressed across multiple fusion approaches, e.g., materials. The implications of these views will be explored in the scenarios in chapter 4.

3.3.6 Conclusions on timeframe estimates

The main conclusions can be summarised as follow:

- **There is strong divergence between public and private ambitions**, with generally the public being more cautious, and giving the impression they have a higher control and consideration of all of the technical challenges. Practical experience remains an important KPI to have in mind and public programmes have the advantage of operating multiple devices over many decades. However, **the public fusion programme is moving very slowly**, and further delays seem likely as part of the ITER re-baselining exercise.
- This provides an opportunity for the quicker ambitions of the private sector – and **it seems likely that in the 2024-2028 timeframe a handful of private firms will successfully complete and operate their next devices**. This could be a major catalytic moment for the sector if the expected milestones for net energy gain are achieved. It would also provide first evidence of some 'leapfrogging effect' this would be particularly evident if the private initiatives achieve this ahead of ITER first plasma.
- It remains hard to extract the main trend **regarding the risk of slippage**. Undoubtedly some private initiatives will miss their timelines, and a few could fail outright. As some have put it **'not all shots at goal will score'**, but the number, variety and backing suggests at least a few will score, for example confidence in the sector is high that the CFS SPARC device will be successful in its goals at the next device stage.
- **Uncertainty and slippage risk increase significantly at the pilot plant stage as this requires tougher technical challenges to be addressed** and a further, larger amount of funding to be secured, although the latter may follow naturally from success. The timeframe between next devices and pilot plants for the private initiatives is also tight and in our opinion increases the risk of time slippage from the stated goals.
- **Nevertheless, it remains possible, probable even, that one or more private initiative could build and operate a pilot plant already in the 2030's.** This would significantly leapfrog ITER and have important implications. At the same time, it is probable that a private pilot plant would still have important technical challenges to resolve. The step to a commercial plant may not be straightforward.
- **By when, how and by whom the main technical challenges will be addressed is not very clear.** There are currently several technical challenges remaining on the agenda of research (materials, tritium technologies, RAMI, …). As most of the technology approaches rely on these technical components, fast and successful achievements are crucial. However, the next devices are unlikely to solve these remaining challenges, and it is also unclear if private pilot plants intend to address all of these issues.
- **The dependency between the private and public sector could be considerable,** particularly the lessons from ITER DT operation, but also other public research, despite the self-confidence of the private sector. This dependency is not reflected in private initiative timelines, but slippage of ITER could be quite impactful.

- **The moment at which public fusion initiatives hand over the main leadership to private initiatives could be important,** especially for DEMO and the focus of future public fusion research.

3.4 Main findings

This section describes some of the main findings from the work, emerging from the work to fill the previous sections and also dedicated research into specific topics to address issues raised in the request for service, and more. The following section addresses:

- How **public-private interactions** are important, on articulating their complementarity regarding research, business development, funding opportunities but also regarding governance and decision making;
- **Success** - there is a common strong belief in the fusion sector that at least one activity, public or private, will succeed, emphasising the need for an interconnected ecosystem;
- **Funding** could be a barrier, as the required finance increases, however there are reasons to believe that sufficient private finance will be available for the most serious initiatives. The picture for public finance is more uncertain, the success of ITER is crucial to its future.
- **Regulation** is a key issue, with the sector emphasising the need to have a regulatory regime separate from nuclear fission, one that is proportional to the (lower) risks of fusion energy, the UK is adopting such a regime;
- **Public acceptance** will be important to the eventual adoption of fusion energy, so far it is relatively unknown in the public perception, mostly linked to long timescales or nuclear fission;
- **Staffing** is also emerging as an important issue, with high competition for qualified staff among the emerging private sector, the supply of trained staff could be a hindrance to growth;
- **Estimation of the expected cost of fusion, and especially LCOE**, remains vague or even impossible. Firms understand the need to focus on cost, and the likely target range of LCOE but estimates of outcomes are too uncertain;
- **Spin off activities and** securing business plans with non-Fusion products and/or services may help overcome possible funding gap, there are opportunities, especially in the medical sector and with magnet technologies. **Advances in other fields** such as AI/computation, precision manufacturing, 3D printing are helping the sector move faster, the expectation is that the benefits will be incremental in most cases.

3.4.1 Public-private interactions and partnerships

Findings on public-private interaction

Both public and private initiatives have identified some key differences, complementarities and challenges linked to their interactions and the possibility of developing partnerships:

- **Public programmes are often sceptical of private initiatives ambition and claims** – Public programmes often view private firms claims as a 'sales-pitch' to investors, and that the full complexity and problems of fusion are not fully comprehended, or if they are then they are neglected in favour of an overly positive storyline. This leads to a high level of scepticism.
- **Public programmes believe that private companies do not sufficiently rely on lessons learned** – Interviews have indicated that public organisations and laboratories are somewhat defensive, and take an implicit criticism that private firms are developing concepts that public research tried before and dropped for various reasons.

- **Different (but complementary) approaches between public and private initiatives** – Private initiatives are seen to bring originality and agility to fusion energy, and are more often success-oriented which may allow them to achieve their (often clearer, narrower) milestones in a timely manner. Public initiatives, on the other hand, aim to address fundamental scientific questions, these questions require more time and funding. One thing to note is that private and public initiatives also distinguish each other on the technical aspects. For example, in magnetic confinement fusion, most public organisations and laboratories are aligned with ITER in terms of design and timeline (with some variants), while private fusion companies propose stronger changes in configurations, mechanisms, fuels, etc.
- **Public initiatives seem to encompass much more the entire system –** While the public sector really aims to develop the entire fusion system by also including fusion enabling technologies in their R&D activities (e.g., blanket breeding, Tritium technologies…). This slows development. Most private companies seem to postpone in-depth consideration of the most serious long-term issues until later. At this stage of their development many private companies focus on one particular part of the fusion system and rely on the success of public research for the rest.
- **Private firms have more freedom for risk-taking and iteration** – Private initiatives can be less limited by budgetary and administrative constraints, and can be more willing to take additional risks in some areas (e.g., learning by doing, learning by breaking, multiple fast iterations, etc.). However, they also need to be careful in their iteration cycles as funding is not infinite. The bureaucracy of the public sector can impede / slow on project developments, but it is also the case that they cannot afford for a device to 'go wrong' as further funding would be jeopardised.
- **Private firms are (necessarily?) more secretive in sharing key knowledge/technologies** – The publicly funded fusion sector is usually more transparent about their activities. Private companies build upon public research, leaning heavily on this at first. Later as they develop their own knowledge they face a trade-off between being protecting their technologies and competitive edge, and engaging in enough collaborations in order not to miss relevant information and partnerships. This approach to sharing, which can lead to not reciprocating to the same degree as public initiatives, increases public initiative scepticism of the private initiatives and can create a trust barrier to sharing useful information and data.
- **Private firms acknowledge dependency on public initiatives for some key technologies** – Public initiatives find the narrow focus of private companies on particular aspects of fusion, i.e., developing high-temperature superconducting magnets, as delivering important technologies but also neglecting system aspects crucial for fusion power. Public programmes often noted that fusion-enabling technologies (such as Tritium breeding, understanding plasma science, wall design) were blind spots of private initiatives, whilst some in private firms noted that they will still rely heavily on using the results of publicly-funded research on these issues.
- **'Rising tide lifts all boats'** – Almost all of the fusion initiatives want at least one fusion activity to succeed (their own and/or that of others). Even if the timeline of public initiatives are often much longer than those of the private sector, their relevance is not diminished by the success of others. Whilst there is healthy scepticism of the claims of private initiatives delivering fusion power quickly, there is also a desire that they succeed. This is mainly linked to the fact that strong (financial and human) efforts will be necessary to supply fusion energy to the entire population (e.g., to construct thousands of power plants a year). Public and private partnership may accelerate the path to commercialisation of fusion.

- **Issues on licensing/sharing of IP from public programmes** – One issue highlighted by public stakeholders was how IP and science developed by public programmes should be dealt with. Whether this should be published, for the advantage of all, or whether the funding organisations should license or otherwise receive recompense for their work, for example the Super-X divertor tested in the UK at MAST-U can be a case, whether others would like to replicate the design and where licencing could be considered. The lack of reciprocity in sharing technical developments by the private sector was also noted.

Public-private partnerships

It is important to recognise that there are an increasing number of partnerships and close collaborations between public activities (i.e., mainly ITER) and the private sector, particularly in the supply chain for key components. These actors have identified important complementarities and synergies regarding skill management, but also power plant design, construction and engineering activities. These activities can be further nurtured through policy, and not only in the supply chain, but also to help grow the number of private fusion initiatives in Europe.

In the US, several examples exist of public-private partnerships which are enabled by government programs such as ARPA-E or INFUSE (further described below). These programs can serve as best practices to encourage such partnerships, and further private fusion development, in the EU.

ARPA-E

The Advanced Research Projects Agency-Energy (abbreviated as ARPA-E) is a public agency that was created by President Obama in 2009, as an agency dedicated to supporting innovative US energy projects. ARPA-E aims at advancing high-potential, high-impact energy technologies that are too early for private-sector investment.

There are currently three fusion programs funded by ARPA-E:

- **ALPHA** - The first fusion program of ARPA-E, Accelerating Low-Cost Plasma Heating and Assembly (ALPHA), was released in 2015. It aimed at creating and demonstrating tools to aid in the development of new, lower-cost pathways to fusion power and to enable more rapid progress in fusion R&D. The ALPHA programs intended to focus on finding new options of intermediate ion densities in between the magnetic confinement (very low densities) and inertial confinement (very high densities). The team had the objective to develop and build prototype tools that could demonstrate new methods of reaching fusion conditions and that provided the scientific and technological basis for future reactor designs. Nine projects were funded under the ALPHA program.
- **BETHE** - The Breakthroughs Enabling Thermonuclear-fusion Energy (BETHE) program was released in 2020 and is currently funding 18 projects. It supports the development of timely and commercially viable fusion energy via three research categories:
    - Concept development to advance the performance of inherently lower cost but less mature fusion concepts;
    - Component technology development that could significantly reduce the capital cost of higher cost and more mature fusion concepts;
    - Capability teams to improve/adapt and apply existing capabilities (e.g., theory/modelling, machine learning, or engineering design/fabrication).

As opposed to ALPHA which focused in developing lower costs fusion concepts and related technologies, BETHE intends to decrease capital costs in order to realize grid-ready fusion demonstration.

- **GAMOW** - The Galvanizing Advances in Market-aligned fusion for an Overabundance of Watts (GAMOW) program was released in 2020 . It is currently active and supports 14 projects. The program is overseen by ARPA-E (with a contribution of $15 million funding over three years) and the Office of Science – Fusion Energy Sciences (SC-FES) (with a contribution of $5 million funding over three years). The program focuses on three R&D areas:
    - Technologies and subsystems between the fusion plasma and balance of plant;
    - Cost-effective, high-efficiency and high-duty-cycle driver technologies;
    - Cross-cutting areas such as novel fusion materials and advanced and additive manufacturing for fusion-relevant materials and components.

Many of the leading private fusion initiatives started out with seed funding provided by ARPA-E which enabled sufficient progress to be made to then attract private capital to invest. ARPA-E was cited as a highly important and valuable programme by private fusion initiatives.

INFUSE

The Innovation Network for Fusion Energy (INFUSE) program is a public US-funded program that aims to accelerate fusion energy developments in the private sector by reducing impediments to collaboration involving the expertise and resources available at the US Department of Energy (DOE) laboratories and universities. In other words, the private sector defines and identifies the problem, and public laboratories try to find possible solutions. Several topics are addressed through this program including: fusion-enabling technologies, materials science, diagnostic development, modelling and simulation and unique fusion experimental capabilities.

This program is only accessible to private companies from the US. Private candidates must sign a Cooperative Research and Development Agreements (CRADA) which is a formal written contract between one (or multiple) public laboratories and one (or multiple) private party under which:

- Laboratories provide personnel, services, facilities, equipment, intellectual property, or any other (non-financial) resources.
- Private parties may provide funds and all above mentioned (non-financial) resources.

There are currently around 30 INFUSE programs running in the US, which allows to foster public-private partnerships. Typical projects are usually relatively small, around $250k. Private companies must contribute at least 20% of the project's budget. The INFUSE programme was cited as an important and valuable cooperative activity by many of the leading private fusion initiatives.

NASA COTS

Another successful public-private partnership in the US is the Commercial Orbit Transport Services (COTS). This program that was implemented by NASA in 2005 following the establishment of the US Space Exploration Policy[28]. The objective of the program was to challenge the US private industry to develop a cargo and eventually a crew space transportation capabilities that could meet the needs of

[28] https://www.nasa.gov/commercial-orbital-transportation-services-cots

the International Space Station. More than $500 million was allocated over five years to the programme.

The COTS programme had identified several broad cargo and crew transportation capabilities and bidders could then choose which one to offer. This allowed to stimulate innovation and coverage of different capabilities. In addition, the NASA required that the selected private partners would share in the cost of the COTS system development and demonstration. The reason behind this was to give them the incentive to design, build and demonstrate their systems in a timely manner. A lively space sector has developed in the US over the last decade, supported by COTS, with companies such as Space-X, Blue Origin, ULA and others competing for public funding for launches.

ARDP

The US Department of Energy established the Advanced Reactor Demonstration Program (ARDP) in order to speed the demonstration of advanced nuclear reactors through cost-shared partnerships with the private industry. There are three different development and demonstration pathways through which candidates may receive funding:

- Advanced reactor demonstrations
- Risks reduction for future demonstrations
- Advanced reactor concepts 2020

The initial funding of ARDP is $160 million and the DOE is currently supporting 10 advanced reactor designs. The resulting technologies will be tested and assessed via the National Reactor Innovation Center, a national laboratory, in order to move these reactors from blueprint to reality.

3.4.2 At least one activity will succeed

Every organization, company and project working on fusion energy is convinced that their technology approach is the most appropriate to solve the remaining challenges in fusion energy. This is the basic business approach which underlines why and how decisions are taken to develop a specific technology and choose a given approach.

As noted in section 3.3 many private initiatives plan to pass important milestones in the next 5 years and target pilot plants in the 2030s this would be a formidable success if it could be achieved. However, we also know that given the complexities associated with fusion energy many of these organizations, companies and projects will not fully succeed – and that there can be significant interdependencies in the sector. Despite this there is a strong belief in the fusion community, that “at least one activity or technology approach” will be successful. This belief, coupled with the fact that for the time-being, it is still unclear which approach will be successful (of course, there are approaches with more credibility and track record than others, e.g., tokamak) should result in an approach to promote/support all technologies and ideas to the extent possible. This is also why; it is very important that the fusion community can build on the lessons learned by others to minimize the waste of resources associated with answering questions previously addressed. This emphasizes again the need to ensure that the collaboration between companies, research institutes, universities, investors remain as intense as possible. There is a need to exchange practices, findings, but also failures, to learn from the others, and possibly also see the success occurring in the others’ portfolio. This is likely to be crucial also due to the dependencies between initiatives, both public and private.

A few companies active in the fusion sector do not dedicate their activity to one specific technology approach, as they either provide products and services that may serve many stakeholders and technology approaches (e.g., Kyoto Fusioneering), or, like investors would do, select the technology approach(es) which they consider the most relevant for the time being and spend efforts and money to support its (their) development (e.g., ENN). These players contribute to support the entire community and research by focusing on specific technological hurdles that need to be overcome.

3.4.3 Long-term funding is crucial

As fusion initiatives move from building experimental devices to pilot plants and then to the construction of a complete fusion plant, funding needs will reach new orders of magnitude (i.e., going from tens/hundreds of millions to billions).

In the last few years very large and growing amounts of funding have been attracted to private fusion initiatives, headlines from Commonwealth Fusion Systems (attracting USD 1.8 billion) and Helion Energy (USD 500 million, potentially increasing to USD 2.2 billion) have been eye catching, and others in the field have also been raising large amounts. Private spending on fusion now, for the first time, begins to overtake public spending. For now at least the sector is hot, and there are compelling demand and supply reasons to believe funding can continue to flow, at least from private funds. On the supply side this is buoyant, as large amounts of capital have entered markets due to quantitative easing, and low interest rates have led some investors of all kinds (institutional, sovereign wealth funds, philanthropy, venture capital) to look to riskier investments for returns. This may change somewhat as interest rates have increased in 2022. Some structural reasons, such as inequalities in the US and other countries also contribute, leading to many high net worth individuals who are able, and willing, to fund their pet interests without worrying too much about short term (or any) returns. On the demand side, the continuing (and growing) need for low carbon energy creates a massive potential opportunity, with the energy market worth trillions each year. According the 2021 IEA Roadmap for Net Zero by 2050 in the Global Energy Sector[29], the total annual required investment to reach 2030 climate goals in the energy sector amounts to USD 5 trillion until 2030 and another 4.5 trillion until 2050. Fusion is an attractive solution in this context, as a technology that does not have the intermittency issues of renewables, nor the waste, proliferation risks and poor public perception of nuclear fission. It is the only physical process that can produce energy of which it is known that is exists and work (i.e., the sun), but has not yet been put to work on earth.

In the short-medium term sufficient private finance should be available for the most serious private fusion concepts to secure funding for experimental plants. The potential crunch will come in the following stage, when first pilot plants significantly raise the amounts that are needed, from hundreds of millions possibly to multiple billions. A question mark remains if investors will follow. However, if experimental devices are successful, paving the way for the next step, then it is hard to believe that investors would not be willing to follow with larger amounts. Indeed success of some of the next wave of experimental devices in achieving new milestones in fusion, making it much more tangible in the eyes of investors is likely to attract major funding to those that are successful and likely across the sector as a whole. A bigger question mark could arise if the claims of the private firms prove hollow, continually missing promised timelines, then funding could dry up as investors need to see the possibility of returns. Furthermore, how might investors and markets react if there is a major setback

[29] https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

for the sector, i.e., a catastrophic failure of a device, or a major fraud incident. This could also put a major brake on finance. Mitigating against this risk is the diversity in approaches, e.g., a failure in fusion initiative Y in approach X is fine, as there are multiple other approaches, and each initiative within an approach also has its own specificities. Therefore whilst the affected approach would likely be sharply affected, other approaches should face fewer issues. Furthermore, the size of the potential market prize of multiple trillions, and the serious steps that are being taken, lead us to believe that whilst in the case of a serious setback finance may be reduced or impose stricter conditions on funding, it will still be available in large volumes to drive the most serious and promising initiatives in the sector forward.

Public funding on the other hand is more complex. Overall, public spending has been unusually high in recent years due to COVID related spending, and now continued high spending on defence and military aid relating to Ukraine, and also short term support to alleviate rising energy costs. It is difficult to believe that this will not later require tighter budgets to pay back the public debt incurred. All public spending then comes under pressure. Funding for ITER is expected to be secure, but other publicly funded fusion research and spending on devices may come under pressure and need to be scaled back. In the EU a key barometer on the appetite for further fusion spending will be on the approval process for IFMIF-DONES which will be needed in the next few years. This will provide insight into the challenges that can be expected in securing funding for DEMO in the 2030's. Some bright spots are apparent with increasing commitments in the US, UK and China signalling a continued public interest in fusion. An important question is the extent to which public funding and support may be affected by the success of a private initiative, which could weaken the case for public funded devices such as DEMO. For DEMO, the costs of which could be in a similar range to ITER i.e., multiple, possibly 10's of billions, this will be tricky. It should be hoped that two things work in its favour: (1) similar to what was outlined for the private sector, success of ITER DT operation can be a major catalytic event for fusion, which would almost oblige policymakers to fund DEMO; (2) that lessons have been learnt from ITER that allow for better design, organisation and planning to reduce costs and risks of delays. However, as highlighted above, there is still a long time before ITER DT operation occurs, and if private initiatives have made major successes in this timeframe, and all of them plan to, then public opinion (see 3.4.5) and political arguments against funding DEMO can be much stronger.

The picture on funding is much less clear in some other ITER nations due to a lack of transparency the current status of programmes in India and Russia is unclear. In Japan commitment to ITER and Broader Approach remains strong, however the appetite to fund a DEMO project in future is unclear. The decision on if and how to fund the A-FNS fusion neutron source device in Japan will be indicative of the long-term ambition and funding of public programmes in Japan.

3.4.4 Regulation

The establishment of an appropriate regulatory framework has been identified as a crucial element for the timely deployment of fusion energy. Most of the interview participants both from private and public initiatives confirmed that there should be a distinction on the regulation between fission and fusion energy, as they have certain fundamental differences that affect their environmental impact and safety risks. More specifically, as fusion reactors do not produce high activity and/or long-lived radioactive waste, their environmental risk and impact is much less than nuclear fission. Nevertheless fusion initiatives do take safety seriously, at ITER there is a multiple-layer barrier system that protects the fuel used in the reactor from potential spills into the environment[30]. In addition, in contrast to fission reactors, there is no risk of runaway reaction or meltdown in fusion reactors which overall reduces the safety concerns[31].

Presently, no country has a dedicated regulatory framework that entail the whole lifecycle of fusion facilities[32], yet there are currently ongoing efforts in multiple countries to establish a framework that fits the needs of fusion energy. In **the UK**, the government announced in June 2022 that fusion energy activities and facilities will continue (as they have been for JET) to be regulated under the Environment Agency (EA) and Health & Safety Executive (HSE)[33]. This followed the publication and public consultation on a fusion regulatory approach[34], with the regulatory approach included under the Energy Security Bill passed by Parliament[35].

With regard to **the EU**, there is no homogeneous regulatory approach towards fusion activities yet and each member state implements its own laws and provisions, although they follow to a large extent the European Directives and the IAEA safety standards[36]. ITER follows the French nuclear regulations enforced by ASN (*Autorité de sûreté nucléaire*), which considers ITER as a “basic nuclear installation” and therefore the same rules are applied as with any other nuclear activity[37]. In January 2022 ASN ordered ITER to stop operations until some concerns regarding neutron radiation, arising from distortion in the steel vacuum vessel sections are addressed[38]. The Wendelstein 7-X, the largest fusion facility in Germany, is regulated under the German Radiation Protection Act[39], which sets out the legal framework for the protection of the harmful effects from ionizing radiation and provides the legal basis for radiation protection.

The US has an independent agency that regulates the commercial nuclear power sector since 1974, namely the Nuclear Regulatory Commission (NRC); currently the NRC is investigating the options for an appropriate regulatory framework for fusion energy through public meetings with relevant stakeholders as well as with broader public[40]. In September 2022 it released a white paper presenting three options for fusion regulation for consultation[41]. The options include (1) regulating fusion plants under the ‘utilization facility framework’ which would essentially place it under the nuclear fission regulatory umbrella; (2) Regulating fusion energy systems under the ‘byproduct materials framework’ which would represent a ‘lighter’ regulatory approach; and, (3) a hybrid approach, with a decision step in licensing to decide under which approach to regulate a specific fusion energy system. The Fusion Industry

[30] https://www.iter.org/mach/safety
[31] https://research.binus.ac.id/rigpcs/2013/12/06/fission-vs-fusion/#:~:text=The%20main%20difference%20between%20these,atoms%20into%20a%20larger%20one.
[32] European Commission, Directorate-General for Energy, Study on the applicability of the regulatory framework for nuclear facilities to fusion facilities : towards a specific regulatory framework for fusion facilities : final report, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2833/787609
[33] https://www.gov.uk/government/news/regulation-decision-to-help-accelerate-fusion-energy-progress
[34] Information on the Strategy and consultation can be found here: https://www.gov.uk/government/publications/energy-security-bill-factsheets/energy-security-bill-factsheet-fusion-regulation
[35] https://www.gov.uk/government/collections/energy-security-bill
[36] https://www.iaea.org/resources/safety-standards
[37] https://www.iter.org/newsline/-/3727
[38] https://www.science.org/content/article/french-nuclear-regulator-halts-assembly-huge-fusion-reactor
[39] https://www.nuklearesicherheit.de/en/licensing-and-supervision/the-legal-framework/radiation-protection-act/
[40] https://www.fusionindustryassociation.org/post/nrc-hosts-public-meeting-on-developing-a-regulatory-framework-for-fusion-energy-system
[41] NRC Staff Prepared White Paper: “Licensing and Regulating Fusion Energy Systems” available at https://www.nrc.gov/docs/ML2225/ML22252A192.pdf

Association is playing an important role in the discussion in the US, engaging with the regulatory discussions on behalf of the industry to seek a proportional, risk-based regulatory outcome.

China does not have currently any safety and licensing regulations specifically tailored for fusion; however there are several nuclear safety related laws, administrative regulations, department rules, safety guides and technical documents, yet they do not have equivalent legal effect (i.e., national laws have the highest level of effect while technical documents the lowest). Similarly, in **Korea** there is no fusion-specific regulation, however, the nuclear activities are regulated under the Nuclear Safety Act, while there are several legally bidding documents that lay out the rules about procedures, methods and safety. KSTAR, the largest fusion facility in Korea, is considered as a radiation reactor and falls under the radiation regulation framework[42].

3.4.5 Public acceptance

Public acceptance for nuclear fusion will be a key element for moving forward with the development and eventual roll-out of the technology. Given that nuclear fusion and nuclear fission are both processes involving nuclear physics and sound similarly, they are often confused by the public.[43] Thus, it is important to inform and educate the general public on the differences between them – especially with regards to health and environmental aspects. Given the high-risks associated with nuclear fission, and its association with nuclear disasters of Fukushima and Chernobyl, and long-lived waste issues – it is not surprising that nuclear energy (general term used to refer to nuclear fission but which is not precise and could generate confusion) is perceived with distrust and low acceptance by many. Furthermore, given that fusion technologies are not yet commercially ready, fusion is a little known subject and distant from daily life.[44]

It has been shown that education, communication, regulatory compliance and reducing technology-associated risks are not enough on their own to gain social acceptance. A social license is a process of acquiring 'society's consent' for a technology, project or endeavour and it goes beyond education and public relations.[45]

During the interviews held with the different public and private organisation, public acceptance and obtaining a social license for fusions were not frequently mentioned. In contrast, some companies dismissed the problem of nuclear waste as a relatively easy to solve compared to other challenges associated with fusion. Nonetheless, the emphasis given to energy justice and public engagement during the White House Summit on Developing a Bold Decadal Vision for Commercial Fusion Energy held on 17 March 2022[46] shows that issues around public acceptance of fusion are being taken seriously.

Last but certainly not least, is the question of public spending. Fusion is a hugely expensive technology (see section 3.4.3 on 'funding is crucial'). Public programmes such as ITER are being funded from the

[42] European Commission, Directorate-General for Energy, Study on the applicability of the regulatory framework for nuclear facilities to fusion facilities : towards a specific regulatory framework for fusion facilities : final report, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2833/787609

[43] Based on Turcanu, C. et al. (2020)'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'.

[44] Turcanu, C. et al (2020) Fusion energy: A deeper look into attitudes among the general public. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0920379620304397?via%3Dihub

[45] Hoedl, A. (2021) Social license and Ethical Review of Fusion: Methods to Achieve Social Acceptance. Available at: https://www.arpa-e.energy.gov/sites/default/files/2021-01/410PM_Hoedl%20PRF.pdf

[46] White House (2022). Available at: https://www.whitehouse.gov/wp-content/uploads/2022/03/031522-Fusion-Summit-Event-Agenda.pdf

public's tax money and thus must go beyond private initiatives in ensuring the public's support for fusion. Better public communication of the current (often overlooked) and future benefits from public spending on fusion would help to steer public opinion to be favourable for fusion.

3.4.6 Staffing

One of the most significant elements for the fast development of fusion energy is the availability of the necessary workforce, which includes professions such us engineers, scientists and technicians. Many stakeholders both from the private and public sector identified during the interviews that specialized staff is emerging as potentially one of the main barriers for the successful and timely fusion development. More specifically, it was mentioned that there is a need for further encouragement of younger generation to study plasma physics and fusion energy, so that they can later reinforce the workforce of the public and private initiatives. In that direction, several countries such as the US, the UK and Japan are developing academic programmes, international schools, apprenticeships and collaborations between different universities. Europe has also come a long way to boost the growth of fusion knowledge in all levels of education. As of 2016, there were 13 universities that provide dedicated master programmes in nuclear fusion, while there are many PhD and post-doctoral opportunities in several European institutes[47]. In addition, the EU has set up several funding mechanisms to support research and innovation of fusion energy. The most recent one is the "Euratom Research and Training Programme 2021-2025"[48], which provides a budget of €583 million to be used in the research of fusion-related activities. A part of this budget is reserved for specific education and training activities, including funding Engineering Research grants (funding around 20 engineers), and 'Bernard Bigot' Researcher grants (funding around 10 post-doctoral researchers). EUROfusion, provides €35.7M between 2021-2025 to fund PhD and pre-doctoral students. Overall, funding academic programmes is a costly initiative as it requires a significant budget that will provide tangible benefits at a later time, and can be often seen as an important barrier. Some have also highlighted that whilst large numbers of PhDs in fusion are supported there are not enough jobs in fusion laboratories at the end of the track, and that many people then leave the sector. This may provide a talent stream for private firms entering the sector, but risks in the current situation and the concentration of firms outside of Europe that EU funded PhDs then provide qualified staff for the industry in the US and UK.

The field of fusion requires the development of particular skills and knowledge that have been identified to be at shortage[49], namely:

- Tritium transport modelling in Breeding Blankets;
- Tritium extraction technologies;
- Development and fabrication of Li-based ceramics;
- Nuclear Fusion Safety;
- System Engineering applied to tokamak;
- Integration of the fusion nuclear plant;
- Beryllium Handling, Health and Safety regulation; and,
- Tritium Plant: Water Detritiation and Isotope Separation systems.

Fusion energy sector requires personnel from a variety of fields, such as data scientists, control engineers and technicians, nevertheless there is currently an overall shortage of skilled people in

[47] Donné T. et al., (2016) Review of Human Resources in the European Fusion Landscape
[48] Euratom Research and Training Programme (2021-2025)
[49] Donné T. et al., (2016) Review of Human Resources in the European Fusion Landscape

Science Technology Engineering and Mathematics (STEM)[50]. In Europe the issue has been recognized and several initiatives[51] and programmes are implemented in order to boost the number of skilled people in STEM; similar issues exist elsewhere too, the UK government is investing almost 180 million pounds to support scientists mathematicians and engineers[52], while in the US it is projected that about 3.5 million STEM jobs will be required by 2025[53].

Given the overall shortage of STEM skills globally it is no surprise that firms in the sector report high competition for staff and graduates. Competition for those with required modelling and computational skills is high, with financially attractive opportunities in finance and Silicon Valley being able to attract talent more easily than fusion. Similar issues exist across the broader range of engineering skills. However, there are also opportunities to hire from other sectors for these broader engineering skills, interviewed firms noting that they have taken people on from aerospace or space industries and after a short training period these staff have been effective recruits.

Additionally, another barrier related to skilled and experienced staff is the lag of knowledge transfer. Currently, there are many experts with significant knowledge in the domain of fusion energy, who may transfer their specific knowledge to younger generations of scientists; nevertheless, this is a timely process and it could hinder the fast deployment of fusion energy in the near future.

Determining the needs in human capital in the fusion energy sector can be a very challenging task, as there is little specific and accurate information available regarding the current workforce in the ongoing public and private initiatives.

The Fusion Industry Association (FIA) survey carried out in cooperation with this study provides a quite detailed overview regarding the companies related to fusion. The demographic data of the survey showed that across all of the companies around 1 500 people in total are employed. On average half of them being engineers and 25% being scientists[54]. This mirrors the focus of these companies, which is geared towards engineering of their next devices. In addition, the data showed that there is a significant gender imbalance, with an 80:20 split in favour of males. It is noteworthy that the gender distribution did not change in the last decade, as the results of the Human Resources Survey conducted in 2016 in EUROfusion members showed exactly the same results[55]. Encouraging female representation in the fusion energy sector, could help to address potential shortages, although gender imbalance is common across most STEM sectors globally[56].

The number of people engaged by the major public fusion initiatives globally is harder to estimate but is much larger than the private sector, at least 12 000 by our estimation. Some major employers are shown in Table 3-5, which highlights that ITER and Max Planck Institute for Plasma Physics employ around 1000 people each, while the UKAEA has a workforce of around 1250 people. Russia has also a large workforce in nuclear research, with one of its main institutes employing 5000 people alone, however the share working on fusion is unclear, and likely by far smaller than on fission or other related

[50] Science, technology, engineering, and mathematics
[51] E.g., EU STEM Coalition
[52] https://www.gov.uk/government/news/multi-million-government-investment-in-the-future-of-uk-science
[53] https://www.shrm.org/hr-today/news/hr-magazine/summer2019/pages/the-u.s.-needs-to-prepare-workers-for-stem-jobs.aspx
[54] The remaining 25% is included in the category “Other”.
[55] Donné T. et al., (2016) Review of Human Resources in the European Fusion Landscape
[56] https://www.imperial.ac.uk/news/233901/how-current-stem-gender-bias/

fields. As noted, the list of organisations is not exhaustive, and there are other public initiatives (e.g., the Lawrence Livermore National Laboratory and the University of Wisconsin-Madison in the US, the National Institute for Fusion Science in Japan etc.) that conduct significant research in the field, yet there are no specific information on the staffing of the particular faculty of fusion energy, and therefore they were not included in the statistics.

Table 3-5 Staff in fusion energy sector in several public initiatives worldwide

Name of initiative	Country	Total employees
ITER	35 nations	1 700[57]
EUROfusion	EU	4 800*
UKAEA	UK	1 250
CAS Institute of Plasma Physics	CN	700
FDS	CN	30
CAS Hefei Institute physical science	CN	600
Korea Institute of Fusion Energy (KFE)	KO	437
Institute for Plasma Research, Department of Atomic Energy (DAE)	IN	700
Princeton PPL	US	30
ARPA-Eapl	US	100
F4E	EU	450
National Institutes for Quantum Science and Technology (QST)	JP	1 300
Total		**12 097**

Note 1: the table includes only the public initiatives for which information were available online, and it is not exhaustive, e.g. data for Russia is missing, other national labs are working on fusion in the US.

** the number of employees under EUROfusion includes those working in research institutes across Europe, such as the Max Planck IPP in Germany, the CEA in France, ENEA in Italy and others members of EUROfusion.*

3.4.7 Expected LCOE

Given the important uncertainties regarding the next phases, and especially the construction and operation of a complete plant, only a few of the interviewees had given this significant thought and the uncertainties so far ahead are so large as to make most estimates rather meaningless. However, some indications were provided. Firstly, a handful of firms were clear on the range of LCOE they wanted to target, where they would expect to be competitive in the market, with a target of around USD 50/MWh the most common marker.

Capital costs for pilot plants were also mentioned by some initiatives, ranging from a few hundred million euros to up to 10 billion euros. Variations are very high, based not only on approach but also the size and characteristics of the plant, with capital costs scaling with planned MW capacity. The future cost of the key components will be an important driver, many of these are at low TRL levels and therefore major improvements, and cost reductions can be still be made, these are impossible to know. Capital costs could also vary considerably between approaches.

There was little estimation of potential **operation and maintenance (O&M) costs**, as many parameters are not yet well known – however these are expected to be low in any case, with the capital cost by far the major part of the total cost of a fusion plant. Fuel costs are unclear, in the case of Tritium a major expectation is that beyond acquiring a seed amount of tritium to start-up reactors should breed their

[57] This represents the official total of 1 000 ITER IO staff (the number of staff is capped), and also 200 ITER project associates and 500 external contractors also working at ITER. These numbers can vary over time.

own supply in the fusion reaction. Deuterium and other consumables are not regarded as being high volume nor costly requirements. There are some current concerns over lithium supply shortages but these were not raised by interviewees. For IFE target-based approaches firms did have an idea of the challenge in terms of high volume, precision, and low-cost target manufacture to make it economically viable. Costs and replacement cycles for major components, e.g., if breeding blankets or wall materials would need to be replaced every 10-20 years, were also unclear, but could constitute an important O&M cost element.

Expected LCOE of fusion is also being addressed in the literature. In their paper on potential early markets for fusion energy (2021), Dr Hsu and his colleagues Dr Handley and Dr Slesinski examined possible cost requirements for fusion-generated electricity, process heat and hydrogen production[58]. The authors conclude that there could potentially be a very large market for fusion power plants with an LCOE of US$ 50/MWh. In addition, the competitivity of fusion can be enabled through integrated thermal storage which may allow the fusion core to run continuously while selling electricity when there are high grid prices. This would guarantee a lower LCOE and allow fusion to compete with power grids that are dominated by solar and wind. Other markets such as process heat and hydrogen production will be complex to access for fusion at an early stage, mainly due to technical and financial constraints. A final consideration is that it is impossible to know how the availability of fusion may disrupt markets, nor exactly how markets or infrastructure will develop in the intervening period.

In helping to further understand potential costs, as part of the ALPHA programme of ARPA-E, a study was conducted on the capital costs associated with fusion power plants (2017)[59]. The cost analysis was performed in 4 different fusion reactor designs[60]. Although an LCOE was not computed, the results of the study aimed to provide a costing framework and capital cost estimate range to support LCOE estimates when more detailed design data and information on the different technologies is developed in the future. There are four main takeaways of the study:

- The cost of the core is similar across the four different designs and constitutes less than half of the total direct cost. It is not always the most expensive component.
- Neutronics and tritium handling are not major capital cost drivers, but their cost will remain relatively important. Moreover, engineering work is necessary to upgrade these solutions.
- The power systems comprise between 5 and 20% of the total direct cost. Therefore, it should become a focus area in future work, namely to decrease uncertainty in the pulsed power system design and lifetime under power plant conditions
- Up-front capital costs of a fusion power plant, are likely to depend heavily on the scale of plant and balance of plant components.

LCOE is relevant to compare energy technologies and evaluate their competitiveness – but it does not evaluate other important energy system criteria which are not translated into costs or revenues. Therefore strategic or policy goals such as security of supply, environmental impacts and energy independence, all of which are potential strengths of fusion, are neglected by LCOE.

[58] Handley, M., Slesinski, D. and Hsu, S. (2021). Potential Early Markets for Fusion Energy. Available at: https://link.springer.com/article/10.1007/s10894-021-00306-4

[59] ARPA-E (2017). Conceptual Cost Study for a Fusion Power Plant based on four technologies from the DOE ARPE-E ALPHA Program. Available at : https://woodruffscientific.com/pdf/ARPAE_Costing_Report_2017.pdf

[60] The reactor designs studied are (1) Stabilized Liner Compressor, (2) Plasma Jet Driven Magneto-Inertial Fusion, (3) Staged Z-Pinch, and (4) Sheared Flow Stabilized Z-Pinch.

Although there are many uncertainties with regards to the expected LCOE, it is clear that capital investments for next devices and pilot plants are likely to increase in the coming years decades. With the shift from research activities to demonstration and deployment capital costs may reach amounts running into several billion euros. This also implies that the **financial risks** of fusion activities will become increasingly high. Hence, fewer and fewer investors will be willing and/or able to participate in such projects. Governments may than need to step in and provide additional funding to support the deployment of the fusion sector. This situation is already the case for some major infrastructure, for example, almost all large nuclear fission plants being constructed required at least some form of government involvement or guarantee. This issue is mainly a risk of companies which aim for big facilities (e.g., 1GW power plants).

3.4.8 Links to other non-fusion fields

Fusion innovations with applications in other fields

Research on fusion energy has not only progressed our understanding of the physics, chemistry and engineering principles required for electricity generation from the fusion reaction but has also led to valuable knowledge applicable to other disciplines and areas of knowledge. Areas of existing and future applications of fusion research discoveries include, but are not limited to **other energy technologies** (4th generation fission, HT superconductors, storage, etc), **medicine/medical technologies, superconductors, material sciences, remote handling, telecommunications and theoretical physics.**[61]

During the interviews, several of the private initiatives reported already capitalising or planning to capitalise from potential spin-off applications. At least a couple of projects mentioned **nuclear medicine** as an area of interest for spin-off applications. **Transmutation**, the conversion of one element or its isotope into another chemical element, with applications for treating radioactive waste was also mentioned as an area of interest. Examples mentioned by the sector in interview included innovations related to power system management which are interesting for energy utilities; and feedback control systems which can have applications in AI and Neural networks as well as other commercial applications. The UKAEA mentioned various existing examples of innovations in fusion with applications outside of fusion. They highlighted as an example a spin out company (Reaction Engines Ltd) focused on air breathing rocket engines [SABRE][62]. It was also highlighted that work on lasers at NIF was crucial to the development of EUV lithography, a key technology in the miniaturisation of **semiconductor** manufacturing.

A handful of firms active in fusion have identified the development of spin-offs and alternative revenue streams as important to their business model and being able to support the overall economic viability of the company and provide value for stakeholders. Firms with this view highlighted that they aimed to decouple these alternative income streams from the fusion part of the company, as either independent departments under the same umbrella or by spinning them off as new companies. In this way their core focus on fusion energy can also be maintained, while this new revenue generating activity has sufficient autonomy. They noted that these activities should be carefully managed to not distract too much from the overall goal of fusion energy.

[61] See EuroFusion (2017) Fusion Research – spinning off short-term benefits. Available at: https://www.euro-fusion.org/fileadmin/user_upload/Fusion_Spin-offs/PDF/Spin-offs_GB_20_4_17.pdf
[62] https://reactionengines.co.uk/advanced-propulsion/sabre/

In contrast, many of the interviewed companies viewed spin-offs only as a **'plan-B'** option in case their original aim (fusion energy) is not attainable, or as a 'nice to have' along the way. With fusion energy a primary goal, alternative applications of fusion innovation, in for example medical technologies, cargo screening or HTS magnets, are not seen as a major or urgent part of the business plan and they also do not believe that this is a major 'selling point' for the investors. A handful of companies were even clearer that it is **necessary to be 100% focused on fusion energy** as it is hard enough to achieve this goal. One firm, SHINE Technologies[63], is interesting as its core business is in industrial neutron imaging, applying relevant fusion-related technologies, and it has a business plan based on developing medical isotopes, then recycling nuclear waste and then fusion energy in future.

On the public side, EUROfusion, has a Fusion Technology Transfer Activities programme (FUTTA III) dedicated to supporting the transfer of fusion research into other applications. The programme consists of 6 brokers based in Germany (x2), Belgium, France, Italy and Spain tasked with supporting technology providers with the **identification of relevant applications and use-cases for their inventions through market positioning**. In addition the brokers help to bring different stakeholders together, help interested buyers in finding the right solutions and advising on relevant funding opportunities to accelerate the technology and know-how transfer. The predecessor of the current programme, FUTTA II, resulted in 8 technology transfers, 21 success stories and 4 funded demonstration projects.[64] Examples of technology transfer demonstrator projects included protective tungsten-based coatings for combustion chambers used in aerospace applications and new tungsten-based coating materials with applications in cooling electronics, air treatment and surface cleaning[65].

Important technological developments outside of fusion

Development of enabling technologies such as Artificial Intelligence (AI), supercomputing, 3D printing, materials science, etc plays an important role in the way that fusion will develop. There are possibilities that large breakthroughs are made in other areas of technology development can enable a faster development in fusion for example, more advanced computation can help the design of breeding blanket or speed up simulation of fusion experiments. Recently, scientists announced that they have trained an **AI system to control and sculpt a superheated plasma inside a nuclear fusion reactor**[66].

For fusion projects based on lasers the developments of laser technology will be key. Laser development over the next decade will allow enable further understanding of block ignition from radiation pressure laser drivers. Lasers with performance of ~10 PW[67] and rep-rates of less than 1 shot per minute are examples of the ongoing rapid development of the field.[68] Compared to the lasers deployed at NIF, currently the world-leader in IFE, massive improvements can be made on the basis of current technology – this is part of the rationale behind private start-ups in IFE.

Several companies mentioned advances in **material science** as an important area in support of fusion energy development. For example, there is still a need for **structural material** development to be able to operate under the harsh conditions required for fusion for several decades. **Nano-material** science

[63] https://www.shinefusion.com/phases/
[64] http://techtransfer.euro-fusion.eu/wp-content/uploads/2022/04/FUTTAII-Dissemination-brochure.pdf
[65] Ibid.
[66] Shead S. for CNBC (18/02/2022) DeepMind scientists say they trained an A.I. to control a nuclear fusion reactor. Available at: https://www.cnbc.com/2022/02/18/deepmind-scientists-trained-an-ai-to-control-nuclear-fusion-.html
[67] 1 Petawatt (PW) = 10^{15} Watt
[68] See HB11 Energy (Accessed on 17/05/2022) 'How it Works'. Available at: https://hb11.energy/how-it-works/

has also been mentioned as important in IFE target development. Companies also mentioned the need for better **superconducting materials** and/or improved supply chains for these materials.

The commercialization of more efficient thermal-to-electricity cycles is also identified as an important aspect to minimize fusion energy cost and enhance its competitiveness[69].

Developments in **manufacturing and engineering** were also highlighted as important enablers by several companies. For example, some firms are piloting the use of **3D printing**, on the basis that metallic 3D printing can facilitate the manufacturing of specific and complex components while reducing the waiting time for such components significantly. With regards to this, several companies reiterated the conclusions of a paper[70] that early **engagement with the industrial supply chain providers and the development of computational engineering testing and verification** are important element to prevent prolonged timescales to fusion development.

On the other hand, there is a danger that the **development of fusion can be hindered because enabling technologies that are not advanced enough yet to execute the design**. A past example of this is the case of the Stellarators where slow advances in computational power slowed down the development of this concept. It is unclear if such issues will be encountered in future.

[69] In interview and also in Samuel E. Wurzel and Scott C. Hsu (2022) Progress toward fusion energy breakeven and gain as measured against the Lawson criterion. Physics of Plasmas 29, 062103 (2022)
[70] Surrey, E. (2019) Engineering challenges for accelerated fusion demonstrators. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6365852/

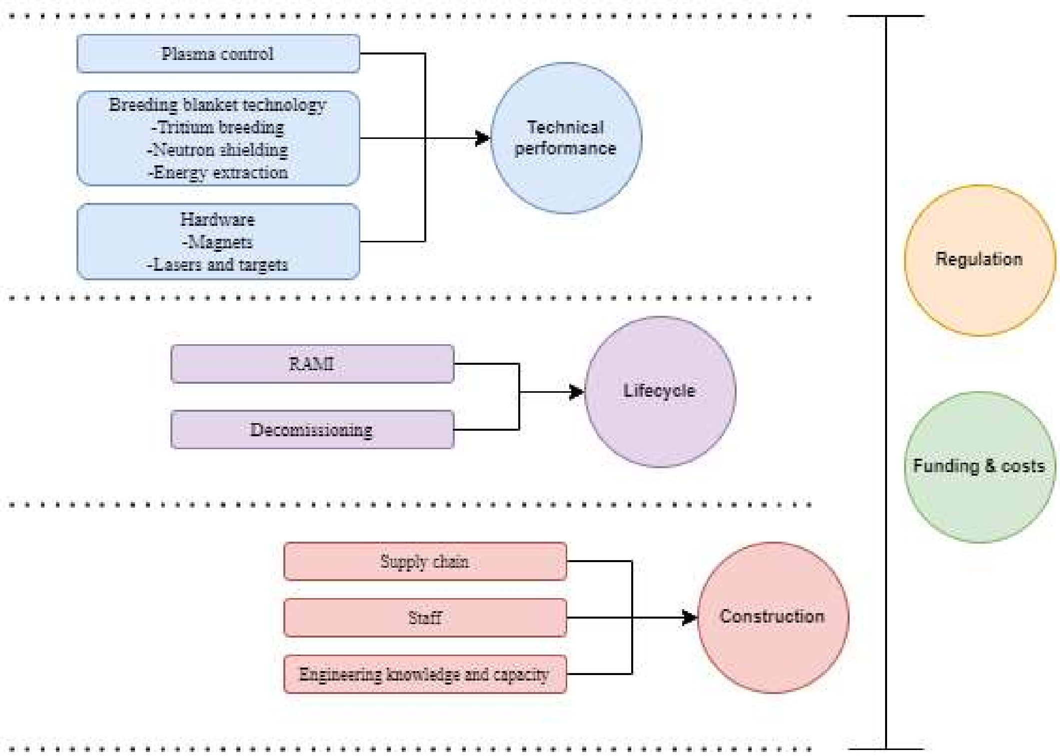
4 Future scenarios of fusion development

This chapter brings together the findings from desk review, interviews, survey and expert validation as presented in chapter 3 to provide an analysis of the potential future of fusion development.

4.1 Challenges and barriers for fusion development

Analysis of publications and feedback in interviews allows for a clear picture of the most common challenges and barriers to fusion development to be highlighted. Not all challenges and barriers apply to all fusion approaches, as some approaches are designed in a specific way to fundamentally avoid or mitigate technical challenges, i.e., those based on aneutronic fusion attempt to avoid the majority of the serious neutron and tritium related challenges. The following section provides a short overview of the key barriers towards commercialisation of fusion energy, which serves as a background and basis for defining the scenarios to be analysed in this work. The main barriers are summarised in the following figure and are elaborated in the remainder of this section.

Figure 4-1 Summary of main challenges for fusion energy



Technical performance

Currently the most prominent and urgent barrier to commercial fusion energy is the basic technical performance as no fusion initiative to date has demonstrated energy gain. During the interviews several factors were flagged that require further improvement to increase the performance of fusion devices and achieve energy gain.

Plasma control: Key to the performance of MFE approaches and necessary energy gain are the conditions of the plasma. Optimizing the plasma conditions requires understanding of the plasma behaviour, mitigating instabilities, turbulence control and increasing plasma pressure and energy confinement times. These are highly technical objectives that demand advancements in magnetic field strength and control, software and diagnostics and measurement systems. Because advancements in the plasma performance are necessary for reaching energy gain, they are decisive for when the first (MFE) powerplant will be constructed.

Breeding blanket technology: Except for a few novel or hybrid approaches, the majority of the traditional MFE approaches (Tokamaks, Spherical Tokamaks and Stellarators) propose wall power flux and tritium breeding blanket, which are key components of the design. Divertors are under intense development to extend wall lifetimes. The breeding blanket serves multiple purposes i) facilitate tritium breeding inside the reactor by reacting lithium with neutrons from the fusion reaction ii) shielding the reactor vessel and nearby components, such as the magnets, from the high energy neutrons to prevent damage and iii) extracting the heat from the reactor:

- **Tritium breeding:** Breeding tritium inside the reactor is crucial to ensure self-sufficiency and sustained fusion. However it is also one of the most challenging issues that should be resolved. Theoretically breeding tritium inside a MFE reactor is possible but it has rarely been demonstrated in practice[71]. Public initiatives are working on tritium breeding and fuel cycles[72], most notably ITER will do crucial experiments with breeding blanket concepts. The results of these experiments are highly anticipated by many in the fusion community, including private initiatives, none of which are yet working with Tritium, and few of which plan to at the next device stage. Some of the interviewed private initiatives acknowledged that they were dependent on other parties to develop tritium technologies because they were not able to develop everything in-house. Other more ambitious companies revealed ambitions to develop tritium cycles themselves, with novel design concepts such as liquid metal blankets or curtains for breeding. It should be noted that these ideas would theoretically deliver the needed breeding ratio, but have not been demonstrated yet. The most tangible steps towards solving this challenge at present are planned to be carried out by the public fusion initiatives, but again, with a long timeline for expected progress, this could significantly influence the timeline towards the first fusion plant. Some private firms, such as Kyoto Fusioneering are becoming active in trying to address this specific issue. It should also be noted that most blanket designs need enriched ^{6}Li, much beryllium, or both to achieve a breeding ratio > 1. Whilst it is a relatively common element, lithium is currently in short supply due to high global demand for batteries, the ^{6}Li isotope is also found only in low concentrations.
- **Neutron shielding:** during a DT fusion reaction high energy neutrons are released and can damage and degrade the components they interact with. The superconducting systems need to be protected as they are prone to overheating from the excessive neutron radiation. Interviewed companies state that shielding introduces a trade-off between thickness and efficiency, ideally shielding should be as thin as possible, but it should also prevent neutron damage. This is particularly difficult for the Spherical Tokamak design where the geometry leaves very limited space for shielding the central solenoid, divertors become much more important in this approach, therefore the success of the Super-X divertor at MAST-U represents an important step forward, especially for spherical tokamaks.
- **Energy extraction**: once energy gain is achieved, this energy needs to be extracted from the reaction to produce electricity and this was flagged as an important challenge by numerous

[71] Experiments at JET in the UK have made progress on this issue
[72] E.g., University of Rochester in the US, Max Plank at Kalsruhe in Germany

fusion initiatives. The principles of heat extraction are straightforward and in the majority of cases will make use of standard heat exchangers, however, to date none of these systems have been built and integrated into a fusion device, which presents its own specific challenges e.g. long length of heat pipe circuits.

Hardware: other key hardware is also crucial, including:

- **Magnets:** These are crucial to most MFE-based approaches and an area where private firms have shown significant breakthroughs in the last few years. More compact and powerful magnets have been demonstrated by utilising high-temperature superconducting technology. The magnets open up various new possibilities for fusion energy. However, the supply chain and cost of these new magnets, and indeed magnets already used across fusion, remains a key challenge, with one rule of thumb suggesting they account for up to 1/3 of the cost of a fusion device. Expanding supply chains and controlling and reducing costs is a crucial challenge to ensure that advances in magnet capabilities can be economically viable in fusion devices in future.
- **Lasers and Targets:** There are a few technological challenges that are specific to IFE approaches that can potentially influence the timeline up until the first fusion plant. These IFE approaches employ a 'target' that contains the fuel and an energy driver to fire a large amount of energy at it, forcing it to implode and generating fusion reactions. Part of the technical challenges deal with improving the performance of these elements. This translates into improving the specifications of the energy driver, and to-date lasers have been the most common and promising energy driver (for example at NIF), and therefore increasing the power and the efficiency of the energy driver are important technological barriers for reaching energy gain. For example, at NIF current total efficiency (Laser energy to shell final kinetic energy) is in the region of 1-1.5% for indirect drive and 4-5% for direct drive[73]. Also, the energy coupling needs further improvement to increase the efficiency of the operation and enable energy gain, particularly for indirect drive.
  Many IFE initiatives also recognize that once energy gain is possible with IFE, technical advancements are necessary to transform the process of experimental shots into an operational powerplant. This requires a high repetition rate; one of the interviewed companies strives for a shot every 30-60 seconds for their first powerplant and states that to achieve this, significant improvements to the energy driving system are needed. Other concepts would need even shorter repetition cycles, i.e., multiple shots per second. A high repetition rate will also require a high number of targets and IFE initiatives foresee this is as a major challenge. Achieving the necessary high precision and low cost of manufacturing these targets, and the ability to quickly and precisely place and replace these targets, whilst keeping the laser cool. Depending on the number of operational hours and the repetition rate, a powerplant quickly requires thousands to tens of thousands of targets per day.

Lifecycle

Once the technical performance issues have been resolved, the full lifecycle of the technology becomes the next critical barrier in nuclear fusion development. Multiple issues regarding the lifecycle include:

[73] From slides shared by Dr E.M.Campbell from an MIT Seminar March 2022: Perspectives on Inertial Fusion Energy

RAMI (Reliability, Availability, Maintainability, Inspectability): A concern that is closely related to the durability of the first powerplant designs is how they can be well maintained to facilitate continuous high performance and extend the lifetime of the machine. This is an important design consideration, in terms of accessibility, and also in terms of the remote handling and/or robotic technologies that will need to be developed. Public initiatives are already making some efforts to address these barriers. This barrier is unlikely to heavily influence the timeline for the next devices, but it will be an increasingly important consideration for the first pilot plants which should demonstrate key aspects. It will be essential for the first commercial plants, contributing to the success of its design and its maintenance costs. Designers should estimate the time required to repair possible malfunctions, such as a damaged magnet coil.

Durability: This presents an important difference between experimental facilities or pilot plants and the first commercial power plants, with the latter required to achieve high availability and low maintenance. This requires addressing how magnets, wall materials, lasers, cooling systems etc deal with constant operation.

Decommissioning: At the end of the functional life, the fusion power plant will need to be decommissioned. For nuclear fission this involves the plant shutdown, removal of nuclear material and the environmental restoration of the site. The whole process is complex and typically takes 20 to 30 years to complete[74]. It is unknown at this point how the decommissioning of fusion plants compares to that of fission, as for instance it is difficult to predict what the environmental impact will be of continuous fusion powerplant operation. Several interviewed initiatives mentioned that the eventual decommissioning is a topic that is acknowledged and worked on, however, this is currently in its infancy

Construction

The third critical barrier is the construction and deployment of fusion plants, the associated issues for construction and deployment will become increasingly important as the technology matures and moves towards widespread deployment. However, some issues relevant to this challenge are already starting to be felt.

The supply chain

The availability of the supply chain was seen as an important concern by many of the interviewed initiatives for both the development phase and the eventual deployment phase. No fusion initiative develops and produces all its components/hardware in-house and therefore has a dependency on other manufacturers and specialized companies to supply necessary materials, software or components. One of the private initiatives disclosed that the availability of a supply chain was a key factor to decide in which country it would continue its activities and build a new testing facility. The supply chain is also essential for the construction of a power plant, and supply chain problems can result in delays, ITER has been a prime example of these problems. Hence, the readiness and the availability of the supply chain is an important factor that can influence the timeline of fusion development, especially the duration of plant construction. This was recognized by the majority of the interviewed initiatives. A current example of supply chain issues comes from the invasion of Ukraine, which due to sanctions is hampering delivery of Russian components to fusion experiments, for example in the area of neutral beam injectors where Russian firms are leading suppliers.

[74] https://energy.ec.europa.eu/topics/nuclear-energy/decommissioning-nuclear-facilities_en

Staff

The development of fusion requires highly educated people with very specific educational backgrounds for instance with specializations in nuclear or plasma physics, and other relevant disciplines. This pool of people is limited and constrained by the amount of people that choose to pursue a path in nuclear fusion, and the rate at which highly qualified staff, e.g., with PhD's can be trained. In addition general technical expertise is required, and shortages in STEM (Science, Technology, Engineering and Mathematics) skills are a common issue across the developed world for manufacturing and other relevant sectors. Various companies state that it is difficult to find good staff and more people need to be trained to accelerate the development and eventually scale fusion. More importantly, the construction and operation of fusion plants on a large scale will require millions of people to be sourced and trained and the speed at which fusion can be deployed will greatly depend on the availability of workers.

Engineering knowledge

The initial DEMO fusion power plant will be a first-of-a-kind design and similar to ITER, a highly complex machine. Construction of such a machine deals with the integration of many highly complex and advanced components and requires specific knowledge of how to engineer everything together. The construction of ITER has demonstrated the enormous engineering complexity and has had many significant delays. Part of this has been put down to the lack of a major engineering project integrator with the capacity and management experience to fully oversee the project. Not only the capacity, but also the knowledge and experience of the industry may hamper the realization of the initial pilot and commercial plants as few if any engineering firms have experience in building fusion devices.

Regulation

Whereas the aforementioned barriers have a degree of hierarchy, regulation poses a potential barrier throughout the entire fusion research and development process. As noted earlier in section 3.4.4 the private sector is pushing hard for suitable regulation for the fusion industry. Companies are worried that fusion will fall under the same regulatory framework as nuclear fission. Although both technologies have radioactivity and related health and safety concerns, they are different in many respects and the dangers they pose. The nuclear risks from fusion are understood to be much smaller than for fission, and that therefore a proportionally lighter touch regulatory approach is appropriate. Many believe it also necessary, warning that applying the same regulatory approach as for fission would result in high and unnecessary regulatory expenses and that this would mean the capital costs for fusion would likely be higher than those of fission, making it uncompetitive. Important enablers or limiters of fusion development from a regulatory perspective are:

- ✓ Safety standards and tritium handling
- ✓ Waste handling
- ✓ Licensing processes
- ✓ Government budgets (potentially subsidies such as feed in tariffs to decrease financial risk in the first years)

The vast majority of the interviewed initiatives stress the importance of regulation for the future of fusion. They 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.

Licensing processes for powerplants can also be very lengthy, taking up to ten years in some cases, and can be an important consideration for timelines and scenarios.

Funding and costs

Similar to regulation, the financial aspects of fusion are a highly important factor that is present throughout the complete development process of fusion and could be a barrier to fusion development and deployment throughout the entire commercialization process of fusion energy. It was found that initiatives mostly flag funding and economic viability as the two key challenges.

Access to funding: Funding is essential to both public and private fusion initiatives and the success of fusion development is to a degree dependent on the amount of funding that is available for the initiatives working on fusion development. Despite the significant increase of researching funds attributed to the private sector (see section 3.4.3), the R&D process of fusion could be accelerated if more funding is made available still. Funds could be used to develop additional and more advanced testing facilities, hire additional staff and take more risks. It was articulated by several interviewed companies that their current funding does not allow for them to undertake all research activities they want to and that certain challenges could be solved quicker if they had more funds available.

Not only is funding an important factor for fusion related research, it is also a key factor once the initial commercial fusion technology are ready for the market. The first commercial power plants require very high investment costs (for example KDEMO is estimated at $10-20 Billion) to be developed and will still carry significant investment risk: at this point the durability of the reactor, subsequent downtime and the resulting maintenance costs are still unknown, making the financial returns very unpredictable.

Economic viability: From a financial perspective there is still a lot of uncertainty about the economic viability of fusion (see also 3.4.7). Multiple initiatives have stressed the importance of economic viability of fusion and stated that fusion's LCOE needs to be competitive with other baseload energy sources such as fission and potentially fossil fuel powered plants (presumably with CCS). Although some private initiatives presented their target LCOE, significant uncertainties remain regarding the capital costs, maintenance and downtime costs, regulatory costs, fuel costs and the total lifetime of a fusion plant. These will need to become clearer, particularly for investors, as fusion initiatives approach commercialisation.

4.2 Key dimensions for scenarios

4.2.1 Key scenario dimensions

As structured in chapter 3, the key overarching steps in fusion development are the construction and successful operation of a next experimental device, one which should prove some (but not all) essentials of the specific fusion approach – particularly power multiplication / net energy (Q>1); followed up by a pilot plant that brings all (or almost all) aspects together to demonstrate a fusion power plant is technically and economically feasible; and finally the first commercial power plants which fully address all issues including life-cycle (RAMI) issues and provide power at a competitive cost. These form the basic steps in our scenarios, however we also look to expand on a few key dimensions to the scenarios, with a particular focus on milestones and challenges at each development step, and what their timing and achievement (or non-achievement) could mean. We elaborate these below, before defining the scenarios.

4.2.2 Dimensions important for next experimental devices

For the next devices we identify two specific dimensions that are most important for the scenarios. Firstly, ITER, as the premier next device globally and the centrepiece of current public fusion efforts; Secondly, the achievement of net energy gain, which is the goal of both ITER and the various private fusion efforts – and which can be viewed as a crucial catalytic moment for the sector.

ITER: this is the most crucial of all ongoing public fusion efforts and represents the expected base case for fusion development in Europe (also Japan and Korea). Public DEMO programmes and many of the private initiatives also depend in one way or another on the technology and/or science expected to come from ITER, e.g., in testing of blankets, tritium breeding, plasma science, etc. Among the key timeframe milestones for ITER are:

- ***ITER first plasma*** – this would herald a step towards functioning of the machine and provide confidence it could work. The overall benefits to fusion science may not be great, but it would clearly signal that the project can be successful and would encourage continued public and (indirectly) private investment. However, conversely it also represents a step with more downside risk, i.e., if it is delayed or technical problems are experienced, then this can reduce confidence in the sector, and potentially impact on funding and even participation. First plasma is already expected to be delayed from the 2025 schedule due to COVID and other disturbances in the last few years. It is not yet known until when it is delayed, but 2028-2030 could be a reasonable base assumption. The actual schedule will be confirmed once the revised ITER baseline is released, likely in early 2023 (but probably only approved in late 2023).
- ***ITER DT operation*** – this is expected to confirm high levels of energy gain (Q~10) that would demonstrate the viability of fusion as an energy source. This would represent a key breakthrough moment for fusion as a whole. It is an essential step for many initiatives which are dependent on these scientific outcomes, especially DEMO, which will rely on ITER experimental proofs and science before designs can be finalised. We note that the DT campaign at ITER would not immediately deliver the necessary data and proofs for DEMO, this may take 1-3 years. Interviews with those in the sector indicate a hope that the original schedule for DT operation in 2036 can be maintained in the revised baseline, however it would not be unexpected for this to be put back at least 1-2 years.

Net energy gain: scientific and engineering net gain can be distinguished, other important related aspects include achieving 'ignition / burning plasma' which has only been briefly demonstrated so far in inertial fusion at the NIF. Achieving any of these milestones would not necessarily demonstrate the viability of fusion power, as gain may be small, too small to provide actual 'wall-plug' net gain. Additionally, it is certain that many aspects necessary for a power plant (e.g., materials, tritium, RAMI, etc;) would remain unsolved, although partial solutions may be tested. However, net energy would represent a major breakthrough in the sector and very likely prove a catalyst for significant additional investment, especially in private fusion initiatives. The impact of this achievement could vary per fusion approach, e.g., MCF different to ICF, as does the relevance of Q values between the two approaches (i.e., ICF requires higher Q to be viable for power production). Elaborating the key milestones:

- ***Net scientific energy gain*** i.e., when the energy released by the fusion reactions (as evaluated at the plasma boundary) is greater than the specific energy used to achieve the reactions, or Q>1 (P_{fus}=P_{heat}). This will be a very important milestone for any fusion approach or initiative, demonstrating at a basic level that fusion energy is possible. The first occasion that this is achieved is likely to represent a watershed moment for fusion energy, helping to bolster the case for continued public funding of fusion energy (including towards DEMO) and, more importantly, especially if achieved by a private firm, likely to attract much more private investment. This would increase the impetus and urgency to move towards pilot power plants. In the base case ITER is expected to achieve a Q of around 10 in DT operation, this gain will be in terms of plasma heat, e.g. inputting 50MW of heat to the plasma and achieving a 500MW heat output. However, the conversion steps to generate the input heat (estimated at 100-600MW electrical power input at ITER), and later conversion of heat to power again are not included (ITER will not generate power, the heat will be vented), nor are the energy needs of the rest of the balance of plant.. Only NIF of the other planned or active devices of the public initiatives seems able to achieve net scientific gain. Many of the private initiatives hope to achieve this before ITER, and a handful of the most ambitious and advanced hope to already achieve this in the 2024-2027 period.
- ***Ignition / 'burning' plasma*** achieving conditions where the plasma becomes self-heating, where no external energy is needed to sustain the plasma at operational temperatures is an important milestone. This would significantly increase the energy efficiency of the system, bring the possibility for power generation much closer. It is estimated that in a tokamak with a DT fuel mix ignition can be achieved at a Q~5.

The survey of private fusion initiatives carried out as part of this work shows when the private part of the fusion sector expects these milestones to be achieved. Public fusion experts, based on interviews, are more sceptical of these ambitious timelines.

Table 4-1 Survey results, private fusion activities opinion on timing of key fusion milestones

In which period do you think	Before 2025	2025-2030	2031-2035	2036-2040	2041-2045	2046-2050	After 2050	Never	Don't know	Count (n)
The first fusion experiment will achieve scientific net energy?	11	13	1	0	1	0	0	0	1	27
The first private fusion experiment will achieve scientific net energy?	8	17	1	0	0	0	0	0	1	27
The first fusion experiment will achieve engineering net energy?	2	9	11	2	1	0	0	0	1	26
The first private fusion experiment will achieve engineering net energy?	2	10	12	1	0	0	0	0	1	26
The first fusion plant will deliver electricity to the grid?	1	3	14	7	2	0	0	0	1	28
The first fusion plant demonstrates a low enough cost/high enough efficiency (Q) to be considered commercially viable?	1	2	12	6	3	0	1	0	1	26

Source: Trinomics and FIA survey (2022)

4.2.3 Dimensions important for pilot plants

At the pilot plant stage the most difficult technical problems come into much more serious focus. We detail a number of these below and some of the aspects relevant for the scenarios.

First pilot power plant: in a base case EUROfusion roadmap scenario this would be the DEMO plant in the EU, or similar in one of the other major fusion nations. Equally it could be a first pilot plant by one of the private initiatives. This pilot plant would at least demonstrate net engineering energy gain, and most likely also 'wall-plug' energy gain. It should integrate all, or almost all, elements necessary for a commercial power plant. It would aim to demonstrate a design from which a final design can be extrapolated and/or refined. This may need a second pilot plant iteration in some cases to address all issues, such that a first generation of commercial fusion plants could be designed and built. Among the key timeframe milestones would be:

- ***Net engineering energy gain***, when the energy released by the fusion reaction is greater than the energy required to sustain the fusion reactions (i.e., after energy extracted from the reactor is recirculated to sustain the systems powering the reactor) – such that excess power can be produced, and sold. The Q value to achieve gain will vary significantly per device, fuel and other characteristics, but a range of around 5-8 is thought necessary for magnetic confinement based devices. For inertial fusion approaches the values would be significantly higher, with Q values of around 100 believed necessary. The first occasion that net engineering energy gain is achieved is also likely to represent a watershed moment for fusion energy, even more so than net scientific energy gain, this would bring fusion to the point that the first commercial power plants become a possibility. It is possible that ITER can demonstrate this theoretical possibility, but without the ability to extract any power, DEMO would be the next step to demonstrate this in practice. Demonstrating net engineering gain already at the next device stage, as noted above, would add significant urgency and impetus (and likely funding) to build pilot plants to take the next steps in integrating a fusion power plant system.
- ***First electricity on the grid***, the moment when the first electricity from a fusion plant is sent to the grid would represent a major step for the sector. It may be possible to achieve this without having sufficient energy gain for commercial viability, i.e., some may aim for this only to show it is possible.
- ***Performance at power plant equivalent levels***, i.e., that the power multiplication is high enough to ensure **wall-plug energy gain**, and high enough to make a power plant feasible (one estimate for MFE approaches put this at a Q value of around 20[75]). This is demonstrated by putting net electricity onto the grid. Performance would also need to demonstrate **sustained operation**, in steady state approaches a demonstrated ability to sustain the fusion reaction for long periods of time, or in pulsed approaches the demonstrated ability to achieve the required rep-rates to enable sustained power generation. **Sufficient availability** (load hours) will also be a factor closely link to sustained operation, availability may not be as high as necessary for a power plant, but should give a strong indication that this is possible to achieve.

Resolution of (or major progress on) key technical challenges: a variety of key technical challenges will likely remain to be solved at the pilot plant stage. The survey of private fusion initiatives asked which were the most major challenges in the short (to 2030) and medium-long (after 2030) term. The

[75] Samuel E. Wurzel and Scott C. Hsu (2022) Progress toward fusion energy breakeven and gain as measured against the Lawson criterion. Physics of Plasmas 29, 062103 (2022)

results, presented in Table 4-2, show that in the short-term, and consistent with the focus on next experimental devices the major challenge is to demonstrate power multiplication (high Q), with plasma science a closely linked challenge. Beyond this, funding is seen as the next major challenge, and neutron resilient materials are also highlighted. Other key issues such as tritium self-sufficiency receive less attention. After 2030 the picture changes, as initiatives expect to move onto pilot plants, the key challenges are expected in addressing full life cycle issues (maintenance, waste, etc;), neutron resilient materials, regulation and tritium self-sufficiency. The relatively low ratings for cryo-plants and plasma exhaust imply that firms believe these issues are less severe/have easier paths to solutions. The main challenges for the after 2030 timeframe are discussed further below.

Table 4-2 Survey results, private fusion activities opinion on major challenges for fusion

What do you see are the main challenges for fusion energy	Up to 2030					After 2030				
	Major challenge	Minor challenge	Not relevant in this time-frame	Don't know	Count	Major challenge	Minor challenge	Not relevant in this time-frame	Don't know	Count
Fusion power efficiency; achieving high-enough gain (high Q) fusion power	21	1	1	2	25	4	8	5	3	20
Plasma science	15	8	0	2	25	3	10	5	2	20
Cryo-plants (heat management)	3	15	4	3	25	4	9	4	3	20
Plasma exhaust	6	11	3	4	24	7	6	5	3	21
Pulse Duration	6	9	5	4	24	5	8	4	4	21
Tritium self-sufficiency	8	9	5	3	25	10	7	3	2	22
Neutron resilient materials	12	6	5	3	26	13	5	1	2	21
Nuclear safety/regulatory approval	9	12	4	2	27	13	6	1	2	22
Integrated systems engineering	10	10	2	2	24	7	8	3	3	21
Full life-cycle issues (e.g., maintenance, waste, recycling, decommissioning)	7	7	9	2	25	16	2	3	2	23
Funding	18	5	1	2	26	8	9	4	2	23
Other (please specify)	4	1	0	3	8	0	0	1	4	5

Source: Trinomics and FIA (2022)

Full life-cycle issues: regarded as one of the critical issues for a pilot plant and eventual commercialisation, this encompasses operational issues in terms of maintenance and dealing with waste streams, and then through to end-of-life management and decommissioning. In terms of operational issues the pilot stage will need to demonstrate availability and the ability to maintain and repair the plant. For the majority of plants, which are using tritium this will require further development of remote handling and radioactive safety technologies and processes, these will need to demonstrate that key components, including those that may be radioactive from neutron exposure such as blanket modules and first wall materials, can be safely handled and replaced, and the used components handled appropriately (stored, recycled, disposed) at the end of their expected lifetime. This is likely to require further advances in remote handling and robotics, due to high temperatures (long cool down times) and radioactivity preventing direct human interaction with reactor components. Current technological progress in this area is only around TRL 1 or 2, lagging behind many other components. The UK has setup the Remote Applications in Challenging Environments (RACE) centre to develop these technologies, and activities have also been carried out by the EU and Japan under the Broader Approach IFERC project. Life-cycle issues will also require that there are established processes to handle this waste. This can draw on long-standing experience in the nuclear fission sector, but fusion specific processes will be needed. Issues related to decommissioning will need to be thought through in designs too. Milestones could include:

- ***Demonstrated repair and/or replacement of reactor components*** – using appropriate remote handling, robotics or other approaches that demonstrate the ability to carry out maintenance in a timely and safe manner. This will be needed to provide confidence that a fusion power plant can be maintained and operated over the long-term. Cost considerations will also be important at this stage in view of the targeted LCOE of plants and the role of these operational costs.
- ***Demonstrated waste handling and decommissioning processes*** – which show that activated materials can be safely handled and that designs are made with eventual decommissioning in mind. Decommissioning can lean on lessons learnt from the decommissioning of JET, planned after 2023, and in the timeframe of this step of other public (and possibly private) devices that will retire in the 2030's.

Neutron resilient materials: as outlined earlier developing materials to line the inside of the fusion reactor is a necessity for a power plant in most approaches. Similar to life-cycle issues current technological progress in this area is only around TRL 1 or 2. Materials need to operate in a high temperature, neutron rich environment for a prolonged period, and therefore need to demonstrate resilience to these extreme conditions. Without this resilience then regular replacement of wall materials would be likely to impose a very high cost constraint on fusion power, and also significantly increase the volume of nuclear waste (albeit short-lived nuclear waste) that needs to be dealt with. In the EU the research pathway for fusion will look to build a neutron source facility, IFMIF-DONES, to test materials in fusion-like conditions. This will build upon the developments carried out by IFMIF-EVEDA in the Broader Approach programme. In the UK a facility called CHIMERA (CCFE) is to be developed which will similarly look to re-create fusion-like conditions to test materials. Other programmes are also active which will support research in this area, and some private companies only focused on this issue are emerging, e.g., Oxford Sigma. However, solutions in this area remain an open question for many of the private initiatives. Among the key milestones:

- ***Demonstration of neutron resilient materials*** – which can cope with the high temperatures, heat flux, neutron exposure and high magnetic fields of a fusion device for an extended period of time. Demonstration of materials that can retain their properties to enable safe and sustained long-term fusion plant operation would be a major step towards making fusion power possible.
- ***Demonstration of alternative approaches to materials*** – a handful of the private initiatives aim to side-step the primary issue of first wall materials using innovative approaches. As noted below, some intend to do so through using aneutronic fuel mixes. Others (e.g., First Light Fusion, General Fusion) are looking at alternatives such as using liquid metal (lithium) as a wall/blanket-style material; Others are considering direct energy conversion. These alternatives then pose their own specific technical challenges.

Tritium self-sufficiency: the majority of fusion initiatives, but not all, propose a Deuterium-Tritium fuel mix to provide the most efficient way to meet fusion conditions. As noted previously this is one of the major challenges for many fusion initiatives, and whilst the breeding concept is known and some proofs have been carried out, the technology is not well developed at present and has not operated in an actual device, i.e., it is currently at TRL 1-2. If this cannot be addressed it could prove a significant hindrance to most fusion initiatives. Activities are ongoing to address the Tritium cycle, with work to develop Tritium blanket technologies ongoing in most public fusion programmes and intended to ramp-up, e.g., CHIMERA and H3AT (CCFE) in the UK, EUROfusion work on test blankets for ITER and similar in Korea and other nations. Less work is being carried out so far by the private initiatives into tritium, although some specialist companies have also been founded to address these issues, e.g., Kyoto Fusioneering, who are not developing a reactor or a plant, but focusing on developing and selling products or reactor components, amongst which they focus on tritium technologies. ITER is intended to be a test-bed for a number of different blanket concepts. Some private initiatives have developed novel approaches to this issue such as using liquid metal blankets. Among the key milestones could be:

- ***Demonstrated successful Tritium breeding in fusion power plant-like conditions*** – using mainstream blanket technologies, and technologies to handle tritium gases, extraction and recovery, to achieve a breeding ratio close enough to (at DEMO / pilot stage) or greater than 1-1.15 (necessary for growth and expansion of fusion power based on DT – given limited global tritium supply). This could also include the success of alternative approaches to breeding blankets, such as the use of liquid metals (Lithium) as proposed by some private initiatives e.g., General Fusion.
- ***Demonstrated successful operation of non-tritium approaches*** – a handful of the private initiatives seek to avoid the tritium issue by using alternative fuel mixes, notably pB11 and D-He^3, as these lead to aneutronic fusion and/or may also allow for direct energy conversion rather than the use of blankets. Whilst these alternative fuels and approaches are attractive from a reduced neutron perspective, they pose significant alternative technical challenges. These include the significantly higher temperatures required to achieve fusion, and for He^3 the lack of a natural terrestrial fuel source (although one firm claims to have developed an industrial approach to manufacture this fuel[76]), amongst others.

4.2.4 Other important dimensions

Commercial power plants, as the final step following successful pilot plants. This step will still require final issues and engineering challenges to be resolved. It is also worth noting that whilst the next step commercial plants are dubbed 'commercial' it remains highly likely that the cost of the electricity from these plants would remain relatively expensive and, as has been the case for every new energy technology in the last decades, require public support (subsidy) to enter the market at first (it is assumed there is a gap in the market for fusion – see section 4.3). Scale and learning effects would be expected, and necessary, to bring fusion energy to actual commercial competitiveness. It is assumed (see following section) that there is a market for fusion energy in the coming decades.

Many other important dimensions were also identified and discussed in section 3.4 or 4.1, for example the role of **regulation, funding, staffing, developments in other fields, and public acceptance**. Each could play an important role at any stage of any scenario. Other issues are less discussed but can

[76] By fusing Deuterium in a particle accelerator https://www.helionenergy.com/faq/#:~:text=Helium%2D3%20is%20an%20ultra,%2Defficiency%20closed%2Dfuel%20cycle.

become important, particularly later in fusion development, for example **supply chain issues and costs**. Most of these issues are likely to be common across scenarios, and are highlighted in the scenario discussions when relevant. The size and direction of impact of these dimensions can vary, for example staffing issues will be influenced by success (or delay) in fusion, as these can attract more (or fewer) people to work in the sector. Regulation can be important as a factor in determining the speed of development, fast development scenarios require an accommodating regulatory regime in key countries, however a regulatory regime following nuclear fission would be likely to seriously slow fusion development.

Catalytic events have been referred to previously as there are a handful of moments, particularly around the demonstration of net energy gain, that could potentially act as huge positive catalyst moments for fusion – these are considered in the scenarios. In contrast, there is also the potential for **negative catalytic events**, for example failure of ITER in commissioning causing catastrophic damage to the machine, or failure of one of the private initiatives where investors face significant losses. These and other negative occurrences (fraud, disaster, fatal accidents, etc;) can also be considered, and could potentially have significant negative impacts on the sector as a whole. The potential impact of such an event has been discussed with experts and a few important points noted:

- Such an event would undoubtedly be a setback for the sector as a whole. In the public sector difficult questions would be asked around continued funding for fusion, with the risk that this would be reduced, and that new devices, and/or preparations for these, are not funded.
- In the private sector a major setback would be most serious for the affected firm, and those following a similar approach, i.e., a major setback in inertial confinement would affect all firms pursuing this approach, but also for the sector as a whole. This would likely result in more difficult access to capital as more risk-averse investors avoid fusion, and other investors do more detailed due diligence or demand greater returns/assurances. However, at the same time most investors should go into fusion with their 'eyes open' to the high risks.
- Depending on the type of event it could negatively affect the public perception of fusion energy, influencing public funding and possibly creating siting issues.
- In the long-term it is thought such a setback would only be temporary, experts pointing to the examples of the cold fusion 'hoax' in the early 1990's which slowed public funding for a short time, and Fukushima in nuclear fission which led some countries (e.g., Germany) away from nuclear power, and others to postpone decisions expected to invest in new fission plants, but where we see now fission regaining momentum in many countries, which are deciding in favour of new nuclear in response to the climate crisis and current energy price crisis.
- Positively, given the multiple approaches to fusion, a major setback in one approach would not necessarily remove the possibility of others succeeding, i.e., there are 'multiple shots at goal'.
- The other long-term driver is the energy market opportunity in the context of climate change and the energy transition, which represents trillions of euros of investment globally each year. The market pull of which will remain strong and urgent, and means fusion will still tempt those who believe in it as a potentially lucrative solution.

The focus of this work is on fusion energy for electricity generation, however there are a few fusion initiatives focused on **other applications for fusion energy** as their primary targets, notably space propulsion. One firm, Shine Technologies[77], also envisages a route to fusion power but starting from its development of neutron sources for medical purposes, then following into nuclear materials transmutation / cargo scanners, and then towards fusion power. It is already successful in the first market. Success in these other fields could have spillover successes for fusion for electricity generation.

4.3 Scenarios

Common scenario assumptions

The scenarios will be analysed on a fixed assumption for the world outside fusion. Key characteristics of the overall context include:

- Climate change mitigation remains a key policy goal and challenge globally into the 2050's
- A market opportunity for fusion power remains as:
  - Growing energy demand globally increases the need for power sources, as does the standard need to replace older power production capacity.
  - No other major breakthrough energy generation technologies are discovered, e.g., renewables are well established and expanding, but face issues (see next), whilst batteries and hydrogen increasingly play a role in the energy system as a means of storage/as energy carriers, but a potential market for fusion remains.
  - Intermittency of renewables remains a challenge for the energy system.
  - Nuclear fission continues to have major environmental and cost risks and public perception issues that cannot be fully mitigated.
  - Energy independence and security, post Ukraine-crisis, becomes increasingly important, the opportunity for fusion as something that offers high availability and can be operated with minimal fuel imports is an important advantage.
- Uncertainties are certain – it is not possible to predict random events, e.g., Ukraine-Russia, Fukushima disaster, undoubtedly similar events will occur in future, but it is impossible to know, nor predict how fusion development could be affected.

Defining scenarios

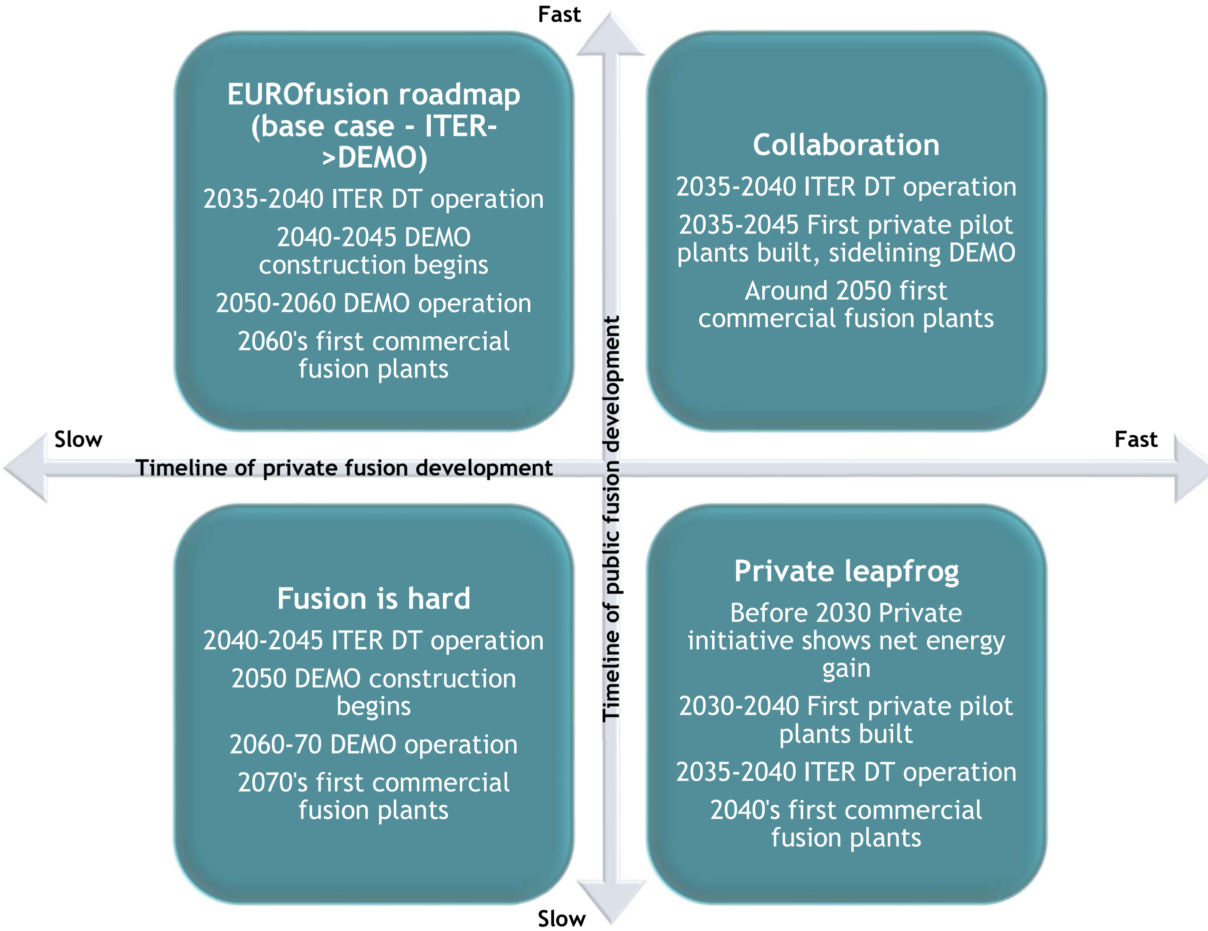
This work has developed four scenarios through which to consider and analyse the implications of different pathways of fusion development. The development and definition of scenarios builds upon the timeframe analysis of the previous chapter, and takes into account the key challenges and barriers highlighted in the previous section. Our approach to the scenarios is based on a classic scenario quadrant which contrasts the speed of public and private fusion development as the two main axes:

1. **The timeline of success of the publicly funded fusion initiatives**, and especially the EU activities, namely via the EUROfusion roadmap, e.g., ITER -> DEMO, plus IFMIF-DONES and the Stellarator line. Internationally the main efforts also follow an ITER->DEMO equivalent pathway. In inertial fusion whilst NIF can still have an impact in the coming years there is not a convincing commitment anywhere for new public ICF facility.
2. **The timeline of success of private fusion initiatives**, which covers the diverse range of efforts globally which are growing in number, attracting increasing amounts of funding and making bold promises on how they have a faster pathway to fusion energy than the publicly funded ITER->DEMO pathways.

This framework provides for four over-arching narratives, as shown below:

[77] https://www.shinefusion.com/mission-vision/

Figure 4-2 Scenario narrative outline



4.3.1 EUROfusion roadmap (base case - ITER->DEMO)

In this scenario, the development of fusion follows roughly the EUROfusion roadmap, private initiatives do not play a major role.

Next device

In the **public programmes** ITER first plasma occurs around 2028-2030, and this event gives confidence to the programme. ITER begins DT operation in the 2035-2040 timeframe, and demonstrates net energy gain in the order of Q=10 as hoped for, it also achieves ignition showing that a self-heating plasma can be achieved. Other approaches make some progress, i.e., NIF is able to demonstrate scientific energy gain in the 2020’s but no public follow-on inertial fusion facility is planned or built in the US or elsewhere; The W7-X (stellarator) and NSTX-U, MAST-U (spherical tokamaks) progress their approaches during this period but do not have the capabilities to progress to a level similar to ITER. IFMIF-DONES is built during this period and begins operation around 2030.

In this scenario **private initiatives** do not play a leading role. Whilst a few of the private initiatives do succeed in demonstrating progress prior to ITER DT operation, for example achieving net (scientific) energy gain in the late 2020’s, a handful of initiatives fail and none of the approaches are able to demonstrate ignition. These mixed outcomes slow the sector somewhat, although funding for pilot plants is secured by the most successful initiatives.

Pilot plants

In the **public programmes**, DEMO concepts in the EU (and elsewhere) are finalized following ITER DT operation (around 2040) and DEMO construction begins before 2045, possibly earlier in UK (STEP) and China (CFETR). The difficulties experienced by private initiatives next devices and the success of ITER bolster the case for public funding for DEMO. One or more of the DEMO plants begins operation around 2050. Operating in the 2050's DEMO integrates all key system components – including life cycle relevant capabilities for repair and replacement, and waste handling; of materials resilient to the reactor conditions (tested and validated at IFMIF-DONES); and of tritium breeding and self-sufficiency. Most importantly the DEMO plant(s) demonstrate net engineering gain and performance at power plant equivalent levels that provide high confidence in commercial power and one of DEMO plants puts electricity onto the grid for the first time in the 2050's.

For the **private initiatives** that successfully move to the pilot plant stage, complexities in integrating a full power plant design and some setbacks mean that the first private pilot plants only begin operation around 2040 and have varying degrees of success. At least some of the key technical issues are not fully solved, and the pilot plants do not provide full confidence that a commercial plant can be extrapolated and built based on these designs. The sector, especially the MFE-based approaches, increasingly look to DEMO to show how these final issues can be resolved.

Commercialisation

Following DEMO success the private initiatives pick up the baton, and begin to develop and deliver the **first fleet of commercial plants (based on the MFE tokamak approach) in the 2060's.** This first generation requires significant public support to reduce risks and guarantee returns for investors. One or two alternate fusion approaches (stellarators, spherical tokamak, IFE-based) also reach the commercial plant stage in the late 2060's/2070's.

4.3.2 Collaboration

In this scenario, there is a greater emphasis on public-private collaboration and interaction as private initiatives also move forward on a similar timescale to the public fusion initiatives.

Next device

For the **public programmes** this follows the same course as the EUROfusion roadmap scenario (see previous section).

In this scenario **private initiatives** succeed in demonstrating significant progress prior to ITER DT operation. In the mid-2020's a handful already demonstrate net (scientific) energy gain and one or two of these are also able to demonstrate ignition. Whilst a few initiatives still struggle, the success of the next devices of multiple approaches attracts significant funding and interest, particularly for the successful initiatives, but also more broadly across the sector. This funds the development of pilot plants, and also increased research into the other key technical issues.

Pilot plants

In this scenario we consider the **private initiatives** first as they move faster at this stage. After the success of their next devices the first wave of private initiatives begin construction of their pilot plants, the first of which are completed around 2036-2038. These pilot plants are able to build further on the earlier successes, demonstrating in the period up to 2045 scaling of the designs so that net engineering gain and performance is achieved at levels that give confidence for commercialisation and the first electricity is put onto the grid. These pilots also successfully demonstrate resolution of a few of the key technical issues, e.g., tritium sufficiency. However, some question marks remain over other key technical issues, e.g., materials and life-cycle related issues.

In the **public programmes**, the success of the private initiatives, operating pilot plants at almost the same time as the ITER DT campaign begins leads to a re-examination of goals. The first results from ITER DT operation are as promised, giving the public programmes the confidence they can deliver, also generating scientific and other results valuable to the fusion sector as a whole. However, the narrative on fusion has evolved to the point where most people see the private sector, due to its faster progress and large investments, taking the lead in future fusion development. Politically this makes funding DEMO difficult in all nations, except China. Public programmes in the EU and elsewhere note that some key issues are not yet solved by the private pilot plants, and therefore DEMO workstreams and funding are re-purposed towards addressing these questions. Working with private initiatives to help understand the key questions still to be solved, and where public money could be best directed. The particular issues are unknown, but it could be envisaged for example that IFMIF-DONES and equivalent facilities in the UK and China start to achieve necessary progress on materials questions in the 2040’s, and repurposed DEMO programmes focus on life-cycle issues that the private initiatives are also struggling with.

Commercialisation

The collaboration between the public and private sector, with the public fusion programmes focusing on resolving the most difficult remaining issues, allows for the first commercials plants to designed and construction to begin around 2045. The **first fleet of commercial plants (based on multiple approaches) enters operation around 2050.** This first generation requires significant public support to reduce risks and guarantee returns for investors.

4.3.3 Private leapfrog

In this scenario, the private initiatives play the leading role, finding a way to keep close to their ambitious timelines and side-lining the public programmes as they ‘leapfrog’ ahead.

Next device

In this scenario the first **private initiatives** succeed in both keeping their timelines for next devices and in achieving many of their targeted goals with these devices. Already from 2024 the first initiatives show results demonstrating significant progress, and more next devices come online each year in the 2025-2030 period, most of which provide encouraging results. Milestones achieved in this period already include net (scientific) energy gain and ignition, one or two claim also to achieve net engineering gain. Whilst one or two few initiatives still struggle, and fail, these do not change the huge excitement being generated by successes in the sector. The successes attract significant funding and interest, particularly for the successful initiatives, but also more broadly across the sector. This funds the development of pilot plants, and also increased research into the other key technical issues.

The **public programmes** follow the same timeline as the EUROfusion roadmap scenario (see previous section), but this timeline now has ITER first plasma occurring after some of the private initiatives are already trumpeting their successes. This provides fuel for critics and sceptics of ITER to question its value, although ITER continues DEMO becomes much more questioned. Starting around 2035-2040, ITER begins its DT experiments, however, due to the speed with which the private initiatives have developed ITER funding is slowly tapered off after 2040, and plans for DEMO plants are shelved.

Regulatory regimes in the UK, US and leading EU countries are accommodating to fusion, separating it from fission regimes.

Pilot plants

The **private initiatives** build on the success of their first devices, and move quickly to their pilot plant stage. The first of these are completed in the early 2030's. These pilot plants are able to build further on the earlier successes, demonstrating the necessary scaling of the designs so that net engineering gain and performance is achieved at levels that give confidence for commercialisation. The first electricity from a fusion pilot plant is put onto the grid around 2035. These pilots also successfully demonstrate resolution of most of the key technical issues. The leading private initiatives, and an increasingly active service and technology supplier ecosystem, focus on the key technical issues in parallel to the pilot plant development and operation, utilising the significant funds available, taking iterative approaches, and utilising advances in other fields they are able to make faster progress than many expected. Some initiatives build second pilot plants in the late 2030's to apply these solutions and demonstrate a fully integrated power plant system.

Staffing becomes an increasingly acute problem for the private initiatives in this scenario, whilst people are attracted from public programmes the speed of the growth of the sector is faster than the pipeline of qualified fusion experts coming through educational institutions.

The **public programmes**, seeing the speed of success of the private initiatives, face tough choices as it becomes apparent that ITER will only be a sideshow to the development of fusion energy, and that DEMO will be unnecessary. DEMO plans are shelved in all nations. Public programmes reorient their activities and funding is reduced, but still play a role in developing science, knowledge and staff useful for the sector as whole.

Commercialisation

The success of pilot plants in the 2030s and resolution of major technical challenges allows for the **first commercial fusion plants to be rolled out from the early 2040's.** Two or three fusion approaches reach this stage in the 2040's.

4.3.4 Fusion is hard

In this scenario, neither public nor private fusion initiatives are able to progress at the speed they wish due to various difficulties and technical challenges proving very difficult to resolve.

Next device

In the **public programmes** ITER first plasma occurs after 2028-2030 with some delays compared to the re-baselining. Issues are encountered in the further upgrade and commissioning of ITER which delay DT operation into the 2040-2045 timeframe, which could pose difficulties with the maximum timeline extensions specified in the ITER agreement (i.e. up to 2052). ITER is able to demonstrate net energy gain in the order of Q=10 as hoped for, it also achieves ignition showing that a self-heating plasma can be achieved, however other unexpected technical issues emerge. Pressure on public budgets in this timeframe mean that IFMIF-DONES is not fully funded, and the timeframe for this facility slips back into the 2030's.

In this scenario **private initiatives** do not play a leading role. The first of the private initiatives to build their next devices do so around 2025, although most slip 1-3 years from their targeted timelines. The results are patchy, net (scientific) energy gain is shown, but none of the approaches are able to demonstrate ignition. One or two of the most high-profile initiatives fail to meet their milestones, their concepts being shown not to scale or perform as hoped. These mixed outcomes slow the sector significantly, investors taking a more cautious attitude to funding, not all initiatives are able to find funding for their pilot plants.

Pilot plants

In this scenario regulators take a more cautious approach in a few key nations, slowing construction and licensing processes and imposing higher costs on fusion initiatives. Staffing is problematic as the difficulties in the sector do not attract enough top talent to the field.

Some of the **public programmes** follow-up ITER with DEMO, however the process to secure funding is long and contentious. DEMO construction only begins in the late 2040s, as designs take time to finalise, particularly for materials where the delays to IFMIF-DONES lead to difficulties in specifying the materials. DEMO in the end is ready by around 2060. DEMO operation in the 2060's is a success, integrating all key system components, net engineering gain and performance at power plant equivalent levels. One of the DEMO plants puts electricity onto the grid for the first time in the 2060's.

For the **private initiatives** that did secure funding for their pilot plant stage, complexities in integrating a full power plant design and significant setbacks mean that the first private pilot plants only begin operation around 2040 and have varying degrees of success. Some of the key technical issues are not fully solved, and the pilot plants do not provide full confidence that a commercial plant can be extrapolated and built based on these designs. Investors become more wary. The sector, especially the MFE-based approaches, increasingly look to DEMO to show how these final issues can be resolved, delays to DEMO affect the timeline for the private sector as a whole.

Commercialisation

Following the eventual DEMO success the remaining private initiatives and major industrial players that now enter the market, pick up the baton, and begin to develop and deliver the **first fleet of commercial plants (based on the MFE tokamak approach) in the 2070's.** This first generation requires significant public support to reduce risks and guarantee returns for investors.

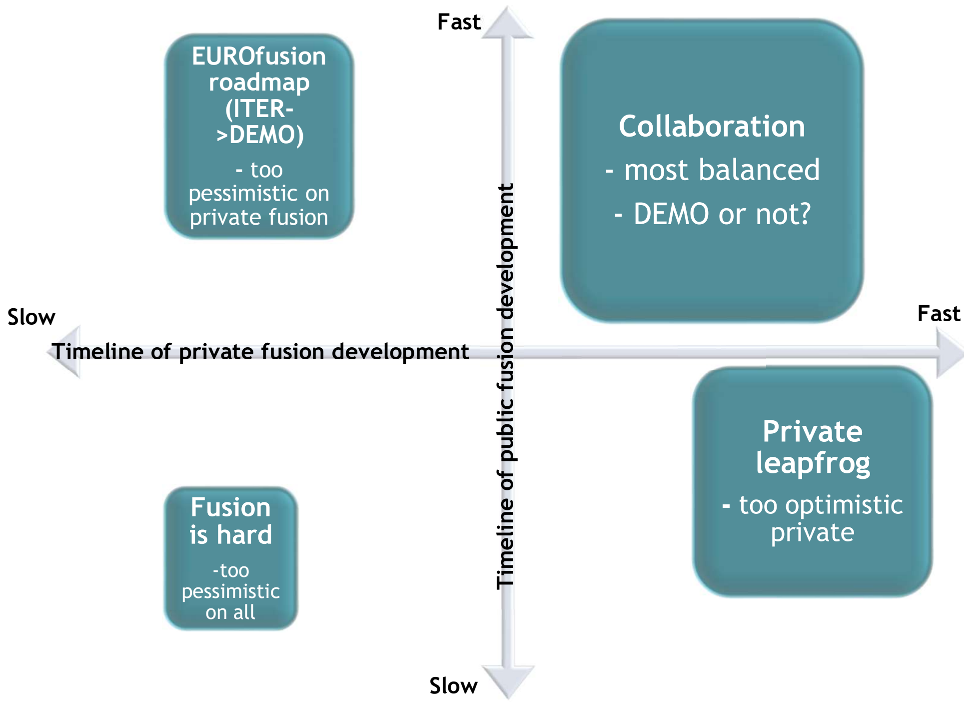
4.4 Analysis of scenarios

4.4.1 Probabilities and risks

If consideration is given to the probability of these scenarios occurring then in the opinion of the team there are a few key points that can be made about each:

- **Fusion is hard** – this scenario is the most pessimistic of all. In our opinion, the likelihood of this outcome is relatively low, it would likely require an unexpected event (accident, fraud, other) to slow long-term progress to this extent. However, it is not impossible, particularly for the public programmes, to be slowed in this way due to their relatively low number and risk aversion in public spending.
- **EUROfusion roadmap** – based on an almost exclusively public pathway to fusion. The EUROfusion roadmap was published in September 2018 and makes no mention of private fusion initiatives, which is not that unusual given the relatively small size and low maturity of private initiatives at that time. However, the growth in the number of firms, the scale of funding and the milestones achieved in the last few years since 2018 highlights that private fusion is something to be taken seriously. A scenario that largely writes these initiatives off, that estimates that despite significant funding, serious and talented teams, achievements made, construction underway on next devices and a variety of approaches, that these have little to offer, seems quite short-sighted. Therefore, whilst still possible, we believe this is not the most likely outcome.
- **Private leapfrog** – this scenario represents the dream of the private initiatives, and is very optimistic and ambitious. It encapsulates what on one hand may be called bullishness, on the other an overly dismissive appraisal of the challenges that remain to be resolved. The narrow focus on more achievable aims, e.g., net energy, and progress already made towards next devices suggests optimism may not be misplaced to achieve these aims, but this is only part of the fusion power challenge. There is an implied dismissiveness of the progress made by the public programmes and the real challenges they have long worked on. There remains a strong 'black box' feeling to many approaches and how they will address the most difficult challenges, maybe there are solutions that are not public or a more exotic approach can succeed, however the uncertainty that surrounds these initiatives recommends caution in evaluating timelines. This scenario is certainly possible, desirable even given the climate and other energy challenges, but remains a long way from fruition.
- **Collaboration** – this scenario strikes a balance between the speed of public and private fusion development. It does not neglect the private sector, nor does it believe all the promises made. It also notes the long experience and successes in the public fusion programmes – where taking an approach that considers all risks and all parts of the system can reduce the risk of setbacks. The critical point in this scenario is at which point the public and private fusion initiatives converge and start working at a similar level and in a similar timeframe, when the leadership may be passed to the private industry. Understanding the implications for the public fusion programme, especially DEMO, when this occurs is crucial. In our opinion, a variation on this scenario is the most likely outcome.

Figure 4-3 Visualisation of probabilities per scenario, size of box reflecting probability (opinion of study team)



4.4.2 Critical moments and implications

It is highly likely that in the period 2024-2028 more than 5 private fusion initiatives will complete a next fusion device. The leading initiatives (CFS, General Fusion, TAE, Helion Energy, Zap Energy, Tokamak Energy) have already secured funding for these devices and are in various stages of design, procurement and construction. Most of these have the goal to demonstrate net energy and/or ignition, for example SPARC at CFS intends to demonstrate a burning plasma and Q>5.

Implications for the EU fusion programme if these succeed include:

- If the success is prior to ITER first plasma it would reflect poorly on the ITER programme.
- If private initiatives are successful after ITER first plasma has already occurred then it would be easier to make a positive story and help to build momentum in the sector overall.
- If the successful private initiatives are mainly non-European, as is likely given the current geographical distribution of firms, then risks increase that European leadership in fusion will be lost.
- Success of the private initiatives could lead some staff to leave public programmes to move to these organisations.

It is likely that in the period 2030-2040 some private fusion initiatives will complete a fusion pilot plant. Many of the leading initiatives already have an outline for what their pilot plant should look like and have a planning timetable towards this (e.g., CFS with ARC, TAE with DA VINCI). Whilst funding for these devices is not yet confirmed, and would be dependent on the success of their next devices, the types of investors attracted and presumed interest if a next device is successful give high confidence that funding would be available at this stage. It is likely that some components or system elements for a fusion power plant will not be ready at the pilot plant stage.

Implications for the EU fusion programme will be dependent on the timing of ITER DT operation:

- If a private pilot plant is successful prior to ITER DT operation:
    - Serious questions may be asked regarding the continued relevance and funding of ITER.
    - Further staff migration from public to private is likely.
- If ITER enters DT operation before a private pilot plant:
    - Implications for ITER will likely be relatively small.
    - This likely signals important dependencies on the work of ITER amongst the private initiatives.

The type of success of a private pilot plant will have an important bearing on the choices for public fusion programmes, especially DEMO. If the success is somewhat narrow, i.e., net engineering gain, possibly also electricity on the grid are demonstrated but some important system components are missing or not at the level for a fusion power plant:

- In the case of narrow private pilot success then the case for funding DEMO remains strong as an integrated system addressing all elements is the key strength of DEMO.
- If a private pilot is more broadly successful, i.e., also demonstrating that most/all key technical aspects are dealt with, then the case for DEMO would be significantly weaker as it will be addressing problems already solved, and 10 years or more later than private initiatives.
    - If the case for DEMO is weaker, then public programmes will need to re-orient. Potential goals could include targeted projects and programmes to address the most urgent remaining technical challenges, reversion to fundamental fusion science, follow-up of approaches with potential but not looked at by others.
- Particularly in the narrow case, but also possible in the broad case, it could be feasible for a public-private partnership to be developed to deliver DEMO. This could deliver benefits for both public and private parties in pooling funding and sharing knowledge and risks.

5 Lessons learned and recommendations

This concluding chapter summarises the key lessons that can be taken from this exercise and forms recommendations on how the EU can respond to these.

- Private fusion initiatives are likely to achieve net energy in the 2024-2028 period, they may also demonstrate ignition and other important fusion milestones.
- Few in the fusion sector doubt the value of ITER, and some believe it is still likely to be first to demonstrate Q>1. Even amongst those that believe another initiative will achieve net energy first, the great majority still believe that ITER is worthwhile and can do highly valuable science and act as a training centre for people working in the fusion field.
- DEMO design activities are underway and are likely to become more explicit under FP10. Final DEMO design will await the results of ITER DT experiments.
    - **Recommendation:** Experience from ITER strongly recommends that industrial players and engineering systems integrators are involved in the DEMO design activities. This should help to reduce risks of delays and cost overruns.
- Materials are likely to remain one of the key challenges for fusion, the IFMIF-DONES facility would be a welcome major addition to the projects globally that are set to tackle this issue. The long lead times for planning and construction, and also for materials to be validated, mean that this facility should be operational as soon as possible. Delays on this facility risk delays to fusion energy as a whole.
    - **Recommendation:** ensure that a positive decision is taken on funding IFMIF-DONES and that work is coordinated with other countries which also work on materials (UK, US, China) and with potential partners (Japan).
- Private fusion initiatives are clustered in the US, and to a lesser extent UK. If there is a desire to build a similar EU private fusion community then urgent action is needed to support the creation of such initiatives. Action would need to be quite urgent as existing companies have a significant headstart.
    - **Recommendation:** For the EU, if there is a desire to promote more private fusion initiatives in Europe, then creating programmes similar to ARPA-E and INFUSE is recommended. Further research would be beneficial to specify the key parameters of such a programme and how it could work in the Horizon funding framework, or in the current phase i.e., before 2028.
- The visibility of fusion within EU policies, models and programmes is very low and can be improved.
    - **Recommendation:** the EC should ensure that fusion is included within the scope of relevant EU funding programmes, strategies and modelling exercises. Some notable areas to be active include, the EU Taxonomy for Sustainable Finance, ensuring that fusion is specifically listed as a sustainable investment, separate from nuclear fission (which is a contentious technology in the current discussions). Other examples include ensuring fusion is one of the dimensions in EU long-term energy modelling scenarios (post 2040/2050); ensuring that fusion is among the technologies that can be financed under specific funding mechanisms when it achieves the requisite level of maturity, e.g., Breakthrough Energy Catalyst, Innovation Fund.
    - **Recommendation:** Linked to visibility, the EC should also be careful to support messaging on fusion that encourages a positive public perception, avoiding strong links to nuclear fission.

- Regulatory approaches to fusion are important – regulation should be proportionate to fusion risks, not based on fission. The UK has already adopted regulation on this basis and the US is forming its approach. The EU regulatory process for fusion appears to be developing much more slowly.
  - **Recommendation:** the EC should push for regulatory agencies in the main MS to develop their approaches on regulation for fusion to provide clarity for the sector.
  - **Recommendation:** the EC should continue to work via international agencies, e.g., IAEA, to seek to harmonised regulatory approaches to fusion globally
- A diversity of approaches to fusion is emerging, a narrow focus on tokamaks in the EU is restrictive. A focus on ITER-DEMO is necessary, but expanding the scope to other fusion approaches could stimulate more activities, and in the area of stellarators greater clarity on the future after W7-X would be helpful.
  - **Recommendation:** the EC should examine to what extent upgrades at W7-X or a pilot plant device based on the stellarator could also be funded.
  - **Recommendation:** examine how the EU could leverage its expertise in laser technologies to create a public inertial fusion energy programme – this would help to accelerate progress in this area beyond what is happening at NIF and elsewhere. It would also have synergies with two of the EU-based firms (Marvel Fusion, Focused Energy) which are pursuing IFE approaches.
- Contingency planning would be valuable, in the case that one or more of the private fusion initiatives succeed in developing a functional pilot plant before 2040 which provides a clear path to commercial fusion as this would have significant implications for DEMO.
  - **Recommendation:** The EC should have a clear idea of how to respond to potential 'leapfrogging' by the private fusion initiatives, having given thought on how to progress (or not) with DEMO and how the European fusion programme may be reoriented if such a 'leapfrogging' occurs.
- Staffing is likely to increasingly become an issue in the coming decades, ensuring a pipeline of qualified scientists, engineers and technicians will be crucial to avoiding that staffing becomes a hindrance to the sector. EUROfusion and others in Europe are active in promoting pathways into fusion, although the pathway from PhD into labs or the sector itself is not always clear, nor is it clear if the pipeline of staff coming through these pathways is sufficient to meet a growing demand from the EU fusion sector.
  - **Recommendation:** The EC should work with EUROfusion and industry stakeholders to better understand the size and nature of this issue, and to develop approaches to retain talent in the European fusion research and industrial community.
- In whichever scenario outcome is closest to reality there will be a massive industrial effort required to scale up the roll-out of fusion power once the first commercial power plants are proven. It could take decades after this for fusion to make up a substantial share of global energy production. In future, it would be useful to carry out work to examine how supply chains could be primed to cope with the scale of this opportunity and to ensure EU industry plays an important role.
  - **Recommendation:** supporting EU industry to be well positioned – either as fusion energy developers, or as key suppliers to leading fusion initiatives, is crucial to fully benefit from eventual fusion energy commercialisation. Better understanding of approaches to achieve this (e.g. public-private approaches successful in other sectors) would help to already support and position EU industry in this way.

Annexes

Provided separately

Trinomics B.V.
Westersingel 34
3014 GS Rotterdam
The Netherlands

T +31 (0) 10 3414 592
www.trinomics.eu

KvK n°: 56028016
VAT n°: NL8519.48.662.B01

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct centres. You can find the address of the centre nearest you online (european-union.europa.eu/contact-eu/meet-us_en).

On the phone or in writing

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

— by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),
— at the following standard number: +32 22999696,
— via the following form: european-union.europa.eu/contact-eu/write-us_en.

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website (european-union.europa.eu).

EU publications

You can view or order EU publications at op.europa.eu/en/publications. Multiple copies of free publications can be obtained by contacting Europe Direct or your local documentation centre (european-union.europa.eu/contact-eu/meet-us_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex (eur-lex.europa.eu).

EU open data

The portal data.europa.eu provides access to open datasets from the EU institutions, bodies and agencies. These can be downloaded and reused for free, for both commercial and non-commercial purposes. The portal also provides access to a wealth of datasets from European countries.